UK Government

RAF018/2425: Refresh of Industry Technology Modelling Assumptions

Final report

Department for Energy Security and Net Zero (2026)

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Acronyms

Acronym	Definition
ADU	Atmospheric Distillation Units
AEM	Anion Exchange Membrane
AHE	Aqueous Hydroxide Electrolysis
ALK	Alkaline Electrolysis
ASK	Annular Shaft Kilns
ASU	Air Separation Unit
ATR	Autothermal Reforming
BF-BOF	Blast Furnace Basic Oxygen Furnace
CaL	Calcium Looping
CaO	Calcium Oxide
CAPEX	Capital Expenditure
CCGT	Combined-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CD-MD	Microwave Assisted Convective Drying
CHP	Combined Heat & Power
CSA	Calcium Sulpho-Aluminate
DAC	Direct Air Capture
DESNZ	Department for Energy Security and Net Zero
DRI-EAF	Direct Iron-Electric Arc Furnace
DSR	Demand Side Response
EAC	Electric Arc Calciner
EAF	Electric Arc Furnace
EPD	Explosion Puffing Drying
e-SMR	Electrified Steam Methane Reforming
FCC	Fluid Catalytic Cracking/Cracker/Converter
FR	Radio Frequency Drying

Acronym	Definition
GHG	Greenhouse Gas
GVA	Gross Value Added
HPC	Hot Potassium Carbonate
HVAC	Heating, Ventilation, and Air Conditioning
IGCC	Integrated Gasification Combined Cycle
IR	Infrared Drying
LEILAC	Low Emissions Intensity Lime and Cement
LPG	Liquefied Petroleum Gas
LPSSD	Low-Pressure Superheated Steam Drying
MDEA	Methyldiethanolamine
MEA	Monoethanoloamine
MFSK	Mixed-feed Shaft Kilns
MOE	Molten Oxide Electrolysis
MOU	Memorandum of Understanding
MSE	Molten Salt Electrolysis
NZIP	Net Zero Industrial Pathway
OPEX	Operating Expense
PC	Portland Cement
PEM	Proton Exchange Membrane
PFRK	Parallel Flow Regenerative Kilns
PSA	Pressure Swing Adsorption
RW	Refractance Window Drying
RW	Window Drying
SME	Subject Matter Expert
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysers
TRL	Technology Readiness Level
VDU	Vacuum Distillation Units
WGSR	Water-Gas-Shift Reactor

Executive summary

The UK Government has legislated a net zero target for GHG emissions by 2050. DESNZ is developing its NZIP2 model which is a tool that produces and assesses net zero consistent pathways to inform carbon budget recommendations. NZIP2 is an optimisation model used to identify the least cost decarbonisation technology pathway for industry based on a site level techno-economic analysis. Informing NZIP2 is a database of techno-economic assumptions on investment and operating (non-energy) costs, efficiency, technology readiness level (TRL), available year, and lifetime, of various baseline and decarbonisation industrial technologies. DESNZ intends to update the database of baseline (based on fossil fuels) and abatement technologies with the latest evidence to ensure the industrial pathways developed are informed by the most recent and accurate technological assumptions. Some of these technologies are considered cross-cutting (e.g. Low temperature heat, High temperature heat, CHPs), meaning they are utilised across a broad range of industrial sectors, whilst others are sector-specific.

Legacy technological parameters within NZIP2 were derived from technology databases such as the Useable Energy Database[1] which relied on sources cited as early as 1998. Most of the financial parameters were derived from sources dating before 2015. Guidehouse has provided an evidence-based update to the parameter assumptions for each of the technologies contained within NZIP2 and has established a process for long-term ongoing update of technology parameters in the future. The refresh of technology assumptions was aimed at ensuring that the database includes the latest view on decarbonisation technology costs in comparison to baseline technology costs. This was achieved by complementing literature review of the latest evidence with an extensive industry stakeholder engagement to validate the various technological parameters. To complement the updated techno-economic parameters, Guidehouse has also provided a technical electrification potential for each sector and how it evolves across each sector.

Beyond the latest evidence, a key improvement of the updated database is the recognition of the impact of scale of installation of CAPEX and OPEX parameters for cross cutting technologies. In the legacy database, the same value was used for CAPEX and OPEX for each cross-cutting technology for all sectors. In the latest iteration, for each cross-cutting technology, a sector is allocated a representative capacity range, and the appropriate CAPEX and OPEX values for that capacity range is allocated. For example, in the case of Low Temperature Heat, CAPEX for a gas boiler for food and beverage sector utilises CAPEX values identified for a capacity range of 1 – 5 MW, whereas chemical sector utilises CAPEX values identified for a capacity range of 25 MW. More than 50% of technologies assessed had a deviation of > +/-50% with respect to the older NZIP2 values. These deviations occurred primarily due to more recent information capturing technological innovation (e.g. for Carbon Capture technologies) and better allocation of financial parameters based on sector specific capacities and applications for cross cutting technologies (e.g. Combined Heat Power and Low Temperature Heat).

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[1] UKERC Energy Demand Theme (University of Bath team) (2010) 'Industrial Energy Use (UK)'

The project also captured the potential for demand side flexibility for electrified technologies for various industrial sectors needed to model participation in grid balancing services. This was achieved by combining insights identified through literature review and industry interviews on process characteristic of various industrial operations to summarise the following 4 variables: Flex capability (yes or no, and duration of notice period), Max peak demand reduction (%), Demand shift timing (before or after peak or both), Demand shift duration (hours), Ramping (up and down – hours).

Electrification potential

Guidehouse has made sector-wide RAG classifications of technical electrification across three five-year time horizons: 2025, 2030, and 2035, based on the availability of relevant electrification technologies (Table E1). The recommendations made are based on technical electrification potential. These are not predictions of actual realised electrification – likely to be lower due to several practical constraints (e.g. relative power price, grid constraints, site-related spatial constraints, etc.), which may render alternative decarbonisation technologies more attractive. Further information on a sector-by-sector basis is included in the report.

Table E1: Summary of Guidehouse's sector-wide RAG classifications for electrification potential

Sector	2025 RAG Rating	2030 RAG Rating	2035 RAG Rating
Ceramics	Amber	Amber	Amber
Chemicals	Red	Amber	Amber
Glass	Amber	Green	Green
Food & Drink	Green	Green	Green
Mechanical Engineering	Green	Green	Green
Non-ferrous Metals	Green	Green	Green
Pulp & Paper	Green	Green	Green
Vehicles	Green	Green	Green
Textiles	Green	Green	Green
Lime	Red	Amber	Amber
Cement	Red	Amber	Amber
Refineries	Red	Red	Red
Iron & Steel (Primary & Secondary)	Amber	Amber	Amber
Hydrogen (Gasification only)	Unknown	Unknown	Unknown
Electrical Engineering	Unknown	Unknown	Unknown

Green = High readiness or adoption

Amber = Moderate readiness or adoption

Red = Low readiness or adoption

Grey = Not applicable or no data

Retrofit versus greenfield costs

Within the accompanying database to this report, Guidehouse has provided additional information, where available, on: **(1) the retrofitability of certain decarbonisation technologies (i.e. is the technology more suited as a retrofit or greenfield solution), (2) associated retrofit costs, and (3) associated production downtimes for the retrofitted plant**. An additional comments column has been added to justify any categorisations, as well as a column for relevant sources of literature.

NZIP2 technology database recommendations

Guidehouse has made the following recommendations:

- **Improve the granularity of energy-use breakdown:** Currently used ECUK energy consumption breakdowns do not provide sufficient granularity to map energy consumption and emissions to more than one cross-cutting technology per sector. For example, all energy use in NZIP2 corresponding to Low Temperature Heat technology is assumed to be boilers, when in reality a number of direct heating applications not reliant on steam are employed within industry. Further sector specific literature review and interviews would be necessary to identify breakdown of low temperature and high temperature heat technologies by end use applications (e.g. boilers, ovens, types of furnaces etc.)
- **Expand the list of technologies that can be adopted:** Throughout the process, Guidehouse has advised on where technologies should be included or excluded from the current NZIP2 model. The following table summarises alternative technologies to consider for NZIP2:

Table E2: Alternative technologies to consider for NZIP2

Technology group	Alternative technologies
Cement	LEILAC, Indirect Calcination, Mineral Carbonation
CCS	Solid Adsorbents - Pressure Swing Adsorption/Vacuum Swing Adsorption, Non-amine based chemical solvents e.g. HPC, Membranes, Cryogenic Separation with Membrane/ Pressure Swing Adsorption[2]
High temperature heat - electricity	Induction heating, Di-electric heating, Infrared heating, Plasma torches
CHPs	Internal combustion engines, fuelled by natural gas, hydrogen or biogas

- **Update financial parameters:** Guidehouse recommends utilising the current maturity of technologies (e.g. TRL and expected start date) and data confidence scores, along with a qualitative judgement for potential cost reductions based on the nature of the technology (e.g. novel technologies versus well-established). Guidehouse also recommends the modelling of future cost reductions by applying learning rates where possible. These should be supplemented with additional evidence on the uptake of technology (e.g. number of units sold per year). As such, the following data confidence/future disruption **framework** Table E3 has been developed to provide recommendations for future updates to the NZIP2 technology database.

Table E3: Guidehouse's proposed framework for evaluating the need for future updates to the NZIP2 database

Technologies / Processes	Future Disruption	Data Confidence
Drying – Ceramics	None	Low
Paper production, High temperature heat	None	Low-Moderate
Iron & Steel Furnaces	None	Moderate
Baseline Drying, Baseline CHPs	None	Moderate-High
Motors, Baseline – Low temperature heat	None	High
Crackers	Moderate	Moderate
MEA CCS	Moderate	Moderate-High

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[2] Note that with CCS, different combinations of technologies can also be used, especially when the purity of CO2 required is high. For example, oxyfuel combustion can be combined with amine-based post-combustion carbon capture systems.

Technologies / Processes	Future Disruption	Data Confidence
Electric low temp heat, Heat pumps	Moderate	High
Novel Iron & Steel Furnaces (e.g., HISARNA);	Moderate	Low-Moderate
Electric Cold Top Furnace	Moderate-High	Moderate
Oxyfuel CCS; H2 fired technologies	Moderate-High	Moderate-High
Hydrogen production – Electrolyzers	High	High

Where high data confidence exists and the technology is expected to be highly disruptive, the recommendation is to adjust based on expected cost reductions where possible, with industry validation once every five years. If no future changes in costs are expected and no future disruption is expected, then corrections should still be made for inflation over time. For technologies where high disruption may be expected but a low confidence score is present, the recommendation is to engage industry for better estimates on preferred decarbonisation routes if currently uncertain. For low data confidence and no expected future disruption, first evaluate the impact of modelling results for any significant impacts. If material, engage industry for better estimates. Regardless of data confidence, technologies with high expected disruption should be refreshed every 2 years if material to modelling results.

Demand Side Response (DSR) findings and recommendations

Guidehouse has provided an indicative magnitude of DSR potential by industrial sector. Findings from the research suggest that the Pulp & Paper, Lime, and green Hydrogen production sectors have the highest practical DSR potential in a future where decarbonisation via electrification is embraced. Sectors were qualitatively categorised as “high”, “moderate” and “low” for practical DSR potential based on the following 5 considerations:

- Whether the process already participates in DSR.
- Whether the most energy intensive process steps (e.g. electrolysers, kilns, furnaces, other low-temperature heat applications) can be practically ramped up/down in response to DSR signals without significant operational constraints.
- Whether the process includes or allows for easy and economical integration and management of physical buffer storage for raw and intermediate products to reduce electricity consumption in preceding and succeeding steps.
- The electricity demand in the process can be shifted for a significant enough duration to ease grid congestion.
- Any other sector specific constraints or enablers identified during the stakeholder interviews.

Table E4 and Table E5 summarise the indicative magnitude of DSR potential by sector. The DSR potential is a qualitative indication of the proportion of the total energy consumption based on the findings of this study. There was no data available for energy consumption of green hydrogen production in the UK, hence it is not reflected in Table E4.

Table E4: Indicative magnitude of DSR potential by sector against the log of current annual energy consumption (TWh, from 2024 ECUK tables).

Sector	Log Current Annual Energy Consumption (TWh)	Future Practical DSR Potential
Chemicals and Refineries	159	Low
Food & Drinks	42	Low
Iron & Steel	20	Medium
Paper	20	High
Cement	15	High
Non-ferrous metals	12	Medium
Vehicles	11	Medium
Glass	6	Medium
Ceramics	5	Medium
Lime	(Not specified, but shown as approximately 1)	High

Table E5: Summary of practical DSR potential by sector

DSR Potential Rating (listed in order of potential)	Prioritised sectors	Practical DSR potential summary
High	Hydrogen production	Electrolyser stacks can be ramped up and down easily.
High	Paper	Operating the pulp storage tower as a pseudo-battery helps unlock flexibility from pulp production step.
High	Lime	Management of silo capacities and aligning kiln maintenance periods with network needs can unlock flexibility.
High	Cement	Management of silo capacities and aligning kiln maintenance periods with network needs can unlock flexibility.

DSR Potential Rating (listed in order of potential)	Prioritised sectors	Practical DSR potential summary
Moderate	Glass	Mills silo capacity management allows some DSR potential. High operating temperatures, stable energy input requirements and continuous operation of energy intensive processes limits overall DSR potential.
Moderate	Ceramics	Mills silo capacity management allows some DSR potential. High operating temperatures, stable energy input requirements and continuous operation of energy intensive processes limits overall DSR potential.
Moderate	Vehicles	Batch process steps e.g.: welding and assembly can participate in DSR via shift optimisation. Dispersed manufacturing and continuous paint shop operation limit DSR potential.
Moderate	Non-ferrous metals	Smelting in electric furnaces and rolling/extrusion are batch steps, hence can be shifted to provide DSR. Duration of demand shift limited by close scheduling of electric arc furnace batches.
Moderate	Iron & Steel	Electric arc furnaces and the hot rolling mills run in batches and can provide DSR via shift optimisation. Duration of demand shift limited by close scheduling of electric arc furnace batches.
Low	Chemicals & refineries	Product quality and safety regulations, and limits on duration of product storage heavily limits DSR potential despite the batch nature of the processes in these industries.
Low	Food & Drinks	Product quality and safety regulations, and limits on duration of product storage heavily limits DSR potential despite the batch nature of the processes in these industries.

Introduction

The UK Government has legislated a net zero target for GHG emissions by 2050. Achieving this target requires a rapid transition to reduce emissions across all sectors, but particularly across industry - which accounts for 17% of current emissions. Several inputs are needed to drive the emissions reductions necessary across industry. These include investment from industrials to transition, policy frameworks to incentivise decarbonisation, and coordinated development of electricity, hydrogen, and CO2 transport infrastructure in the quantities needed at a local level.

To inform the development of decarbonisation pathways for industry, DESNZ has developed the Net Zero Industrial Pathway model (NZIP2). Underpinning this model is a database of counterfactual and abatement technologies including information on costs (CAPEX, OPEX), technology suitability, and availability. DESNZ is continuing to develop and improve NZIP2 and intends to update the database of counterfactual and abatement technologies with the latest evidence to ensure the industrial pathways developed are informed by the most recent and accurate technological assumptions.

NZIP2 requires information on investment and operating (non-energy) costs, efficiency, technology readiness level (TRL), available year, and lifetime, of various baseline and decarbonisation industrial technologies. This information will inform future asset replacement cycles within industry to forecast future fuel consumption and emissions released. The technologies are categorised as baseline technologies (i.e. those which are in use today to support production), and alternative decarbonisation technologies (i.e. those which would be adopted to decarbonise industrial processes). Some of these technologies are considered cross-cutting, meaning they are utilised across a broad range of industrial sectors, whilst others are sector-specific. Within the research, we recognise the importance of cross-cutting technologies such as heat pumps, electric boilers, CHPs, etc, that offer the most significant decarbonisation potential given the broad applicability range across different sectors.

The objectives of this research project have been to:

- Update and evidence the parameter assumptions for each of NZIP2 technology. This project covers cross-cutting and sector-specific technologies,
- Capture the inputs needed to model participation in grid balancing services for electrified technologies.
- Establish a process for long-term ongoing update of technology parameters in the future.

Scope of activities

Table 1: Breakdown of the scope of activities for Guidehouse's research

Phase	Title	Activities	Output
0	Mobilise	*Prepare and organise resources, teams, and plans to establish a smooth start to project execution.* • Hold weekly status meetings with core DESNZ team • Kick off and scope project	• Shared meeting minutes • Agreed project scope and project governance agreed
1	Development of Technology Evidence Base	*Gather, analyse, validate data to build a solid foundation of evidence that supports NZIP2.* • Conduct literature review • Establish quality assurance of evidence base • Deliver interim report	• Indicative grouping of technologies based on data availability • QA Plan agreed • QA Log delivered • Validation of deliverables • First draft interim report delivered • Additional validation needs identified
2	Stakeholder Engagement	*Identify, analyse and establish relationships with key stakeholders involved in NZIP2.* • Develop Stakeholder Engagement Plan • Deliver Stakeholder Engagement Plan	• DESNZ validated long list of stakeholders • Email to stakeholders • Final list of stakeholders • Scenario results • Focus group presentations • Draft power sector modelling results workbook • Final model results
3	Documentation & Report	*Develop and present comprehensive final reports and project evaluations.* • Draft final report & database • Close out final report	• Report structure agreed with DESNZ • First draft final report delivered • Feedback from DESNZ and wider stakeholders collated • Final report delivered • Final presentation prepared • Findings summarised in presentation

Guidehouse's research was organised into 4 tasks, including 3 core delivery tasks, each supported by continuous project management. Each task consisted of individual research activities that correspond to the research objectives. The tasks were:

- Task 0 – Mobilise
- Task 1 – Development of Technology Evidence Base
- Task 2 – Stakeholder Engagement
- Task 3 – Documentation & Report.

Summary of database

The NZIP2 database includes 321 technologies across 16 industry sectors that contribute to direct energy use or emissions. Most of these technologies are cross-cutting, meaning the same technology type is used to model industrial processes in multiple sectors. Examples of such industrial processes include, but are not limited to, low temperature heat, high temperature heat, CHPs, and drying and separation. Cross cutting technologies account for 80% of technologies in NZIP2, while the remaining 20% of technologies are sector specific technologies for Iron & Steel, Cement & Lime, Chemicals, Paper, Hydrogen, and Refineries sector. Table 2 below summarises Guidehouse's classification of the technologies reviewed in NZIP2, as well as absolute count of technologies associated with each technology type.

Table 2: Summary of updated NZIP2 technologies

Technology type	Technologies included	Technology count within updated model
Low temperature heat	Primarily Boilers based on various fuels and heat pumps.	138
CHP	Combined Cycle Gas Turbine, Open Cycle Turbines, Steam Turbines, Fuel Cell	37
High temperature heat	Furnaces and Kilns	48
Drying / Separation	Spray Drying, Convection Drying	34
CCS	CCS applications for Chemicals, Iron & Steel, Cement & Lime, and Hydrogen production	25
Motor	Electric motors used across sectors	10
Iron & Steel	Furnaces and steel finishing	5
Cement & Lime	Dry Kilns and cement processing	6
Chemicals	Steam Crackers & Reformers	7
Paper	Press section, paper processing & finishing	4

Technology type	Technologies included	Technology count within updated model
Hydrogen	Electrolysis	3
Refrigeration	Refrigeration for Food & Drink and chemicals	2
Refineries	Oil refinery with mixed output	2

Research methodology

NZIP2 technology database

As shown in Figure 1, the process for researching and updating the NZIP2 technology parameters was broken-down into five steps:

Figure 1: Process for researching and updating the NZIP2 technology parameters

Step 1: Identify NZIP2 parameters for various technologies and capacities within literature and assigning data quality ratings, as well as capacity ranges. For example, heat pumps can be categorised as air source or ground source, as well as thermally or electrically driven. Similarly, specific CAPEX (£/kW) for boilers decreases as scale of the boiler increases.

Step 2: Summarise a range of values identified from literature for various capacity ranges for each technology and identify the most representative value for each capacity range. The methodology for this is elaborated in the following sections.

Step 3: Develop sector profiles building on DESNZ's sector process maps to establish the representative capacity ranges and technologies (specifically for cross cutting technologies) commonly utilised within a sector. For example, typical size of boilers within Food & Drink industry is 1 – 5 MW, while within Chemicals industry it is > 25 MW.

Step 4: Validate outputs of the previous steps using stakeholder interviews. Stakeholder interviews were primarily used to review the list of technologies, validate our assumptions on sub-technologies and capacity ranges defined within the sector profiles developed in Step 3, collect feedback on cost parameters from equipment manufacturers, and understand the feasibility and constraints associated with DSR.

Step 5: Based upon validated sector profiles and technology parameters, create a final database by identifying the most appropriate value of the technology parameters developed for various capacity ranges and sub technologies to the final DESNZ technology codes.

The following sections define our methodology for identifying a single value for financial parameters.

Methodology for identifying a single value

For cross-cutting technologies such as boilers and CHPs that are used in multiple sectors, the overarching logic for identifying a single value from the multiple values identified during the literature review revolves around applicable capacity ranges for the technology and sector in question. The database employs three steps:

In **Step 1**, we filter for relevant data points to be included from the literature review. These values have been identified as part of the overall data quality scoring and quality control process.

In **Step 2**, the median is then taken for these values to derive a single value for various capacity ranges applicable for the technology. For example, in the case of low temperature heat, the median value for the following capacity ranges is identified: < 1 MW, 1-5 MW, 5-25 MW, and > 25 MW

In **Step 3**, the most representative capacity range utilised within a sector for a given technology is identified and the corresponding CAPEX and OPEX values are allocated. For example, in the case of low temperature heat, food and beverage sector utilises CAPEX and OPEX values identified for a capacity range of 1 – 5 MW, whereas chemical sector utilises CAPEX and OPEX values identified for a capacity range of 25 MW.

For sector-specific technologies, the process of deriving a single value is more straightforward because there are no cross-cutting technologies that can be applied at different capacity ranges across multiple different sectors. In this case, only step 3 is employed. The median is taken for applicable data entries that have a >=3 data quality score (refer to section on Data confidence scoring mechanism). In some cases, we might exclude a source that has a data quality score >=3 based on judgement.[3]

A major gap within literature is reliable and consistent Fixed OPEX values for various technologies. Most scientific literature tend to assume annual Fixed OPEX to be 2.5% of CAPEX. To address this gap and determine the most appropriate Fixed OPEX value we have used the following rules:

- Establish a single value for CAPEX $(CAPEX_{NZIP2})$ using rules described above.
- Where multiple sources provide CAPEX & Fixed OPEX values, Fixed OPEX as a % CAPEX is calculated for each source and the formula below is used:

  $$Fixed\ OPEX_{NZIP2} = CAPEX_{NZIP2} * Median\ (Fixed\ OPEX\ as\ a\ \%\ of\ CAPEX)$$

- If at least one source for a technology specifies CAPEX & Fixed OPEX values, Fixed OPEX as a % of CAPEX is calculated and multiplied with $CAPEX_{NZIP2}$
- If sources identified for a technology do not report Fixed OPEX, it is assumed to be 2.5% of CAPEX.

Financial values encountered during the literature review are reported across a wide range of parameters and time periods. DESNZ requires financial values to be expressed in 2021 GBP, and capacity units to be expressed in m’£/Mt or m’£/PJ depending on the sector in question. To ensure consistency across parameters taken forward for NZIP2, all financial values are transformed based on conversion principles in Appendix A – NZIP2 methodology.

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[3] For example, where equipment manufacturers engaged as part of the study provided technology parameters, these were prioritised over values found in literature.

Data confidence scoring mechanism

A two-step process has been adopted for assigning a quality score for literature sources and database values.

Step 1) Literature sources – a data quality score from 1-5 is assigned to all literature values. The basis for the score is shown below in Table 3. This score determined whether the figures contained within the source was be used to establish the single database value.

Step 2) Database single value – a data confidence score from 1-3 is assigned to each value in the database defined as follows:

- 3 (high confidence) – database value has been validated by stakeholders and/or there is high confidence in underlying literature values (multiple sources agree within reasonable tolerance)
- 2 (moderate confidence) – stakeholders could not validate, multiple sources were identified within literature with large variation, or CAPEX for two different technologies with high confidence were combined to come to a single value (e.g. CCS technologies)
- 1 (low confidence) – stakeholders could not validate, literature dependent upon single source or additional manipulation needed to derive single value for NZIP2 technology

Table 3: Guidehouse's data quality scoring mechanism

Level	Description
05	Data obtained from existing Guidehouse research or a trusted third-party publication referencing supplier quotations/project implementation or technology Pre-FEED level analysis released less than 5 years ago
04	Data obtained from existing Guidehouse research or a trusted third-party publication referencing supplier quotations/project implementation or technology Pre-FEED level analysis released less than 5 years ago
03	Cited data within scientific literature of techno-economic studies less than 10 years old OR data published by trusted government/international research agencies (IEA, Danish Energy Agency etc)
02	Cited data greater than 10 years old but it is a meta-review OR lacks traceability of original estimate
01	Estimation based on key components or comparable processes using sources published greater than 10 years ago

Demand Side Response (DSR)

Table 4 and Table 5 summarise the indicative magnitude of DSR potential by sector. Findings from the research suggest that the paper, lime and green hydrogen production sectors have the highest practical DSR potential in a future where decarbonisation via electrification is embraced. It should be noted that the DSR potential indicated relates to only a proportion of the Sectors were qualitatively categorised as “high”, “moderate” and “low” for practical DSR potential based on the following 5 considerations:

- Whether the process already participates in DSR.
- Whether the most energy intensive process steps (e.g. electrolysers, kilns, furnaces, other low-temperature heat applications) can be practically ramped up/down in response to DSR signals without significant operational constraints.
- Whether the process includes or allows for easy and economical integration and management of physical buffer storage for raw and intermediate products to reduce electricity consumption in preceding and succeeding steps.
- The electricity demand in the process can be shifted for a significant enough duration to ease grid congestion.
- Any other sector specific constraints or enablers identified during the stakeholder interviews.

Table 4: Indicative magnitude of DSR potential by sector and log of current annual energy consumption (TWh). Total industrial energy consumption: 456 TWh. There is no data available for energy consumption of green hydrogen production in the UK.

Sector	DSR Potential Rating	Log of Current Annual Energy Consumption (TWh)
Chemicals and Refineries	High	159
Food & Drinks	High	42
Iron & Steel	Moderate	20
Paper	Low	20
Cement	Low	15
Non-ferrous metals	Moderate	12
Vehicles	Moderate	11
Glass	Moderate	6
Ceramics	Moderate	5
Lime	Low	(Not specified, but shown as very low)

Table 5: Summary of practical DSR potential by sector

DSR Potential Rating (listed in order of potential)	Prioritised sectors	Practical DSR potential summary
High	Hydrogen production	Electrolyser stacks can be ramped up and down easily.
High	Paper	Operating the pulp storage tower as a pseudo-battery helps unlock flexibility from pulp production step.
High	Lime	Management of silo capacities and aligning kiln maintenance periods with network needs can unlock flexibility.
High	Cement	Management of silo capacities and aligning kiln maintenance periods with network needs can unlock flexibility.
Moderate	Glass	Mills silo capacity management allows some DSR potential. High operating temperatures, stable energy input requirements and continuous operation of energy intensive processes limits overall DSR potential.
Moderate	Ceramics	Mills silo capacity management allows some DSR potential. High operating temperatures, stable energy input requirements and continuous operation of energy intensive processes limits overall DSR potential.
Moderate	Vehicles	Batch process steps e.g.: welding and assembly can participate in DSR via shift optimisation. Dispersed manufacturing and continuous paint shop operation limit DSR potential.
Moderate	Non-ferrous metals	Smelting in electric furnaces and rolling/extrusion are batch steps, hence can be shifted to provide DSR. Duration of demand shift limited by close scheduling of electric arc furnace batches.
Moderate	Iron & Steel	Electric arc furnaces and the hot rolling mills run in batches and can provide DSR via shift optimisation. Duration of demand shift limited by close scheduling of electric arc furnace batches.
Low	Chemicals & refineries	Product quality and safety regulations, and limits on duration of product storage heavily limits DSR potential despite the batch nature of the processes in these industries.
Low	Food & Drinks	Product quality and safety regulations, and limits on duration of product storage heavily limits DSR potential despite the batch nature of the processes in these industries.

Approach

The approach for DSR research is summarised in the following six steps:

Figure 2: DSR research approach

Step 1: Review existing in-house databases on DSR evidence and results from prior work.

Step 2: Additional literature review to expand on existing data.

Step 3: Synthesis of results from existing data and literature review to build an initial metric overview.

Step 4: Validation and extension of the metric overview using wide range of internal Guidehouse expertise.

Step 5: Use of stakeholder interviews to validate metric overview, address gaps and collect qualitative insights on typical process steps, current and future electrified technologies, enablers and constraints for DSR participation.

Step 6: Use of findings from databases, literature review, and interviews to synthesise sector profiles that provide not only a quantitative summary of parameters for that sector, but also qualitative summary of typical energy profiles, process steps, current and future electrical technologies and practical constraints or enablers for DSR participation.

Summary of parameters

The following quantitative parameters summarised in Table 6 Table 6: DSR parameters below, have been collected within the scope of this project. The focus of the research was on process change DSR rather than grid dependence. Therefore, this does not include self-generation and/or installation of energy storage on-site.

Table 6: DSR parameters

Parameter	Definition	Key assumptions
Flex capability (yes or no, and duration of notice period)	Is the specific process typically able to provide DSR? How much notice period does the process need to provide flex?	Process and sector specific.
Max peak demand reduction (%)	How much can the load be reduced at most compared to its baseline consumption?	Often a process can be fully shut down, but that is not always the case. E.g. Hydrogen electrolyser stacks require a minimum load to operate.

Parameter	Definition	Key assumptions
Demand shift timing (before or after peak or both)	Can the process be shifted in time, for example before and/or after the peak windows?	Often, if a process's electricity demand can practically be shifted, it should be able to shift to both before and after the peak windows.
Demand shift duration (hours)	How long can the load typically be reduced, and how often can that be done?	Highly dependent on plant specifics (e.g. buffer storage capacity, production capacity, way of operations), but aimed at capturing typical durations and frequencies per sector.
Ramping (up and down – hours)	How fast can the process go from minimum load to maximum load and vice versa?	Technical ramping speeds is technology or process specific. But in practice there could be additional site related limitations (e.g. additional safety measures).

Prioritisation of sectors

Guidehouse agreed with DESNZ to prioritise the sectors where the potential for DSR participation is most significant i.e. those with large current / future potential electricity demand. On this basis, we agreed to prioritise the following sectors: 1) Cement, 2) Ceramics, 3) Chemicals, 4) Food & Drink, 5) Glass, 6) Iron & Steel, 7) Lime, 8) Non-Ferrous Metals, 9) Paper, 10) Hydrogen production, 11) Vehicles, 12) Refineries. All other NZIP2 sectors have not been investigated for DSR and are not included in this report.

Additionally, the research focussed on understanding the DSR potential from these sectors from a process change perspective rather than a grid dependence perspective. Therefore, self-generation and/or energy storage technologies were not primary considerations when determining a sector's DSR potential.

Stakeholder engagement

A comprehensive stakeholder consultation was conducted to ensure the transparent and inclusive participation of industry, sector associations and OEMs in the validation of technology parameter inputs for the updated NZIP2 database.

In addition to validating the technology parameter inputs, the stakeholder consultation aimed to qualitatively understand the potential for DSR uptake within each sector represented in NZIP2 and, where applicable, identify further evidence sources in support of the updated NZIP2 technology parameters supplementing gaps raised in the literature review. A detailed description of the evolution of our stakeholder engagement process is elaborated in Appendix B.

Summary of interviewed stakeholders

For completed interviews, participants representing an NZIP2 sector or core technology are presented in Table 7 and Table 8 below. The textiles, hydrogen production and construction sectors were de-scoped from the stakeholder consultation and therefore did not receive interview.

Table 7: NZIP2 sector stakeholders

NZIP2 Sector	Participants
Cement & Lime	Mineral Products Association
Ceramics	*Kiln supplier to the ceramic sector.*
Chemicals & Refining	Sabic UK Petrochemicals Limited
Electrical Engineering	Schneider Electric
Food & Drink	McCormick, PepsiCo, British Sugar, Apetito
Glass	NSG Pilkington
Iron & Steel	*Anonymised steel manufacturer*
Mechanical Engineering	Rolls Royce
Non-Ferrous Metals	Mining & Mineral Markets Ltd.
Paper	Palm Paper
Vehicles	Society of Motor Manufacturers and Traders, *Anonymised vehicles manufacturer*

Table 8: OEM stakeholders

Technologies	Participants
Thermal Storage	Caldera Thermal Solutions
Boilers	*Anonymised boiler manufacturer.*
Heat Pumps, Spray Dryers, Electrified Heating Technologies	GEA
Kilns (for ceramic sector)	*Anonymised kiln manufacturer.*
Drying	European Spray Dryer Technologies
Steam crackers (for chemicals sector)	Technip Energies

Cross-cutting technology overviews

Cross-cutting technologies included in the database are: Low temperature Heat, CHPs, Drying/Separation, Motors, High Temperature Heat, and Refrigeration. The following sections summarise high level findings on the various cross cutting technologies including financial parameters.

Low Temperature Heat

Boilers represent the most common low temperature heating application within industrial processes and space heating. Within the database, technoeconomic parameters for Low Temperature Heat Technology provide values for steam and hot water boilers based on natural gas, coal, biomass, and electricity and heat pumps. Other low temperature heat application observed within industry such as ovens, fryers, and other novel electric technologies are not represented within NZIP2. Guidehouse has also documented how typical thermal capacity ranges of boilers vary across NZIP2 sectors. This is important because technology costs (CAPEX per MW) for boilers decrease with larger capacity installations. TRL 9 was observed for all boilers, including hydrogen. From an investment point of view, natural gas boilers are the cheapest, whereas biomass boilers and heat pumps are the most expensive.

The CAPEX of heat pumps is high due to large installation costs, which can amount to ~2x times the equipment cost. Unlike boilers, stakeholder interviews indicated that CAPEX per MW does not decrease with increasing capacities for heat pumps, and scale of installation has minimal impact on CAPEX per MW. A bigger influence on the costs of heat pumps is the temperature rise required within a process. Current day commercial heat pumps can deliver temperatures up to 200 °C with demonstrations reaching 280 °C although this is dependent on heat source and sink configurations[4].

Stakeholder interviews indicated that for boilers < 5 MW capacity, electrification is expected to be the preferred decarbonisation alternative post 2030. Electrification is an option for high-capacity applications, but network capacity constraints remain a major barrier. As of the time of writing this report, the general sentiment from the interviewed stakeholders is that hydrogen is expected to be the preferred decarbonisation pathway for temperatures > 200 °C.

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[4] MAN Energy Solutions, Industrial heat pumps, IEA Heat Pump Technologies Task 1 - Technologies - Annex 58

CHPs

CHPs in the NZIP2 model are associated with various input fuels. Similar to boilers, solid fuel CHPs are considerably more expensive in investment and to operate and maintain in comparison to gas-based CHPs. TRL levels are assumed at 9 for most configurations. Hydrogen CCGT CHPs, at the time of writing, are in the pilot phase with an expected timeline for rollout in the UK set at 2027 based on market activity. Fuel cell-based CHPs have not been commercialised for capacities > 1 MW.

Drying/Separation

Drying/Separation is listed as a technology for Textiles, Paper, Food & Drink, Ceramics, and Chemicals. Drying applications within all the sectors except ceramics utilise indirect heat in the form of steam. Literature and interviews indicating that within Food & Drink, and Chemicals, most common drying technologies include spray dryers and fluidised bed dryers, Textiles and Paper industry typically employ steam-based contact drying whereas Ceramics employ direct fired tunnel dryers and spray dryers. For sectors where steam is the source of heat for drying applications, CAPEX and OPEX parameters were assumed to be the same as low temperature heat (i.e. boilers).

High Temperature Heat

High temperature heat is listed as a technology for Vehicles, Electrical Engineering, Mechanical Engineering, Ceramics, Glass, Non-ferrous Metals and Chemicals. The primary application for high temperature applications identified for these sectors are furnaces and kilns (specifically for Ceramics). Furnace applications by sectors vary significantly. For glass, high temperature applications have been assumed to annealing furnaces (as glass melting furnaces are already listed as a separate technology). For Vehicles, Non-ferrous Metals, Electrical & Mechanical Engineering, melting furnaces are most commonly applied.

Evidence for CAPEX inputs of industrial furnaces is limited. One source was identified for a generic gas fired cylindrical furnace. Additionally, the Danish Energy Agency published information on CAPEX and Fixed OPEX for burner systems based on gas, electric (heating elements), and solid fuel but did not include the complete components of the furnace. To determine financial parameters for electric and solid fuel-based furnaces, it was assumed that they differ only in the cost of the heating element/burner and all other components are similar. Data available was for 1 – 5 MW capacity range of furnaces.

Electrification (resistance and induction-based technology) was identified as the most common alternative for decarbonisation with a TRL of 9. Hydrogen based furnaces are in pilot stage with a TRL of 7 – 8. Due to lack of literature on Hydrogen furnaces, CAPEX for the technology is assumed to be 30% more expensive in line with observations for CHPs and boilers.

Retrofit versus greenfield

A key factor to consider when applying technology parameter assumptions is whether the specified alternative decarbonisation technology can be retrofitted within an existing process, or whether a new, “greenfield” development is necessary instead. The difference in costs between these two scenarios can be significant.

Utilising insights from the literature review and stakeholder engagement, a perspective has been provided on whether retrofit or greenfield is the more likely scenario for technologies within NZIP2.

An example of where retrofit is more applicable is post-combustion carbon capture technologies which capture CO2 from flue/exhaust gases from an existing industrial process. Other decarbonisation solutions require more fundamental alterations of existing processes. For example, in Iron & Steel, if entirely new production facilities were required that involved the replacement of an existing blast furnace, then this sort of development would be described as a greenfield development.

Interviews conducted as part of the stakeholder engagement process emphasised the prohibitive costs than can be associated with greenfield developments. Others highlighted certain technologies within sectors (e.g. chemical crackers) where retrofitting of existing processes can occur in sequence which can minimise associated production downtimes. Spatial constraints are also a key factor with regards to preferred decarbonisation technologies. For example, the full electrification of a complex industrial process at a site where space is constrained can render less intrusive decarbonisation technologies more appealing.

Within the accompanying database to this report, Guidehouse has provided additional information, where available, on: (1) the retrofitability of certain decarbonisation technologies (i.e. is the technology more suited as a retrofit or greenfield solution), (2) associated retrofit costs, and (3) associated production downtimes for the retrofitted plant. An additional comments column has been added to justify any categorisations, as well as a column for relevant sources of literature. Key insights from the retrofit versus greenfield assessment for CCS, Crackers, and hydrogen-fuelled technologies are summarised in Table 9 below.

Table 9: Insights from retrofit versus greenfield assessment

Technology	Insights
CCS	**Mono-ethanol amine (MEA) CCS** • Conducive to retrofitting as technology is post-combustion • 10% more expensive than greenfield • Downtime: Expected be negligible (less than a month) **Oxyfuel** • Significant modifications required to fuel burning process • 30 – 40% more expensive than greenfield (based on cement sector) • Downtime: Up to 6 months of production loss
Crackers	**Hydrogen** • Retrofitting involves changing the firing system of an existing cracking furnace to a hydrogen firing system while maintaining the same configuration by applying flue gas recirculation to maintain fuel gas duty. • Retrofitting expected to be 10 - 20% of the cost of greenfield cracker • Downtime: 2 months with partial loss in production as you can upgrade one furnace at a time while other furnaces are operating. **Electric** • Electric retrofitting is technically feasible but requires a much more elaborate upgrade with significant changes to steam balance. • Downtime: Up to 12 months as electric retrofit would require major modifications to cracker
H2 fueled technologies	**Boilers & High temperature heat** • Retrofitting expected to be 10 - 15% of the cost of new H2 boiler. Cost of a H2 burner is ~ 60% more expensive than natural gas burners • Downtime: Expected to be negligible (between 2 weeks – to a month) as any upgrades would be expected to be performed in line with maintenance

Sector Profiles

The purpose of the sector profiles is to provide a summary of both qualitative and quantitative insights gained from research and stakeholder engagement, across NZIP2 technologies and Demand Side Response. Insights are split across the following four sections for each industry sector:

1) A qualitative summary of the sector: the summary aims to introduce the key definitions and processes that define the sector, as well as providing both global and UK-specific context related to the sector's emissions profile.

2) Summary of electrification potential and constraints: this section provides **A) RAG classification of electrification potential up to 2035**: drawing upon available literature a sector-wide RAG classification of technical electrification potential is provided, across three 5-year time horizons: 2025, 2030 and 2035. This is based upon maturity of associated electrification technologies in the sector. It is not an indication of the expected electrification realised which could be lower in reality due to other constraints. **B) Qualitative insights on electrification potential and constraints at an end-use / technology level**: to reinforce the classification, qualitative insights are provided from literature, stakeholder interviews and Guidehouse understanding.

3) NZIP2 Technology tables summarising quantitative and qualitative insights: The qualitative tables summarise information related to the technology, including information gathered from the stakeholder engagement process and internal Guidehouse research. The quantitative table provides a single value for each relevant NZIP2 parameter updated as part of this study.

For product-based sectors within NZIP2 (i.e. cement, lime, iron & steel, chemicals), there are two qualitative tables, the first summarises conventional technologies and the second summarises specific decarbonisation alternatives included in the model.

For energy-based sectors, a single table summarises for each of the relevant cross-cutting technologies included for the sector within NZIP2, the following is summarised: technology assumed, typical capacity, alternative decarbonisation technology, timeline for deployment of decarbonisation technologies and qualitative insights from literature review and stakeholder interviews.

4) Demand Side Response characteristics of the sector: This section summarises mixed-methods insights gained from literature review and stakeholder interviews on practical constraints for DSR potential.

Cement

The global cement manufacturing industry is responsible for 8% of the world's CO2 emissions1, making it the second-largest emitter in industry. In 2020, the UK cement industry was responsible for around 7.3 million tonnes of CO2 emissions, or approximately 1.5% of the UK total. The UK has 6 cement manufacturers across 10 sites, producing up to 9 million tonnes per annum cement (largely Portland Cement). These sites are typically off the gas grid and use liquid or solid fuels to power the pre-calciner and the rotary kiln, which is the most energy and carbon intensive process. Cement itself is a finely ground, non-metallic, inorganic powder, and when mixed with water forms a paste that sets and hardens. It is primarily used as a "glue" to make concrete, which is the second most used substance in the world after water.

The cement industry is part of what is often referred to as the "hard-to-abate" sectors. The total CO2 emissions from cement production can be thought of in two parts: process emissions and fuel emissions. Process emissions arise from the calcination of limestone (CaCO3) to form CaO, commonly known as Lime, releasing CO2 in the process. This process emission is unavoidable and is where 60-70% of total CO2 emissions in the cement industry derive from[5]. Fuel emissions, on the other hand, come from the combustion of fuel to heat rotary kilns as part of the clinkering process, and also to provide heat for the calcination process as well. The percentage split of emissions varies from plant to plant and country to country largely based on the CO2 intensity of the local fuel mix. The large proportion of unavoidable emissions means that carbon capture is the only option to reduce the CO2 emissions from the calcination part of the process.

The calcination process typically occurs at 900°C. Raw meal is fed into the top of a pre-heating tower and enters a pre-calciner, where it is heated by the flames from the kiln where clinker production takes places along with its own flames. The calcination process is then followed by the clinkering process where the meal is passed from the pre-calciner into the top-end of a rotary kiln. Here, lime reacts at a high temperature (typically 1400–1500°C) with silica, alumina, and ferrous oxide to form the silicates, aluminates, and ferrites of calcium, which comprise the clinker. The clinker burning occurs in a rotary kiln. The clinker is then ground or milled together with gypsum and other additives to produce cement.

There are also different process routes used in cement manufacturing: dry, semi-dry, semi-wet, and wet processes. Briefly, these routes pertain to how raw material is handed before being fed into the rotary kiln. In a dry process, the feed material is typically in the form of a dry power, heated using pre-heaters. In a wet process, feed material is made wet through wet grinding to form a slurry, which is then directly fed into the kiln. A wet process has no pre-heater or pre-calciner.

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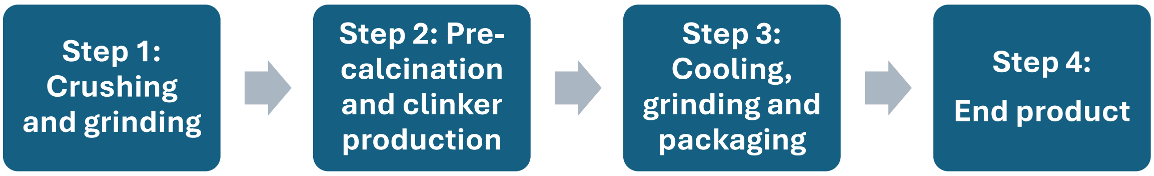
[5] Mark Fischetti, Nick Bockelman & Wil V. Srubar (2023) 'Solving Cement's Massive Carbon Problem' Scientific American Magazine: Volume 328, Issue 2

A semi-dry process adds water to the dry power feed, whereas a semi-wet process removes water from slurry by filter pressing[6]. Of these process routes, wet production typically requires higher energy demands[7]. Today in the UK there are no wet process kilns, with dry and semi-dry processes used instead[8].

The use of amine-based solvents is a mature carbon capture technology applicable to the cement sector. The NZIP2 database covers specific carbon capture technologies such as: amine-based absorption, calcium-looping, and oxyfuel combustion processes, which are described in further detail below. It must be noted that these are not the only potential carbon capture technologies that can be used in the Cement sector.

While specific site processes may vary depending on product requirements, the main steps involved in cement manufacturing are:

Figure 3: Main production steps for Cement manufacturing



Crushing and grinding of raw materials: minerals containing calcium carbonate are combined with materials containing alumina, silica and iron, and then crushed and ground into a raw meal in a raw mill with the desirable chemical and physical properties for cement production. Stakeholder interviews revealed that this step is powered electrically and currently accounts for 26% of total site electricity consumption.

Pre-calcination and clinker production: stakeholder interviews revealed that these steps are usually powered by solid/liquid fuels, with electricity being used to rotate the kiln only. This step currently accounts for 27% of the total site electricity consumption.

Cooling, grinding and packaging of final product: a grate cooler is used to cool the hot clinker by passing air over it as it exits the rotary kiln. The cooled clinker is then ground in a cement mill to produce fine powder which can be blended with supplementary materials/additives and packaged into the final product. The stakeholder interviews revealed that this step can account for 37%[9] of the total site's electricity consumption.

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[6] British Geological Society (2005) 'Minerals profile: Cement Raw Materials'

[7] European Cement Research Academy (2022) 'State of the Art Cement Manufacturing: Current technologies and their future development'

[8] Department for Business Energy and Industrial Strategy (2019) 'Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility'

[9] Edoardo De Lena and others (2022) 'Assessing Heat Pumps as Heat Supply Option for Solvent Regeneration in Cement Plants with Post-Combustion CO2 Capture: Heat Integration, Energy Performance and CO2 Emissions' Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022

The remaining 10%[10] of electricity consumption goes towards space heating and lighting in the offices.

Electrification Potential

Figure 4: Cement electrification potential

Electrification options are currently limited for the Cement sector. Partial electrification of the calcination process is currently in development and could be made technically feasible by 2030, with full electrification by 2035[11]. Electrification of the clinkering process in the rotary kiln is more complex and not expected before 2035. Possible electrification technologies cited for the sector include plasma-driven technologies, as well as shockwave, microwave, inductive heating, or resistance heating[12].

Specifically on plasma-driven technologies, plasma torches generate rotating electric arcs between two electrodes that heat a carrier gas to temperatures up to 5,000°C. This heat can then potentially be supplied to both the calcination and clinkering processes. Plasma torches are themselves are commercially available, but their application in the Cement sector at commercial scale is yet to be realised. The EU-funded ELECTRA project is currently investigating ways to substitute fossil fuel use, replace combustion technologies, and electrify high-temperature heat in the Cement, Lime, and Pulp industries[13]. As part of this project, the world's first plasma-heated cement rotary kiln is being piloted in Sweden, where CO2 is heated to over 5,000°C to form a plasma jet that is then used to heat the kiln[14].

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[10] Edoardo De Lena and others (2022) 'Assessing Heat Pumps as Heat Supply Option for Solvent Regeneration in Cement Plants with Post-Combustion CO2 Capture: Heat Integration, Energy Performance and CO2 Emissions' Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022

[11] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

[12] Cementa / Vattenfall (2018) 'CemZero: A feasibility study evaluating ways to reach sustainable cement production via the use of electricity'

[13] Electra website

[14] Heidelberg Materials Northern Europe Heidelberg Materials (2025) 'Major breakthrough for plasma-heated cement kiln in Sweden'

SaltX is also developing its EAC technology that uses electric plasma. The process is also said to separate and isolate CO2 emissions such that additional carbon capture systems are unnecessary[15]. EACs are expected to potentially replace pre-calciners and integrate with existing equipment easier than with rotary kilns[16].

Electrifying the high-temperature heat sources for the pre-calciner means that, firstly, the CO2 emissions from fossil fuel combustion in this part of the process are avoided. Secondly, the near-pure process CO2 emissions from the calcination stage are not mixed with any combustion-related flue gases and are therefore easier to capture as purity is maintained[17] [18]. However, if fossil fuel combustion is still used to provide high-temperature heat for the rotary kiln, then typically an additional capture system may be required to capture the related CO2 emissions from the kiln, typically a post-combustion capture system that captures CO2 the flue gas[19].

Finally, the LEILAC alternative decarbonisation technology described later in this report also has a fully electrified pathway (e-LEILAC), although the timeline and status of this pathway is unclear[20].

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[15] SaltX Technology Holding AB (2025) 'SaltX Technology Year-end Report Q4 2024'

[16] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

[17] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

[18] Leonardo Varnier and others (2025) 'Combined electrification and carbon capture for low-carbon cement: Techno-economic assessment of different designs' Journal of Cleaner Production, Volume 498

[19] Leonardo Varnier and others (2025) 'Combined electrification and carbon capture for low-carbon cement: Techno-economic assessment of different designs' Journal of Cleaner Production, Volume 498

[20] In 2023, an MOU was signed between LEILAC and Heirloom to incorporate electric kiln technology with the latter's DAC facilities. LEILAC is currently in the Pilot & Demonstration phase, with the LEILAC-2 pilot expected to be online in 2026.

NZIP2 Cement sector technologies

Table 10: Qualitative summary of baseline Cement sector technologies

NZIP2 Technology	Technology assumed	Decarbonisation alternative technology	Timeline for decarbonisation technology	Insights from literature review & interview
Grinding and mixing technology	Ball mills, Vertical roller mills	Decarbonisation of electricity source	Based on greening of electricity source	Grinding and mixing makes up to around 68% of current electricity demand in cement production[21]. Vertical roller mills are a higher efficiency technology currently replacing ball mills within the industry.
Dry kiln, best available technology (BAT)	Rotary kiln	CCS based on amine-based solvents & oxyfuel kilns	2028	For many hard-to-abate industrial sectors, retrofitting and/or expanding plants is more likely to occur than building greenfield plants from scratch. For CCS technologies in general, the use of amine-based solvents to capture CO2 is a well-established practice, having been used for decades in the natural gas processing industry as part of the natural gas sweetening process, also known as amine gas treating, amine scrubbing, or acid gas removal. For many industrial sectors, amine-based solvents are typically employed to capture CO2 from industrial flue/exhaust gases as part of a “post-combustion” set-up. Oxyfuel combustion and CaL can both be classed as post-combustion technologies. CaL is less mature a decarbonisation option. Note that coal/natural gas CHPs are uncommon for the purposes of solvent regeneration and instead boilers are typically used. See entry on “Dry kiln with coal & with natural gas CHP and MEA” for further discussion.
Fluidised bed kiln with waste utilisation	Same as NZIP2 technology	N/A	N/A	Limited evidence in literature of commercialised. Recommended to remove entry.

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[21] European Cement Research Academy (2022) 'State of the Art Cement Manufacturing: Current technologies and their future development'

Table 11: Qualitative summary of decarbonisation Cement sector technologies

NZIP2	Insights from interview and literature review
Alternative low carbon cement	There are a variety of alternative low carbon cement options. Approaches include clinker substitutions or alternative systems not based on clinker. Stakeholders suggested that low-carbon cement based on clinker substitutions already include the addition of materials such as fly ash, blast furnace slag, limestone fines and could expand in the future to include calcined clay etc. For systems not based on clinker, stakeholders suggested that alkali-activated materials (geopolymers) could be used as a potential substitute for PC. CSA could also be used to replace PC. Stakeholders suggested that clinker substitutions would be the most likely option in the UK context, but also that most substitutes such as blast furnace slag or calcined clay need to be imported into the UK.
Calcium looping kiln	CaL is a type of solid looping technology which uses a CaO sorbent instead of an amine-based solvent to capture CO2. Like solvents, CaO sorbents also degrade and must be replenished. CaL can have two configurations in the cement industry, a (1) tail-end “post-combustion” configuration, and a (2) integrated configuration. The tail-end configuration involves CO2 capture from the clinkering process using a carbonator at the end-of-pipe (flue gas), whilst integrated configurations concern integration with existing processes such as sharing of a calciner in the cement production process[22]. The tail-end configuration can be retrofitted to existing plants. In this configuration, the CaL cycle typically involves two interconnected circulating reactors: a carbonator and calciner. CO2 from the flue gas reacts with the CaO sorbent in the carbonator to form limestone. The limestone then goes to a calciner where it is heated to temperatures of 850-950 °C to decompose again into CO2 and CaO. The solid CaO can then be reused to capture more CO2. Per Guidehouse Research’s Global CCUS Project Tracker[23], CaL is a very uncommon carbon separation technology actively investigated or implemented in the industry today. The technology has been piloted as part of the part of the “CLEANKER” project in Italy over 2017-2023, reaching TRL 7[24].

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[22] Giovanni Cinti and others (2025) ‘Calcium looping capture in the cement industry – CEMCAP Conclusions’

[23] Guidehouse Research

[24] CORDIS European Commission, Clean Clinker production by Calcium looping process

NZIP2	Insights from interview and literature review
Dry kiln MEA with coal/ natural gas CHP	The issue of CHPs and boilers in cement CCS was encountered during the literature review and raised with both internal SME’s and during the stakeholder interviews. Post-combustion, amine-based carbon capture systems using solvents such as MEA or MDEA require steam for solvent regeneration and CO2 stripping. It is uncommon to use steam from a CHP for that purpose only. Instead, a boiler is commonly used. High-temperature heat-pumps have also been cited in the literature[25]. However, the Padeswood CCS project (part of the HyNet cluster), is using a new 12 MW CHP to provide heat and power to the carbon capture system[26]. CO2 would be captured from the CHP and the kiln. Stakeholders reasoned that a CHP was being used because there was insufficient grid power available locally. Ideally, NZIP2 could include entries that do not specifically require a coal or natural gas CHP where a boiler is typically used as the source of steam for the MEA solvent (or any amine-based solvent), regeneration process.
BAT kiln Advanced Amine (MDEA)	Whether a solvent is MEA or MDEA or any other amine-based solvent matters largely for variable OPEX-related considerations, rather than CAPEX or fixed OPEX-related inputs. For example, different solvents may have different regeneration duties (different energy requirements for solvent regeneration, typically cited around 2.9–3.1 MJ/kg CO2[27]), different solvent degradation rates, and of course different purchase costs. However, the major equipment related to post-combustion systems using amine-based systems will generally remain the same (e.g. steam reboiler, absorption and stripper columns, direct contact coolers, cross-heat exchangers etc.). MEA can be considered the benchmark solvent within the CCUS industry and is a primary amine, whereas MDEA is a tertiary amine. MEA can be also considered a first-generation solvent. Commercial applications of amine-based solvents may use different blends of amines in their proprietary solutions. Differences in CAPEX and fixed-OPEX are more prominent where different CO2 separation stages (pre-combustion, post-combustion, oxyfuel combustion), and different separation technologies (chemical solvents e.g. amine-based solvents), physical solvents, solid adsorbents, solid looping e.g. calcium looping, membranes, etc.), are involved.

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[25] Edoardo De Lena and others (2022) 'Assessing Heat Pumps as Heat Supply Option for Solvent Regeneration in Cement Plants with Post-Combustion CO2 Capture: Heat Integration, Energy Performance and CO2 Emissions' Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022

[26] Hanson Heidelberg Cement Group (2023) 'Padeswood Carbon Capture and Storage: Consultation Brochure'

[27] Magdalena Strojny and others (2023) 'Comparative analysis of CO2 capture technologies using amine absorption and calcium looping integrated with natural gas combined cycle power plant' Energy, Volume 284, 1 December 2023

NZIP2	Insights from interview and literature review
BAT kiln full oxyfuel	Oxyfuel combustion can be considered a form of post-combustion where combustion occurs with near-pure O2 rather than ambient air. Oxyfuel combustion cement kiln firing may result in a comparatively pure CO2 stream, which depending on the use case at hand, can potentially already be supplied to a CO2 transport and storage infrastructure without any further conditioning. However, oxyfuel combustion systems can also be combined with amine-based systems and cryogenic separation systems as well. Thus, oxyfuel combustion does not explicitly denote the actual carbon separation technology that is being used. However, it remains conventional to state oxyfuel combustion as one of the general taxonomies used to categorise the carbon capture industry alongside: post-combustion, pre-combustion, and inherent CO2 capture. Sources such as the Global CCS Institute may explicitly pair oxyfuel combustion with post-combustion capture in their taxonomy[28]. Per the ECRA, “oxyfuel technology is currently seen as one of the most energy efficient and economic candidate for CO2 capture at cement kilns, although it also increases operational costs significantly”[29]. Interviews suggested that where new plants were being built, oxyfuel technology may be preferred. Otherwise, stakeholders suggested that there was a lot of attention on retrofitting existing plants with amine-based post-combustion systems. Guidehouse Insights research shows that for retrofitted Cement and Lime plants, amine-based chemical solvents are the most CO2 separation technology investigated by the industry, followed closely however by cryogenic separation. CO2 is separated from a flue gas stream using cryogenic cooling and liquefaction. These systems are often paired with PSAs for CO2 purification. An example technology is Air Liquide’s Cryocap technology. Kilns that use oxyfuel combustion may still also go on to use amine-based capture systems however as part of a hybrid system. For example, at its Antoing cement plant in Belgium, Heidelberg Materials is employing the “OxyCal” process as part of its Anthemis project where oxyfuel combustion is combined with an amine-based capture in a hybrid unit. Both full oxyfuel and partial oxyfuel systems ASUs to provide the necessary O2-rich environments.
Partial oxyfuel dry kiln	Partial oxyfuel combustion differs from full oxyfuel combustion in that with partial oxyfuel, combustion near-pure O2 environment occurs at a particular stage of the overall process only, such as at the pre-calciner and pre-heater, and does not include oxyfuel combustion at the firing of the cement rotary kiln.

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[28] Global CCS Institute website

[29] European Cement Research Academy (2022) 'State of the Art Cement Manufacturing: Current technologies and their future development'

An additional carbon capture pathway to investigate for both the Cement and Lime sectors is Calix's LEILAC technology, which can be used to capture unavoidable process emissions (i.e. during the calcination stage)[30]. In this approach, limestone is heated in a reactor and pure CO2 is captured as it is released from the limestone. Furnace gases and air ingresses are kept separate, as fuels are burned in a separate chamber than limestone using a specific pre-calciner installation. Importantly, this technology does not require additional processes but a novel "pre-calciner" design for cement plants, and a new kiln for lime plants. As such, minimal additional inputs are necessary compared to baseline clinker production, with additional electricity needed for CO2 compression.

Carbon mineralisation (or mineral carbonation) is also an effective carbon storage solution. This process is an accelerated form of natural carbonation (i.e. the conversion of CO2 into CaCO3)[31]. Mineral carbonation can include the storage of CO2 in lime[32], cement, or concrete at various stages of the product's lifecycle. This could include the carbonation of demolished concrete, or of materials containing calcium and magnesium (which can then be integrated into new concretes). Mineralisation can be divided into direct and indirect pathways, with direct carbonation concerning the direct reaction of CO2 with a mineral in one step, or indirect carbonation which involves multiple steps[33]. In the CCUS industry today, a number of DAC companies are employing mineral carbonation as a pathway to store CO2 captured from the atmosphere. In the context of industrial decarbonisation, mineral carbonation is more to do with the storage of CO2 after it has been separated and captured from a point-source emitter[34, 35, 36, 37]. Mineral carbonation could arguably be applied to an industrial flue gas directly without CO2 pre-separation[38] . However, carbonation efficiencies reduce in the presence of impurities in a flue gas[39], with extended reaction times and higher processing costs also reported[40].

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[30] Leilac (2021) 'Capturing unavoidable CO2 process emissions in the cement and lime industries'

[31] Dennis Krämer, DECHEMA (2021) 'Carbonation – Binding CO2 permanently into products: 4th Report of the Thematic Working Group on CO2 capture and utilization'

[32] Origen Power Ltd (2021) 'Phase 1 Final Report: Passive Lime Carbonation Project'

[33] Aimaro Sanna and others (2014) 'A review of mineral carbonation technologies to sequester CO2' Chemical Society Reviews, 2014, 43

[34] Samantha Wilcox and others (2025) 'Mineral Carbonation for Carbon Sequestration: A Case for MCP and MICP' International Journal of Molecular Sciences 2025, 26(5)

[35] Till Strunge, Phil Renforth & Mijndert Van der Spek (2022) 'Towards a business case for CO2 mineralisation in the cement industry' Communications Earth & Environment 3, 59 (2022)

[36] Frank Winnefeld and others (2022) 'CO2 storage in cement and concrete by mineral carbonation', Current Opinion in Green and Sustainable Chemistry, Volume 38

[37] Companies such as Heirloom employ mineral carbonation to remove CO2 from the atmosphere. Heirloom heats limestone to release CO2, which it then captures. The leftover lime is then exposed to air to passively absorb CO2 again to form limestone.

[38] Aimaro Sanna and others (2014) 'A review of mineral carbonation technologies to sequester CO2' Chemical Society Reviews, 2014, 43

[39] Nils Thonemann and others (2021) 'Environmental impacts of carbon capture and utilization by mineral carbonation: A systematic literature review and meta life cycle assessment' Journal of cleaner production, 332, Article 130067

[40] Colin Hills, Nimisha Tripathi & Paula Carey (2020) 'Mineralization Technology for Carbon Capture, Utilization, and Storage' Frontiers in Energy Research, 8:142

Table 12: Quantitative summary of Cement sector technologies

NZIP2 Technology	CAPEX (m£/Mt Output)	OPEX (m£/Mt Output[41])	TRL/Model Availability Date	Data confidence
Advanced Amine (MDEA) - BAT KILN (Cormos 2017) (CCS)	291	5.85	9/ 2025	3
BAT kiln full oxyfuel (CCS)	280	7.01	8/ 2028	3
Calcium looping kiln	493	12.32	7/ 2030	2
Dry kiln with coal CHP and MEA CCS	431	10.77	9/ 2025	2
Dry kiln with natural gas CHP and MEA CCS	355	8.86	9/ 2025	2
Dry kiln, best available technology (BAT)	115	4.02	9/ 2011	2
Grinder and mixer with increased clinker substitution	28	1.14	9/ 2011	3
Grinding and mixing technology	28	1.14	9/ 2011	3
Partial oxyfuel dry kiln with CCS	221	5.53	8/ 2028	2

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[41] Output values are either m£/Mt cement or clinker. Consult updated database for further information.

Demand Side Response

The cement manufacturing process has high potential for Demand Side Response (DSR), particularly with regards to the operation of the raw and cement mills, which account for over 60% of the site’s current electricity consumption. The management of silo capacities, which if kept under optimal conditions can store the raw material and cement for up to a year. In a battery like fashion this allows the site to shift mill electricity consumption away from peak network congestion times. Based on stakeholder interviews, cement manufacturers already do this to avoid higher costs between 4-7pm in the winter and align their electricity consumption to times when the grid is at its cleanest. The DSR potential from this is limited by the size of the silos on site. The main drawback from doing so is a drop in efficiency in operating the mills and equipment wear.

Rotary kilns today are mainly powered by solid or liquid fuels and only use electricity to turn the kiln, which accounts for 27% of total site electricity consumption today. As part of their decarbonisation initiative, the cement industry is exploring technologies such as hydrogen powered kilns with hydrogen produced on-site via electrolysis, electrified alternatives such as plasma burners and resistance heating powered kilns, kilns with bivalent heat generation (combination of hydrogen/biomass with electrical heat provision), and carbon capture and storage. If these technologies are adopted, on-site power consumption may increase significantly in the future.

Unlocking DSR from the clinker formation step is, however, relatively difficult. Rotary kilns must operate 24 hours a day throughout their lifetime (~20 year, typically stopping only for a few weeks in a year for annual maintenance. This continuous operation limits the potential for DSR in this energy-intensive step. Furthermore, re-firing the kiln post shutdown is extremely energy intensive.

For plasma kilns, which are 100% electrically powered, the only feasible DSR strategy would be to align the annual maintenance periods, which typically occur in winter when cement demand is low and the network congestion is high, to peak network congestion times. The sites would need a notice period of a few months to plan their annual maintenance accordingly.

For kilns with bivalent heat generation could potentially substitute their electricity consumption with the alternate fuel during these times. The potential of DSR from this would depend on the amount of alternative fuel that is available for the kiln and the kiln design.

Table 13 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from the stakeholder interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked during the stakeholder interview. While they were unable to offer exact figures, they did not raise any objections to the values quoted.

Table 13: Demand side response potential summary of Cement sector

Process	Equipment	Practical DSR potential	Constraints[19]
Grinding and mixing (63% of current electricity consumption)	Raw and cement mills	Max peak demand reduction: Up to 100%[42], depending on silos storage capacity Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours Ramping: <30 mins[42]	Typically limited by silo storage capacity. If the silos are large enough, they can provide up to 100% flexibility
Clinker formation (27% of current site electricity consumption)	Plasma torch powered kilns	Max peak demand reduction: 0% during operation. 100% during annual maintenance[42] Demand shift timing: Before and after peak window Demand shift duration: Up to a week, depending on length on maintenance period[42] Ramping: Information unavailable	The rotary kilns must run 24 hours a day for its lifetime (~20 years) and are typically stopped only for a few days in a year for annual maintenance. The only feasible DSR strategy would be to align the annual maintenance periods with the peak network congestion times.
Clinker formation (27% of current site electricity consumption)	Kiln with bivalent heat generation	Max peak demand reduction: 100%[42] of electricity demand Demand shift timing: Before and after peak window Demand shift duration: Dependent on amount of alt. fuel available and the design of the furnace Ramping: <15 mins[42]	Demand shift duration is limited by the amount of alternative fuel that is available for the kiln.

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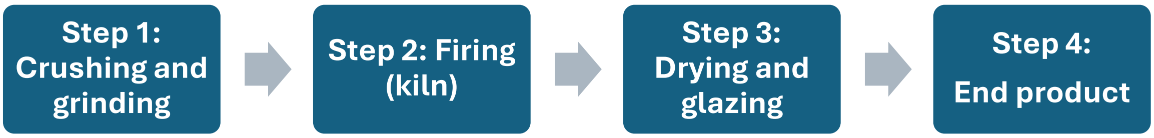
[42] Stakeholder Interviews

Ceramics

Ceramics generally refers to the production of inorganic materials created from non-metallic compounds which are fired at high temperatures in a kiln to form the end-product. These include brick and roof tiles, vitrified clay pipes, refractory products, clay, tableware and sanitary products, etc.

While the general process steps are common for all product types, the raw materials used, the kiln type, and operating conditions will vary with the end-product. In most cases, the firing process is continuous. However, in some cases – clay manufacturing, for example – it is common to see intermittent batch kilns being used.

Figure 5: Main production steps for Ceramics manufacturing



The ceramic manufacturing process begins with procuring raw materials (e.g. complex mixtures of clay minerals and other mineral matter such as quartz, feldspar, carbonates, gypsum, iron oxides, and sometimes organic matter), which are refined and mixed to create the desired composition. The materials are then formed into their desired shape and undergo various thermal processing stages, such as drying, firing, and glazing. The final product is then packaged and ready for use[43]. The main energy input in the ceramics process is heat, with the drying and firing processes occurring at temperatures ranging between 800 to 2,000 ºC.

Raw materials are mixed and then cast, pressed, or extruded into shapes. Water is used for mixing and shaping and is subsequently evaporated in dryers. Heat for drying air is typically supplied by burners but may also be supplied by hot air recovered from kiln cooling zones or CHPs. Various types of dryers can be used such as: hot floor dryers, chamber dryers, tunnel dryers, vertical basket dryers, horizontal multi-deck roller dryers, dehumidifying dryers, and infrared and microwave dryers[44]. Products are then placed into various kilns depending on the end-product, where they are fired. Firing conditions important aspects of the finished product such as mechanical strength, resistance, and stability.

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[43] Khatabook, Ceramic Manufacturing Process
[44] EU-BRITE, Ceramic Manufacturing Industry

Electrification Potential

Figure 6: Ceramics electrification potential (2025 - 2035)

Commercial applications of electric tunnel and batch kilns based on resistance technology are mature.[45] However, extent of electrification for the Ceramics sector is dependent on the type of product being produced.[46] For example, stakeholder interviews suggested that technical ceramics are more conducive to electrification using resistance technology in comparison to sanitary ware due to the cross section of tunnel kilns employed being smaller than those for sanitary ware. Another barrier for electrification is the need for grid upgrades and need for relatively longer shutdown to implement as opposed to hydrogen-based kilns we can be retrofitted. Electric arcs can also potentially be used to reach firing temperatures of 2,750°C in refractory and technical ceramics[47]. Microwave and radio frequency heaters are also commercially available technologies that could potentially be used for firing and sintering in the sector. Further, the EU-funded eLITHE project is currently investigating high-temperature heating systems specifically for the sector[48]. Technologies being investigated by eLITHE include: smelters combining induction and resistance heating, microwave-based calcination furnace for alumina calcination, and tunnel kilns using hybrid burners.

There is debate in literature about whether continuously operated kilns can be fully electrified at full commercial scale. In 2023, the British Ceramic Confederation stated that electrification was being deployed in the sector but for relatively small-scale production levels (or “batch” kilns)[49]. These were said to be unsuitable for heavy clay construction products (e.g. bricks, blocks, roof tiles, drainage pipes etc.), which accounts for most of the sector’s emissions. Large-scale electrification would require larger kilns operating continuously. Further, in 2025, Ceramics UK released a roadmap that stated that electrification could reduce emissions in the sector by 11%, with higher reductions possible using hydrogen and carbon capture technologies[50]. The roadmap also suggested that R&D was still needed to electrify large-scale production.

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[45] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

[46] Dylan Furszyfer Del Rio and others (2022) 'Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems' Renewable and Sustainable Energy Reviews, Volume 157

[47] British Ceramic Confederation (2018) 'BCC response to CCC call for evidence: A zero-carbon economy'

[48] eLITHE website

[49] UK Ceramic Sector Response to ‘Enabling Industrial Electrification: a call for evidence’

[50] Ceramics UK (2024) ‘Decarbonising UK Ceramic Manufacturing Roadmap’

NZIP2

Table 14: Qualitative summary of baseline Ceramic sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Low-temperature heat technology	Boiler	< 1 MW	Fuel-switching, Heat Pump, boiler electrification	Available	For many but not all industrial sectors, the main decarbonisation pathway for boilers would likely be fuel-switching to alternative fuels such as hydrogen and biomass. Heat pumps may be able to supply heat demand up to around 165°C[51].
High-temperature heat technology	Kiln	N/A	Electric Kiln	-	Kiln types deployed across the Ceramics sector depend on the throughput: for continuous production, tunnel kilns are the most common technology; for more specialised production, intermittent batch kilns are the most common technology. Electric kilns, including boosting (10-40%)[52], have overtaken gas and hydrogen alternatives. Hydrogen kilns are currently constrained by a lack of R&D, lack of H2 infrastructure, and significant cost.
CHPs (Steam Turbine & CCGT based on various fuels)	CHP CCGT	< 1 MW 5-25 MW	Fuel-switching	Available	For many but not all industrial sectors, the main decarbonisation pathway for CHPs would likely be fuel-switching to alternative fuels such as hydrogen and biomass.

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[51] Ahmed Gailani and others (2024) 'Assessing the potential of decarbonization options for industrial sectors' Joule, Volume 8, Issue 3, pages 576-603

[52] Stakeholder Interviews

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Drying/separation technology	Spray dryers	-	Electrified heat input to spray dryers	Unknown	In ceramics spray dryers are typically heated by direct-fired gas burners to generate hot air for the drying process. The decarbonised alternative is to provide electric resistive heating in place of the gas burner. This is understood to be in commercial development with some technical constraints to deployment.

Table 15: Quantitative summary of Ceramics sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2
Electric motor technology	Motor	3	0.08	9/ 2011	3
Gas turbine CHP based on natural gas	CHP	81	0.3	9/ 2011	3
High-temperature heat technology based on coal	Kiln	197	5.18	9/ 2011	1
High-temperature heat technology based on electricity	Kiln	119	2.98	9/ 2011	3
High-temperature heat technology based on hydrogen	Kiln	118	2.95	8/ 2028	2

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
High-temperature heat technology based on natural gas / biomethane	Kiln	83	2.07	9/ 2011	3
High-temperature heat technology based on solid biomass	Kiln	197	5.18	9/ 2011	1
Low-temperature heat technology based on coal	Boiler	17	1.26	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	6	0.02	9/ 2011	3
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	6	0.20	9/ 2020	3
Low-temperature heat technology based on LPG	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on natural gas	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on solid biomass	Boiler	22	1.66	9/ 2011	3
Low-temperature space heat technology based on coal	Boiler - Hot water	9	0.65	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature space heat technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3
Steam turbine CHP based on solid biomass	Biomass CHP	34	2.0	9/ 2011	3

Demand Side Response (DSR)

The DSR potential of the Ceramics industry may vary with the end product being manufactured. In general, however, its DSR potential is moderate. The most energy intensive step – firing in the kilns – must operate continuously and has strict temperature requirements. However, if batch kilns are used on site, as is the case with some clay manufacturers,[53] the potential for DSR may be greater.

Depending on the size of the silos on site, the milling step can be operated as a batch process and offer high levels of DSR. The silos can be used as a pseudo battery and enable the mill to power down/turn off during peak network congestion periods and/or periods of high electricity prices. This step accounts for most of the site's current electricity consumption. However, if a site chooses to decarbonise its firing process by adopting electrically powered kilns, the fraction of electricity consumption this step will account for will dramatically reduce, along with the impact of its DSR capabilities, as most of the electricity consumption will be attributed to the firing step.

Achieving DSR from the firing process is difficult as it usually operates continuously and has precise energy input/temperature requirements. According to stakeholder interviews, operators are reluctant to turn off and turn back on their kilns unless absolutely necessary (e.g. for maintenance purposes) as refiring the kilns can take up to 36 hours and can damage the equipment, reducing its lifetime. The only form of DSR a 100% electrically powered continuously operating kiln can offer is aligning the 2-week annual maintenance shutdown with periods where the network is most constrained. Sites would require a few months' notice to schedule this accordingly.

If sites, such as clay manufacturers and other smaller manufacturing sites, use intermittent batch kilns instead of large continuous ones, DSR can be achieved by scheduling the kilns to not operate at peak network congestion periods.

Additionally, if a site decides to adopt a kiln with bivalent heat provision (e.g. gas/hydrogen fired with 10-40% electrical boosting), the DSR potential from the energy-intensive firing process could be improved provided the bivalent kiln is designed to operate at varying fuel compositions and there is sufficient non-electric fuel supply available, according to stakeholder interviews. However, the TRL for this type of kiln is relatively low today.

The drying/glazing steps can offer some degree of DSR, especially if powered by heat pumps / electric boilers paired with some form of thermal energy storage. The strict temperature requirements associated with this step limits its potential.

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[53] Stakeholder interviews

Table 16 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from the information shared with us in stakeholder interviews UK and available literature. It should be noted that a ceramic manufacturing site was not interviewed over the course of the project.

Table 16: Demand side response potential summary of Ceramic sector

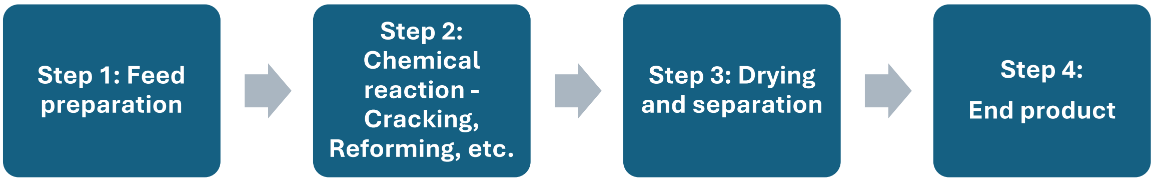
Process	Equipment	Practical DSR potential	Constraints
Crushing and grinding of raw materials	Mills	Max peak demand reduction: Up to 100%, depending on silos storage capacity[31] Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours Ramping: <15 mins[31]	The practical DSR potential is heavily linked to the size and number of silos on the site. The greater the storage capacity, the greater the peak demand reduction and demand shift duration achievable.
Firing	100% electric kiln	Max peak demand reduction: 0% Demand shift timing: N/A Demand shift duration: N/A Ramping: Up to 36 hours ramp up[31]	DSR potential limited by how long the equipment is designed to be able to run 100% on the alternative fuel source (hydrogen, nat. gas, etc.) and the amount of alternative fuel available.

Process	Equipment	Practical DSR potential	Constraints
Firing	Electrically boosted (10-40%19) kiln	Max peak demand reduction: Up to 100% of electricity demand Demand shift timing: Before and after peak window Demand shift duration: Dependent on amount of alt. fuel available for furnace Ramping: Information unavailable	DSR potential limited by how long the equipment is designed to be able to run 100% on the alternative fuel source (hydrogen, nat. gas, etc.) and the amount of alternative fuel available.
Drying/glazing	Heat pump/electric boiler	Max peak demand reduction: 10% Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours Ramping: <15 mins	DSR potential limited by strict temperature requirements.

Chemicals

The chemical industry covers a broad range of processes and hundreds of diverse segments that convert raw materials into various chemical products, often requiring significant heat input. The chemicals sector can be generally categorised into organic, inorganic, plastics, and fertiliser sectors. Processes vary greatly from reactions such as steam reforming, steam cracking[54], to separation (e.g. distillation), with conditions also varying strongly as well (low to high-temperature, and similarly for pressure). Primary chemicals account for a large portion of the sector's total CO2 emissions (60%), with Ammonia production being the large source with a contribution of 49% toward the total emissions[55]. Respectively, steam and power generation consume around 44% and 42% of primary energy use in the Chemicals sector, with the remaining apportioned to direct fuel use.[56]

Figure 7: Main production steps for Chemicals manufacturing



For the Chemicals sector, the NZIP2 model includes reforming and cracking facilities. On the latter, various crackers are currently designated in the NZIP2 model, including electric, naphtha, and ethane, steam crackers, as well as an oil product catalytic cracker. Cracking can generally be understood as the processes for splitting hydrocarbon feedstocks such as naphtha and ethane into mixtures of smaller-chain hydrocarbons that can be then separated and processed further. Cracking is an energy-intensive process, requiring heat generated from the combustion of fossil fuels. Steam cracking in particular has been described as the most energy-intensive process in the chemical industry[57]. Cracking can occur with or without the presence of a catalyst. For example, as opposed to fluid catalytic cracking (FCC), the steam cracking process does not use a catalyst, relying on high temperatures instead. Catalytic cracking processes occur at temperatures ranging between 485-550 °C, whereas steam cracking requires higher temperatures of around 900 °C[58].

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[54] Naif Almuqati and others (2024) 'Catalytic production of light Olefins: Perspective and prospective' Fuel, Volume 366

[55] International Energy Agency (2018) 'The Future of Petrochemicals'

[56] US Department of Energy (2012) 'US Manufacturing Energy Use and Greenhouse Gas Emissions Analysis - Section 2.2 Chemicals sector (NAICS 325)'

[57] CORDIS, European Commission, Cracking steam cracking technology with eco-friendly furnaces, IMPROOF Project

[58] Naif Almuqati and others (2024) 'Catalytic production of light Olefins: Perspective and prospective' Fuel, Volume 366

In terms of the industry landscape, greenfield crackers are very uncommon in Europe, with the chemical sectors in both the UK and the EU said to be in decline. In what is said to be the first new ethane cracker in Europe for 25 years[59], new ethane cracker with a nameplate capacity of 1450 kt of ethylene per year is currently being built by INEOS in Antwerp. A very recent study on the European chemical industry noted a number of difficulties the sector was facing, including issues regarding industrial competitiveness, weak demand, low utilisation rates and profitability, complex and challenging regulatory environments[60]. In 2024, the UK chemicals industry was reported to have contracted for the sixth consecutive quarter[61]. In the UK, the chemicals sector represents around 2% of overall CO2 emissions, and around 19% of industrial emissions[62]. Chemical production sites are clustered geographically, with Hull, Teesside, Runcorn, and Grangemouth at the forefront. At the time of writing, the UK has three operational steam crackers (ethane steam crackers). In terms of decarbonisation technologies, as part of the HyNet cluster, Essar UK will be retrofitting its FCC with a post-combustion carbon capture system using amine-based solvents. As part of the Humber Zero project, Phillips 66's Humber Refinery is also considering retrofitting its FCC with a post-combustion carbon capture system using amine-based solvent. These developments showcase investments being made in olefin-producing assets.

Electrification Potential

Figure 8: Chemicals electrification potential (2025 - 2035)

Electrification is limited for the Chemicals sector with present-day technologies[63]. High-temperature heat applications within this sector include steam cracking, steam generation, and steam reformation for ammonia production.

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[59] INEOS Project ONE website

[60] Cefic / Advancy (2025) 'The Competitiveness of the European Chemical Industry'

[61] Alex Scott (2024) 'UK chemical industry shrinks for 6th consecutive quarter' Chemical & Engineering News, Volume 102, Issue 5

[62] Tom Franklin, Lucy Elphick & Andrew Gill (2024) 'Written evidence submitted by The National Interdisciplinary Centre for Circular Chemical Economy (CCUS0013)'

[63] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

With steam cracking, superheated steam is required at temperatures above 800°C. Electric steam crackers based on resistance heating and shockwave heating are currently being demonstrated at pilot scale. Electrified steam cracking technologies are expected to be available at commercial scale by 2030[64].

Steam is required for several other processes in the chemicals sector. High-temperature heat pumps for up to 200°C are expected to be commercially available from 2025, and high-temperature heat pumps in combination with electric boilers could potentially provide steam between 200°– 500°C[65].

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[64] The world’s first e-cracker pilot began in April 2024 at BASF’s Ludwigshafen site where both direct and indirect heating concepts are being investigated.

[65] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

NZIP2

Table 17: Qualitative summary of baseline Chemical sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
CHPs (Steam turbine & CCGT)	CHP CCGT	>25 MW >25 MW	CCS, fuel-switching	Available	Interviews suggested that large integrated sites would likely have CHPs in capacity range of 100 MW, whereas smaller more remote sites would be in range of 10 MW. CHPs may be able to use chemical by-products as a fuel, but there are possible limitations on use based on how different by-products are from the base design fuel. Industrial clustering may provide additional decarbonisation options such as CCS with the availability of Transport and Storage infrastructure (leveraging also economies of scale), as well as possible hydrogen supply.
Low-temperature heat technology	Boiler	>25 MW	Fuel-switching, electric boilers, heat pumps.	-	Stakeholders suggested decarbonising low temperature heat is not just limited to decarbonising boilers and would involve an evaluation of the steam balance of the cracker plant and potential electrification of steam-based turbomachinery. Nevertheless, electrification and hydrogen-firing for boilers are being explored. Heat pumps may also be considered for low-temperature applications. Electrification and heat pumps may be more applicable for more isolated sites displaced from industrial clusters, given the fact that large-scale T&S infrastructure for CCS for example, are likely not to be present.

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
High-temperature heat technology	Boiler	>25 MW	-	-	Electrification is possible, but there are concerns as to whether the high amounts of superheat can be provided. Heat pumps are unlikely to be used because compression ratios decrease in high-temperature applications, necessitating additional compressors for steam generation. There are also on-going questions regarding the temperatures that heat pumps can reach in tested commercial settings.
Steam reformer (standard) for ammonia production	SMR	-	SMR with CCS, Electrified Steam Methane Reforming (e-SMR)[66]	Available	The NZIP2 model currently includes SMR and ATR for hydrogen production. ATR may also be used for ammonia production[67]. In a typical SMR ammonia plant there are both flue gas CO2 emissions, and process CO2 emissions. Process emissions related to the formation of syngas account for around two thirds of CO2 emissions. These CO2 emissions are already “captured” in a sense because they are formed as part of the syngas stream. Syngas contains higher-purity CO2 as opposed to flue gas emissions[68]. Process emissions are routed to a carbon capture system where the CO2 is typically recovered using amine-based solvents[69]. In 2023, e-SMR was categorised as TRL 6[70].

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[66] Kevin Rouwenhorst (2019) 'Electrified Methane Reforming Could Reduce Ammonia’s CO2 Footprint', report for the Ammonia Energy Association

[67] Kevin Rouwenhorst (2024) ‘Technology options for low-emission ammonia production from gas’, report for the Ammonia Energy Association

[68] Kevin Rouwenhorst (2023) ‘Decarbonizing existing, SMR-based ammonia plants: workshop recap’, report for the Ammonia Energy Association

[69] Illinois Environmental Protection Agency (2014) 'Project Summary for a Construction Permit Application from Cronus Chemicals, LLC, for a Fertilizer Manufacturing Facility near Tuscola, Illinois'

[70] British Columbia Centre for Innovation and Clean Energy (2023) 'Carbon Intensity of Hydrogen Production Methods'

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Drying/ separation technology	-	-	Fuel-switching	Available	The NZIP2 model includes a general entry on “Drying/separation technology” based on various different fuels and technologies such as natural gas, LPG, hydrogen, solid biomass, electricity, and heat pumps.
Naphtha, ethane, steam cracker	Steam Cracker	-	Steam Cracker with CCS.	-	Considering post-combustion carbon capture from flue gases, whether a steam cracker is naphtha, ethane, or generically labelled as “steam cracker”, should not have a major bearing on the costs parameters of such a carbon capture system. This is already reflected in the original NZIP2 model technology list where the applicable CCS entry refers to steam crackers generally. Given the competitiveness of the UK chemical industry, we consider it unlikely that greenfield crackers would be built in the UK in the years to come. Instead, the retrofitting of existing crackers with CCS is more likely.

Table 18: Qualitative summary of decarbonisation Chemical sector technologies

NZIP2	Insights from interview and literature review
Electric Steam Cracker (w/o CCS)	It is advised to remove this entry from the NZIP2 model because when the furnace is electrified, the majority of CO2 emissions from the furnace (which is the locus of emissions in a steam cracker), are eliminated and only emissions from sources other than the furnace remain. These are too limited to justify the use-case for CCS. 90% of emissions may be typically eliminated through electrification of the furnaces.
Steam reformer with CCS for ammonia production	The NZIP2 model currently specifies SMR and ATR for hydrogen production in the Hydrogen section of the database. In the Chemicals portion of the database, SMR has been assumed as the reference technology for ammonia production. However, both SMR and ATR can be used to produce hydrogen necessary for ammonia production, and both can be equipped with CCS.
Steam cracker with post-combustion CCS	Interviews conducted as part of the stakeholder engagement process suggested it was very unlikely, almost close to zero, that greenfield crackers would be built. Instead, for CCS at least, the retrofitting of existing crackers is more likely.

Table 19: Quantitative summary of Chemicals sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
CCGT CHP based on by-products in the chemicals sector	CCGT CHP	65	1.5	9/ 2011	3	PJ
CCGT CHP based on hydrogen	CCGT CHP	85	1.9	8/ 2025	2	PJ
CCGT CHP based on LPG	CCGT CHP	65	1.5	9/ 2011	3	PJ
CCGT CHP based on natural gas	CCGT CHP	65	1.7	9/ 2011	3	PJ
Drying / separation technology based on electricity	Same as low temperature heat	4	0.02	9/ 2011	3	PJ
Drying / separation technology based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Drying / separation technology based on hydrogen	Same as low temperature heat	2	0.07	9/ 2025	3	PJ
Drying / separation technology based on LPG	Same as low temperature heat	2	0.03	9/ 2011	3	PJ
Drying / separation technology based on natural gas	Same as low temperature heat	2	0.03	9/ 2011	3	PJ
Drying / separation technology based on solid biomass	Same as low temperature heat	11	0.83	9/ 2011	3	PJ
Electric motor technology	Motor	3	0.08	9/ 2011	3	PJ
Electric Steam Cracker for high value Chemicals	Steam cracker	712	17.81	7/ 2028	2	Mt

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
Electric Steam Cracker for high value Chemicals with CCS	CCS	1,044	50.99	7/ 2060	1	Mt
Ethane steam cracker for the production of high value chemicals	Steam cracker	609	15.22	9/ 2011	2	Mt
High-temperature heat technology based on coal	High Temp	10	0.27	9/ 2011	1	PJ
High-temperature heat technology based on electricity	High Temp	5	0.14	9/ 2011	1	PJ
High-temperature heat technology based on hydrogen	High Temp	6	0.16	8/ 2028	1	PJ
High-temperature heat technology based on natural gas / biomethane	High Temp	4	0.11	9/ 2011	2	PJ
Hydrogen fuel switching in high value chemicals	Steam cracker	712	17.81	8/ 2029	2	Mt
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Low-temperature heat technology based on coal	Boiler	8	0.63	9/ 2011	3	PJ
Low-temperature heat technology based on electricity	Boiler	4	0.02	9/ 2011	3	PJ
Low-temperature heat technology based on hydrogen	Boiler	2	0.07	9/ 2020	3	PJ

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
Low-temperature heat technology based on LPG	Boiler	2	0.03	9/ 2011	3	PJ
Low-temperature heat technology based on natural gas	Boiler	2	0.03	9/ 2011	3	PJ
Low-temperature heat technology based on solid biomass	Boiler	11	0.83	9/ 2011	3	PJ
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3	PJ
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3	PJ
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3	PJ
Low-temperature space heat technology based on solid bioheat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3	PJ
Oil byproduct catalytic cracker for the production of high value chemicals	Steam cracker	712	17.81	9/ 2011	2	Mt
Naphtha steam cracker for the production of high value chemicals	Steam cracker	816	20.40	9/ 2011	2	Mt
Steam cracker with post-combustion CCS using excess heat	CCS	1,031	50.34	9/ 2025	2	Mt

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
Steam cracker with post-combustion CCS with biomass boiler for the production of high value chemicals	CCS	1,110	54.23	9/ 2025	2	Mt
Steam cracker with post-combustion CCS with natural gas boiler for the production of high value chemicals	CCS	1,044	50.99	9/ 2025	2	Mt
Steam cracker with post-combustion CCS with NGCC	CCS	1,058	51.66	9/ 2025	2	Mt
Steam reformer (standard) for ammonia production	Steam cracker	146	3.66	9/ 2011	2	Mt
Steam reformer with CCS for ammonia production	CCS	353	8.83	9/ 2025	2	Mt
Steam turbine CHP based on coal	CHP	8	0.2	9/ 2011	3	PJ
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Steam turbine CHP based on solid biomass	Biomass CHP	9	0.5	9/ 2011	3	PJ

Demand Side Response

The DSR potential of the chemicals sector varies heavily by subsector. The main sources of energy consumption of this sector are typically the reactors (cracking in the petrochemicals and olefins sector for example) and the separation/drying processes.

Electricity currently accounts for a relatively low portion of the sectors' overall energy consumption. However, this is expected to increase drastically if/when the industry adopts electrically powered equipment such as e-crackers, e-furnaces, etc as they decarbonise their operations.

The amount of power/energy a cracker or reformer uses is linked to its feed rate. This, in turn, is determined by the equipment's design envelope (minimum and maximum rates at which it can operate) and the end-product demand from the site's customers. Stakeholder interviews revealed that electric crackers and reformers can theoretically turn down and turn up their power consumption in response to DSR signals. However, given the strict temperature requirements, this can only be done slowly, and power consumption can only be reduced by up to 20%. Furthermore, the TRL of electric crackers is relatively low today and DSR with electric crackers have not been trialled enough to confirm its potential.

From stakeholder engagement we understand that for a chemical manufacturing process that operates as a batch/semi-batch process, such as in ethylene liquefaction plants[71], there is potential to participate in DSR by scheduling batch operations outside of peak network congestion periods. However, sites will require days to a weeks' notice period to do this.

The separation and drying processes encounter similar types of constraints when it comes to DSR as they too have strict temperature/heat requirements to ensure product quality standards are met.

Table 20 below summarises the DSR potential of the different processes capable of flexing their electricity demand using current/future equipment. The figures quoted are estimates derived from the stakeholder interviews and available literature. For more information on the DSR potential of electrolysers, please refer to the hydrogen production sector profile.

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[71] Ethylene liquefaction is one process step within the broader ethane cracking process.

Table 20: Demand side response potential summary of Chemical sector

Process	Equipment	Practical DSR potential	Constraints
Cracking/ Reforming/ other reactor types	Electric cracker/ reformer/ furnaces	• Max peak demand reduction: 10-20%[72] • Demand shift timing: Before and after peak window • Demand shift duration: Information unavailable • Ramping: Lengthy ramp-up and down. Information on exact figures unavailable	A cracker/reformer cannot operate below a certain minimum load. Furthermore, start-up typically takes days. This limits the ability of an electric cracker/reformer to participate in DSR regularly.
Main reaction step in batch/semi-batch processes	Reactor type varies by subcategory	Max peak demand reduction: Up to 100% Demand shift timing: Before and after peak window Demand shift duration: Process dependent Ramping: Process dependent	
Drying/separation processes	Heat pump/electric boiler	Max peak demand reduction: Up to 100% if batch process. Demand shift timing: Before and after peak window Demand shift duration: Process dependent Ramping: <15 mins	

Food & Drink

The Food & Drink production process converts raw materials into finished products that are suitable for consumption. It involves multiple stages, such as ingredient preparation, mixing, blending, cooking, pasteurisation, sterilisation and cooling, and is typically highly regulated. These stages are generally scheduled closely to each other; therefore, the process can be characterised as a 24/7 batch process. The highest energy demand in the Food & Drink production process is low to medium temperature heat and refrigeration for product cooling.

The Food & 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[73]. The industry employs close to 400,000 people and has a GVA of roughly £28 billion. 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

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[72] Stakeholder Interviews, Cefic views on industrial flexibility – December 2024

[73] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

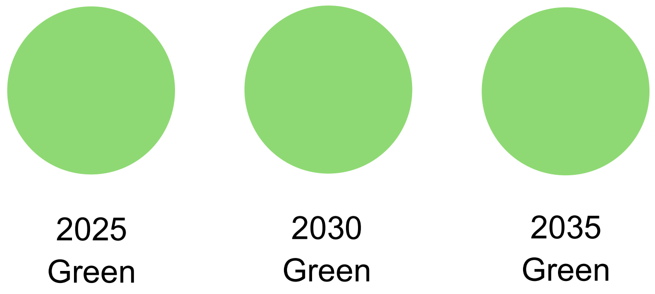
fuels, with electricity accounting from the remaining energy use. The majority of fossil fuel use in this sector is for heat generation and natural gas is the dominant fuel source, contributing roughly 83% of the fuel demand. For sites off the gas network, predominant fuels are LPG and gas or fuel oils. This fossil fuel use makes it one of the largest emitting sectors with around 3 MtCO2/year for all food, beverage and tobacco activities.

Food & Drink is a highly varied and heterogeneous sector, arising from the wide range of products and differing processing steps and technologies. As a result, it is difficult to characterise at an aggregate level. The main unit operations applied throughout this sector include, but are not limited to, the following processing steps: material handling and preparation, size and form management, separation, product processing, heat processing, concentration by heat, chilling and freezing, post-processing, and 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 CO2 emissions onsite, such as gas-fired combustion to generate heat, but excludes processes like fermentation which are part of the production process. Approximately 46% of the useful energy demand in this sector is used for steam generation as well as direct-fired drying and ovens. The typical low-temperature heat technology is gas-fired steam boilers.

Electrification Potential

Figure 9: Food & Drink electrification potential (2025 - 2035)



The Food & Drink sector is considered one of the best candidates for electrification. Through resistance heaters, electric boilers, and heat pumps, literature suggests that the Food & Drink sector could be fully electrified with existing technologies[74,75]. For specific high-temperature drying applications such as that used in milk powder, electrified spray dryers are commercially available, providing drying air at around 250 °C. Otherwise, most process heating applications have a temperature demand of less than 200 °C which is typically met using fossil-fuel boilers.

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[74] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', Study on behalf of Agora Industry

[75] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

Specifically, steam generation through electric boilers and heat pumps offers near-term direct electrification potential. Finally, for drying applications, microwave dryers could also be an option. Microwave systems can achieve very high temperatures of around 2,000 °C.[76]

In 2020, the UK Food & Drink Federation published a report on the decarbonisation of heat in the sector[77]. Electrification of heat was identified as one of the key levers that would have the largest decarbonising effect on the sector. At the time, for boilers and CHPs, connection of these technologies to "renewable gas supplies" was identified as a preferred decarbonisation option due to the high relative cost of electricity.

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[76] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

[77] FDF (2020) 'Decarbonisation of heat across the food and drink manufacturing sector'

NZIP2

Table 21: Qualitative summary of baseline Food & Drink sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarbonisation alternative	Insights from literature review & interview
Low temperature heat	Boiler	1-5 MW	Electrification using heat pump /E-Boiler	Post 2030	Electric boiler replacement technologies are commercially established solutions with relatively acceptable costs for industry. However, the timeline for adoption is constrained by the depreciation of existing gas boilers that dominate across the sector, the majority of which the lifetime is at a minimum 20+ years.
CHP (Steam Turbine and CCGT based on various fuels)	CHP	1-5 MW	Hydrogen CHPs	N/A	CHP systems are widespread in their use within UK Food & Drink due to the high level of low-temperature heat demand. Most applications are for internal combustion engines rather than turbines, since the heat to power ratio of combustion engines (around 1:1) more closely aligns with food & Drink heat and power demands. The notable exception is sugar refining, where CCGT and steam turbine CHP systems are the predominant technology.
Drying/ separation	Spray dryer/ Ovens	-	-	-	Spray drying technologies are high-cost and require significant space on-site. Ovens are the alternative, more cost-effective drying technology commonly employed in UK industry. In the future, UK industry is expected to explore outsourcing spray drying rather than installing this technology on-site.

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarbonisation alternative	Insights from literature review & interview
Refrigeration	Mechanical refrigeration with compressor	-	N/A	N/A	Whilst there are efficiency gains to be made from replacing refrigeration systems at end of life, since the baseline technologies are fully electrified these are not a core focus for decarbonisation within Food & Drink companies

Table 22: Quantitative summary of Food & Drink sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2
Drying / separation technology based on coal	Drying/ separation	11	0.84	9/ 2011	3
Drying / separation technology based on electricity	Drying/ separation	5	0.05	9/ 2011	3
Drying / separation technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Drying / separation technology based on hydrogen	Drying/ separation	3	0.11	/ 2020	3
Drying / separation technology based on LPG	Drying/ separation	2	0.05	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Drying / separation technology based on natural gas	Drying/ separation	2	0.05	9/ 2011	3
Drying / separation technology based on solid biomass	Drying/ separation	15	1.11	9/ 2011	3
Electric motor technology	Motor	3	0.08	9/ 2011	3
Gas turbine CHP based on natural gas	CHP	34	0.9	9/ 2011	3
Low-temperature heat technology based on coal	Boiler	11	0.84	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	5	0.05	9/ 2011	3
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	3	0.10	9/ 2020	3
Low-temperature heat technology based on LPG	Boiler	2	0.05	9/ 2011	3
Low-temperature heat technology based on natural gas	Boiler	2	0.05	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Low-temperature heat technology based on solid biomass	Boiler	15	1.11	9/ 2011	3
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3
Steam turbine CHP based on solid biomass	Biomass CHP	23	1.0	9/ 2011	3

Demand Side Response

Because the Food and Drink industry comprise of a large variety of subsectors using numerous different processes, the DSR potential of the sector is heavily process/subsector dependent. However, in general, the industry’s DSR potential tends to be limited due to the strict quality regulation, which translates into strict temperature/energy input requirements. The batch nature of most of these processes enables it to offer some degree of DSR, however, the batches tend to be scheduled close to one another, leading to a near-continuous thermal demand profile, limiting the demand shift duration potential of the process.

If the site has a suitable degree of buffer storage, the electrically powered blenders/homogenisers used in the raw material preparation stages can be turned down/up in response to DSR signals by operating the buffer storage like a pseudo battery. The duration and amount of flex that can be unlocked will depend on the storage capacity and the amount of time the processed raw materials can be stored for at a time without degrading. However, in some cases, the buffer storage will have to be refrigerated, which would require electricity consumption. This negates the demand turn down achieved by the blenders/homogenisers. For example, stakeholder interviews revealed that their site could offer no DSR as storing the sugar instead of processing it immediately would affect its quality. Furthermore, the sugar would have to be stored in a cool environment to prevent it from degrading, which would increase the site’s electricity consumption and negate any network benefits achieved from DSR.

The current and future electrically powered heating technologies for the heat processing parts of the manufacturing process can theoretically turn up/down and shift their electricity consumption in response to DSR signals. However, as mentioned previously, the strict temperature regulations and the fact that the batches tend to be scheduled close to one another limits the DSR potential achievable. The same applies to any drying/separation process that take place.

Processes that involve refrigeration could offer a degree of DSR as well. Site operators can adopt a pre-cooling strategy, where they shift the operation of the equipment a few hours before their usual operation period and rely on the thermal inertia of the equipment to keep the contents in the desired temperatures. The main constraint here would be how long the temperature can be maintained within the desired range while the power is turned down/off.

Table 23 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from available literature and British Sugar. They have been verified by subject matter experts in Guidehouse and were sense-checked with during the stakeholder interviews.

Table 23: Demand side response potential summary of Food & Drink sector

Process	Equipment	Practical DSR potential	Constraints
Raw material preparation	Blenders and Homogenisers	Max peak demand reduction: Up to 100% Demand shift timing: Before and after peak window Demand shift duration: Up to 2 hours Ramping: <15 mins	The max peak demand reduction and demand shift duration achievable depends on site's buffer storage capacity and electricity requirements for it.
Processes requiring low temperature heat	Heat pump/Electric boiler	Max peak demand reduction: 10% Demand shift timing: Before and after peak window Demand shift duration: Process dependent Ramping: N/A	Strict temperature and product quality requirements limit its potential. Manufacturers are unwilling to participate in DSR at the risk of their end product quality degrading.
Drying/separation	Heat pump/Electric boiler	Max peak demand reduction: 10% Demand shift timing: Before and after peak window Demand shift duration: Process dependent Ramping: N/A	Strict temperature and product quality requirements limit its potential. Manufacturers are unwilling to participate in DSR at the risk of their end product quality degrading.
Refrigeration processes	Heat Pump, MVR, thermal storage and/or E-boiler system	Max peak demand reduction: Up to 100% Demand shift timing: Before and after peak window Demand shift duration: Up to 2 hours, max 3 times a day Ramping: <15 mins	Limited by min/max temperature requirements and ability of equipment to retain coolth. Typically, as long as the temperature of the cooling stays in the desired thresholds, refrigeration technologies can offer DSR.

Glass

The glass manufacturing industry in the UK comprises of 10 distinct manufacturers who operate 17 facilities, a large proportion of which are based around Leeds, Sheffield and Liverpool[78]. These sites mainly produce container glass (~65% of glass manufactured in UK) and flat glass (~30% of glass manufactured in UK). The industry is highly energy intensive, with an annual natural gas consumption of ~6TWh and an electricity demand of ~1TWh. Most of the energy use in the glass sector is attributable to the significant heat required to melt raw materials. The glass production process is a continuous process that requires very stable energy input (mostly heat).[79] While specific site processes may vary depending on product requirements, the main steps involved in glass manufacturing are:

Figure 10: Main production steps in glass manufacturing

1. **Batching of raw materials:** The dry raw materials (mainly silica sand with sodium carbonate, limestone and recycled glass) are crushed and mixed in specific proportions in a mixing silo at the batch plant. These processes are typically completely electrified and may account for ~4% of total process energy usage. Using a greater volume of recycled glass in the raw materials mix can reduce the energy consumption of this process.

2. **Melting of raw materials in furnace:** The batch material is fed into a furnace, where they become molten. Temperatures in the furnace can reach up to ~1,600 °C and they generally run continuously without downtime for the entirety of the asset lifetime, 24 hours a day 7 days a week to ensure a stable temperature. This stage is often the most energy-intensive, accounting for ~80-85% of total process energy usage. Today, these furnaces are mostly natural gas-fired, with some prevalence of electrically boosted furnaces (20-30% electrical boosting). Sites are exploring hydrogen, electric melting and other low carbon liquid fuels to decarbonise their operation. 100% electrical furnaces for the flat glass industry looks highly unlikely before 2050 at current output volumes of ~800 tonnes/day. They may be used in container glass manufacturing sites, where the current output volumes are typically smaller, ~300 tonnes/day.

3a. **Forming (Container glass):** The molten glass is directed through multiple feeder channels from the furnace into forming machines. Compressed air is injected in these machines, causing the molten glass to take the shape of the desired container.

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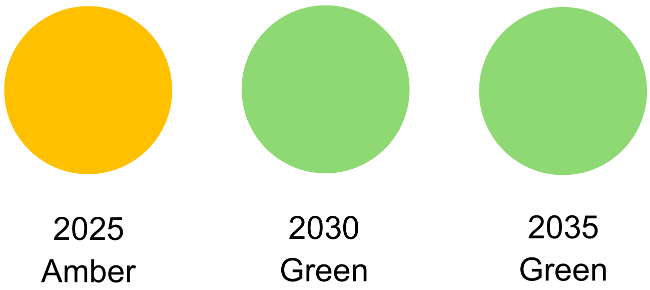
[78] ERM (2024) '[Future opportunities for electrification to decarbonise UK industry](#)', A report for Department for Energy Security and Net Zero
[79] Glass for Europe (2022) '[Continuous energy supply is essential for the flat glass industry](#)'

3b. **Forming (Flat glass):** The molten glass is floated onto a bath of immiscible molten tin at a temperature of 1,000 °C, forming a "ribbon" like shape with a high-grade surface finish.

4. **Cooling of the molten glass in an annealing lehr:** This process involves carefully preheating and controlled cooling of the glass to modify the internal stresses of the glass and achieve the final desired product. Gas heaters and electric heating are the two most common solutions for annealing lehrs.

Electrification Potential

Figure 11: Glass electrification potential (2025 – 2035)



For the melting of raw materials, electric furnaces (e.g. electric cold top furnaces), are an established technology at capacities up to 300 tonnes per day, although larger-scale implementation for flat glass production has not yet occurred[80]. Hybrid furnaces that run on multiple fuels, including up to 80% electricity in contemporary applications, could also be an option for the Glass industry, with such hybrid furnaces being employed in commercial-scale applications since at least the end of 2023[81]. This has the added benefit of allowing for manufacturers to switch to higher proportions of electricity as and when electricity becomes cost-competitive with natural gas.

In terms of forming, in the UK, container glass production is more prominent than flat glass production. The melting of container glass is a process that could be fully electrified through the use of glass smelters that utilise electric resistance technology[82]. Interviews conducted as part of the stakeholder engagement process highlighted that 100% electrified melting technology is feasible at >450 tonnes/day, though the technology is associated with significant lifetime reductions.

For flat glass-related processes, electrification faces the challenge of ensuring product quality. As such, partial electrification could be tested here through a combination of natural gas burners and electric resistance heating[83]. Glass melting tanks used in both container and flat glass processes with an electrification rate of 60-70% are expected to be available on the market by 2035.

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[80] British Glass (2021) 'Glass sector net zero strategy 2050'
[81] ArdaghGroup (2024) 'NextGen Furnace reduces carbon by 64%'
[82] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry
[83] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

An updated 2050 decarbonisation roadmap published by British Glass published in 2024 noted that fuel switching to electricity could reduce combustion-related emissions by 56% compared to 2018 levels. This constituted the largest decarbonisation pathway identified in the report. Hybrid furnaces with electricity inputs of up to 80% are expected to be adopted in container glass manufacturing, and lower electricity inputs are expected in flat glass. Smaller furnaces below 250 tonnes/day are expected to become all-electric. A possible constraint to consider is the shorter lifetimes associated with electric furnaces compared to gas-fired equivalents, although overall costs associated with electric furnaces have been suggested to be lower than gas-fired furnaces[84].

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[84] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

NZIP2

Table 24: Qualitative summary of baseline Glass sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
High temperature heat technology	Furnace	-	Electric Furnace for container glass Hydrogen Furnace for flat glass	Beyond 2035 (for flat glass)	For the glass industry, the furnace is the main focus of high-temperature heat demand. Interviewees highlighted that furnaces within their UK operations operate on dual firing capabilities (gaseous and liquid fuels). This capability was installed as a mitigation against historical interruptible gas supply but means sites with these capabilities can explore low-carbon liquid fuels in the near term. While the interviewee commented that hydrogen replacement of natural gas is one option, unique dual fire capabilities mean lower quality derivatives of SAF fuels may be suitable. Glass product mixes dramatically influence the possible decarbonisation opportunities available in the glass industry, particularly in regard to electric furnaces. For example, in flint glass production using electric melting, a significant energy proportion will disperse into the furnace and deteriorate its furnace structure. There is therefore a decrease in lifetime – interviewees estimated similar repair costs to other furnaces, but that electric furnace lifetime is approximately ½ of other counterparts for flint glass. For flat glass, the technology is not currently available/mature for 100% electrification at a sufficient scale and output (currently commercially mature to >300 tonnes/day). For container glass, a larger industry than flat glass in the UK, 100% electrified melting technology is feasible at >450 tonnes/day, though this technology is associated with significant lifetime reductions. The point of failure in an electric furnace is the electrode which is challenged by available refractory technologies. Currently furnaces are constructed with refractory blocks in which the electrode is housed. This block has a high level of localised degradation and therefore will expire before the furnace has completed full lifetime. Replacing an electrode block requires replacing the entire furnace and this is therefore a significant constraint on electrified furnaces – event at 10/50/80% electrification. Stakeholders suggested that, given the associated output volumes, a 100% electric cold top furnace for the flat glass industry is highly unlikely before 2050.

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
High-temperature heat technology (based on various fuels)	Annealing furnace	1 MW	Electrification	Current	Annealing is the only high temperature application within glass manufacturing and electric alternatives are available.

Table 25: Quantitative summary of Glass sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
Electric cold-top furnace	Furnace	380	11.41	9/ 225	1	Mt Glass
High-temperature heat technology based on electricity	High Temp	235	5.87	9/ 2011	3	PJ
High-temperature heat technology based on natural gas / biomethane	High Temp	161	4.02	9/ 2011	1	PJ
Hydrogen furnace with electric boosting	Furnace	212	6.36	7/ 2030	2	Mt Glass
Regenerative end-port furnace with electric boosting	Furnace	163	4.89	9/ 2011	3	Mt Glass

Demand Side Response

Due to the high operating temperatures, stable energy input requirements and continuous operation of the most energy intensive processes – melting and annealing - the DSR potential in the glass industry is moderate, especially from flat glass manufacturing. Stakeholder interviews revealed that the DSR potential from the melting furnace is heavily limited for the flat and container glass manufacturing process as temperature stability in the furnace is critical. The contents in the furnace need to be maintained at ~1600 °C continuously, and often these processes run close to 24/7 for the entirety of the equipment's lifetime, 15-17 years[85]. The risk associated with altering production load far outweighs the benefits obtainable from DSR.

The annealing lehr offers greater DSR potential at container glass manufacturing sites. The operators would simply have to close a valve, stopping the flow of molten glass into the annealing lehr downstream and storing the molten glass in the forming machine. The DSR potential here would be limited by the amount of molten glass these machines can store at the desired temperature. This is not the case in flat glass manufacturing. Stakeholder interviews highlighted that in the flat glass manufacturing process, unlocking DSR from the annealing lehr would require physically moving the molten glass through the molten tin bath to synthetically create a 'pull' for the annealing lehr. This would result in halting the glass production for ~2 days, which would be undesirable.

If the melting furnace and/or annealing lehr's are electrically boosted or have multiple, backup fuel sources, more DSR can be unlocked from both the container and flat glass manufacturing processes. We understand from stakeholder engagement that there is a planned installation of a flat glass furnace with 20% electrical boosting, which would be the highest globally for the flat glass industry. The electrical boosting can be quickly ramped up and down in response to DSR signals, provided the equipment is designed to be able to run 100% on the alternative fuel source (hydrogen, natural gas, etc.) and there is sufficient alternative fuel available to power the equipment fully. This applies for both the flat and container glass manufacturing processes.

Electricity from the batching of raw materials can be flexed by increasing the amount of recycled glass in the mix to reduce electricity consumption at peak times. The potential for this is higher in the container glass industry than the flat glass due to greater availability of recycled container glass and stricter end-product quality requirements in flat glass manufacturing. However, its impact is negligible as this step accounts for only 4% of total site energy consumption. From stakeholder engagement we understand some companies have installed back-up batteries to cover their site electricity demand. These can provide 3-6 MWh of backup electricity supply and primarily feed control systems and the annealing lehr. Companies are exploring sizing out batteries for DSR, but the large capital costs of doing so is a barrier. Therefore, there is some technical DSR potential from glass manufacturing in the future if sites install on-site energy storage. Its potential would be dependent on the size of the storage technologies installed.

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[85] Stakeholder Interviews

Another potential source of DSR highlighted in the stakeholder interviews was aligning the timing of process ramp-down to alter the batch of raw materials to change the final product in response to consumer demand and warehouse stock with the network management needs. Production campaigns are planned months in advance and have flexibility to plan up to several days in advance for composition changes. A week's notice period would have to be provided to the sites, at minimum, to unlock this flexibility.

Table 26 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input received in stakeholder interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked within the stakeholder interviews. While interviewees were unable to offer exact figures due to the relative nascency of DSR in the glass industry, they did not raise any objections to the values quoted.

Table 26: Demand side response potential summary of Glass sector

Process	Equipment	Practical DSR potential	Constraints
Batching of raw materials (~4% of current process energy consumption)	Mixing silo	Max peak demand reduction: Up to 25% Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours Ramping: <15 mins	The availability of recycled glass and end-product quality impacts of increasing the amount of recycled glass included in the raw material mix limits the electricity DSR potential.
Melting (~80-85% of current process energy consumption)	Electric cold-top furnace	Max peak demand reduction: 0% Demand shift timing: N/A Demand shift duration: N/A Ramping: N/A	High operating temperatures, stable energy input requirements and continuous process operation means flexibility can only be unlocked if the equipment has multiple/backup fuel sources. It may be feasible in container glass manufacturing due to lower outputs, however it is associated with significant lifetime reductions and thus deemed undesirable.
Melting (~80-85% of current process energy consumption)	Hydrogen furnace boosted with electricity	Max peak demand reduction: 100% of electrical demand Demand shift timing: N/A Demand shift duration: N/A Ramping: N/A	DSR potential limited by how long the equipment is designed to be able to run 100% on the alternative fuel source (hydrogen, nat. gas, etc.) and the amount of backup power available.

Process	Equipment	Practical DSR potential	Constraints
Melting (~80-85% of current process energy consumption)	Regenerative end-port furnace with electric boosting	Max peak demand reduction: 100% of electrical demand Demand shift timing: Before and after peak window Demand shift duration: Dependent on amount of alt. fuel available for furnace Ramping: <15 mins	DSR potential limited by how long the equipment is designed to be able to run 100% on the alternative fuel source (hydrogen, nat. gas, etc.) and the amount of backup power available.
Melting (~80-85% of current process energy consumption)	High temp. heat technology based on electricity (resistive heating, plasma burner, etc.	Max peak demand reduction: 0% Demand shift timing: N/A Demand shift duration: N/A Ramping: N/A	High operating temperatures, stable energy input requirements and continuous process operation means flexibility can only be unlocked if the equipment has multiple/backup fuel sources.
Annealing (~10% of process energy consumption)	100% electric annealing lehr	Max peak demand reduction: 20% (Flat glass) - 100% (Container glass) Demand shift timing: Before and after peak window Demand shift duration: Depends on the size of the forming machines Ramping: Information unavailable	The nature of the forming and annealing process limits the DSR potential from this step in flat glass manufacturing. The size of the forming machines i.e. the amount of molten glass coming in from the melting furnace it can store determines the duration of demand shift possible in the container glass manufacturing process.

Hydrogen

Hydrogen can be produced in different ways. The current NZIP2 model includes what can be categorised green as well as blue hydrogen production technologies. On the former, green hydrogen produced predominately through the electrolysis of water in an electrolyser, can also be termed electrolytic hydrogen. Electrolysis can be done with different electrolyser technologies, such as: ALK, PEM, SOEC Electrolysers, and AEM electrolysers[86].

ALK Electrolysers

ALK electrolysers are the most mature form of commercial electrolysis technology. Systems are constructed from inexpensive materials (principally nickel, aluminium, steel, and zirconium), are fairly durable, and deliver competitive conversion efficiencies. However, the physical footprint of ALK electrolysers is much larger than that of alternative technologies, since the cells operate at lower current densities. Although conventional ALK systems operate at atmospheric pressure, some manufacturers offer pressurised systems, which typically operate at around 15 to 30 bar. These systems offer improved efficiencies and reduced capital costs for applications in which hydrogen is required in pressurised form due to a reduction in external compression requirements. Pressurised systems are also more responsive to load variations than conventional ALK electrolysers.

PEM Electrolysers

First developed in the 1960s, PEM electrolysers use a solid polymer electrolyte material and operate at pressures of 30 bar or more. PEM systems deliver electrical efficiencies comparable with ALK electrolysers but have a much smaller physical footprint and a more dynamic operational range. This makes them well suited to distributed applications, installation in crowded industrial sites, and direct coupling with renewable energy resources. However, system costs tend to be higher, largely due to the use of expensive catalyst materials (iridium, platinum, and palladium). To address this problem, manufacturers are exploring various innovations that are expected to drastically reduce the rate of iridium and platinum loading in coming years.

SOEC Electrolysers

SOEC electrolysers are constructed with a solid ceramic electrolyte material and operate at high temperatures of between 600 - 850 °C. The technology is relatively immature - the first megawatt-scale system, supplied by Sunfire, was installed at a refinery in the Netherlands only in March 2023. The principal advantage of operating at high temperatures is that it permits significant increases in electrical conversion efficiency when paired with an external heat source. SOEC electrolysers are therefore well suited to integration into high temperature industrial applications that require a steady stream of hydrogen, such as ammonia synthesis or synthetic fuel production. On the other hand, SOEC electrolysers currently have slow startup

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[86] AEM is not included in the current NZIP2 technology list.

times, short operational lifetimes, and the highest system costs of any commercially available electrolysis technology.

AEM Electrolysers

AEM electrolysers are an emerging alternative to ALK and PEM, designed with an ALK electrolyte separated by a porous AEM diaphragm. This design allows AEM electrolysers to be constructed without expensive catalyst materials, reduces the footprint of the system to a level comparable with PEM, and enables dynamic operation suitable for direct pairing with intermittent renewable energy inputs. However, the relative immaturity of AEM technology means that system costs are currently higher than for ALK or PEM, while stack lifetimes remain shorter. Only a handful of manufacturers focus on AEM technology, mostly manufacturing smaller module sizes of below 1 MW.

Reformation

Blue hydrogen concerns the use of carbon capture technologies in the production of hydrogen. The NZIP2 model currently includes hydrogen production pathways based on the gasification of coal and biomass, as well as the reformation of feedstock such as (but not limited to) natural gas through SMR and ATR. The reformation process involves the gasification of various feedstock to produce syngas (H2 and CO), which is a highly versatility intermediate from which various chemicals, fuels, and electricity can be produced. SMR and ATR differ in the way heat is provided to activate the endothermic steam reforming rection. With SMR, an external burner is used to heat a catalyst contained in tubes. In ATR, a portion of the feedstock is partially oxidised to raise temperature of the process gas before contact with a catalyst[87]. In other words, a feedstock such as natural gas is partially oxidised with oxygen and steam, and then reformed catalytically. With SMR, the feedstock is catalytically converted to syngas by reaction with steam.

Gasification

Gasification is a partial oxidation process, and an established process used to produce syngas. Gasification occurs in gasifiers which are high temperature/pressure vessels where air, oxygen, and steam come into direct contact with the feed material. Thereon, a series of physical transformations and chemical reactions occur. Partial oxidation is a relative term which means that less oxygen is used in gasification than would be in combustion. The partial oxidation process generates enough heat to gasify any remaining unoxidised fuel[88]. Gasification as a process can incorporate multiple carbonaceous feedstocks, and not just coal and biomass as currently specified in the NZIP2 model. Feedstocks can include: petcoke, liquid plastic waste, refinery liquid residue, biomass pyrolysis oil[89]. Thus, gasification can convert wide-ranges of low-value materials into syngas, which can then be used to produce various chemicals, fuels, and electricity. The syngas can be converted (or shifted) to hydrogen

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[87] Duane Myers and others (2002) 'Cost and Performance Comparison Of Stationary Hydrogen Fueling Appliances'

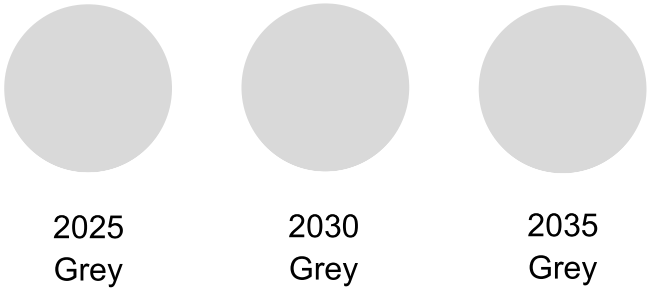
[88] National Energy Technology Laboratory, Gasifipedia, Section 5.1.1. Fundamentals

[89] Harold Boerrigter & Sven Felske (2024) 'Circular syngas with biomass and plastic waste gasification'

and CO2 by reaction over a catalyst in a water-gas-shift reactor WGSR. Note that coal gasification with carbon capture is also relevant for the Power Generation sector, with IGCC plants with CCS having been operated at commercial scale though have fallen out of favour in recent times.

Electrification Potential

Figure 12: Hydrogen Gasification electrification potential (2025 - 2035)



Given that reformation is discussed in the Chemicals sector of this report, the potential of direct electrification for gasification processes remains to be discussed. A number of different electrification technologies could be considered for the core gasification process, including: hydrogasification, hydrogen to gasifier, electrically heated gasification, resistance-heated gasification, inductively heated gasification, and plasma-assisted gasification[90]. The TRL levels of these technologies, however, are no more than TRL 7. Other parts of the gasification process to produce gasification such as pre-treatment, syngas conditioning, and synthesis, can display TRL 9 levels. Overall, the electrification of gasification for hydrogen production appears to be at the demonstration phase and it is unclear when technologies will be commercially available.

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[90] Marcel Dossow (2023) 'Electrification of gasification-based biomass-to-X processes – a critical review and in-depth assessment' Energy & Environmental Science, 2024, 17

NZIP2

Table 27: Quantitative summary of Hydrogen sector technologies

NZIP2 Technology	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Biomass gasification, with CCS	44	1.88	9/ 2030	2
Coal gasification, with CCS	66	3.32	9/ 2100	2
Electrolysis - alkaline	63	1.6	9/ 2011	3
Electrolysis - Solid Oxide Electrolyser	46	2.1	9/ 2011	3
Natural gas steam reforming ATR, with CCS	41	1.55	8/ 2025	2
Natural gas steam reforming, with CCS	42	1.27	8/ 2030	2
Proton exchange membrane	82	2.1	9/ 2011	3

Demand Side Response

Electrolysis is typically very suited to providing DSR from a technical point of view. The electrolyser stacks can be ramped up and down with relative ease at peak network congestion periods. The only constraints to hydrogen production’s DSR potential is the minimum capacity factor at which the electrolysers must operate at to meet offtaker demand.

Table 28 below summarises the DSR potential of the three most common electrolysis technologies today, based on data from literature.

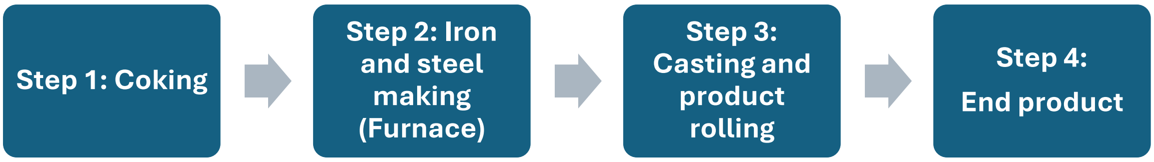
Table 28: Demand side response potential summary of Hydrogen sector

Process	Equipment	Practical DSR potential	Constraints
Electrolysis	Alkaline electrolysers	Max peak demand reduction: Up to 90% Demand shift timing: Before and after peak window Demand shift duration: Unlimited Ramping: Shutdown/Startup in 1 minute if warm, 10 minutes if cold.	The technical minimum operating limit of the technologies, as well as the minimum operating capacity to meet offtaker demand are the only constraints to this process’s DSR potential.
Electrolysis	Proton exchange membrane	Max peak demand reduction: Up to 100% Demand shift timing: Before and after peak window Demand shift duration: Unlimited Ramping: Shutdown/Startup less than 1 min if warm, 5-15 minutes if cold.	-
Electrolysis	Solid oxide electrolyser	Max peak demand reduction: 100% of electrical demand. Demand shift timing: Before and after peak window Demand shift duration: Depends on availability of alternative fuels and design of kiln Ramping: Shutdown/Startup (cold start) in 1 hour or more. Ramp down in <1 min if warm	The technical minimum operating limit of the technologies, as well as the minimum operating capacity to meet offtaker demand are the only constraints to this process’s DSR potential.

Iron & Steel

In the steel production process iron ore is converted into steel. Global manufacturing can be categorised into three main technology routes: BF-BOF, scrap-charged EAF, and DRI-EAF. A key distinction to make in Iron & Steel plants is whether they are integrated or not. A fully integrated steel plant (or steel mill), is where all processes related to primary steelmaking occur in one location, including: coking, ironmaking, steelmaking, casting, and product rolling.

Figure 13: Main production steps in primary Iron & Steel manufacturing



Alternatively, EAFs may produce steel from scrap metal without coking or ironmaking operations (“secondary” steelmaking). Globally, BF-BOF produces around 71% of the world’s steel, with 23% and 6% for scrap-EAF and DRI-EAF pathways respectively[91]. In the UK, 82% of steel is produced via BF-BOF, with the remaining 18% coming from EAF. At the time of writing, the DRI-EAF route is not operational in the UK. In UK Steel’s “Industrial Electricity Prices” report noted that four out of six steelmakers already operate EAFs in the UK, with blast furnace operators planning to switch to EAFs[92]. Tata Steel UK has announced plans to introduce EAF by 2027. British Steel has also announced plans to introduce EAFs, though this has been reportedly delayed till 2032 due to grid power availability issues[93]. From an emissions perspective, the Iron & Steel industry accounts for around 8% of global CO2 emissions. In 2020, the UK steel sector contributed to 14% of the UK’s manufacturing GHG emissions, and around 2.8% of the UK’s total energy-related CO2 emissions. The UK is also a net importer of steel, especially for primary steelmaking due to the lack of domestic iron ore and coking coal supply. The NZIP2 technologies reflect in the main part, primary steelmaking-related technologies (where the majority of energy demand is concentrated, especially in furnaces), and not downstream products or assets. The UK has excess scrap relative to local market utilisation, and thus the UK engages in the export of scrap. The excess scrap pool is an advantage for the EAF pathway. Currently, around 80% of scrap is exported from the UK[94]. UK steel operations are uniquely poised to replace assets due to assets reaching end of life in immediate future.

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[91] Alexandra Devlin & Sanna Markkanen (2023) 'Steel sector deep dive: How could demand drive low carbon innovation in the steel industry', Cambridge: Cambridge Institute for Sustainability Leadership (CISL)

[92] UK Steel, Industrial Electricity Prices – Barrier to growth and competitiveness

[93] Energy Live News (2024) ‘UK 'green steel': Switch to electric furnaces delayed until 2032’

[94] UK Steel, Industrial Electricity Prices – Barrier to growth and competitiveness

Electrification Potential

Figure 14: Iron & Steel electrification potential (primary and secondary combined) (2025 – 2035)

In Iron & Steel, the main electrification potential lies within primary steelmaking rather than secondary steelmaking, the latter of which is already largely electrified. In primary steelmaking, the replacement of fossil fuels with electrified heat in the blast furnace is currently unfeasible[95]. Electrolytic reduction of iron (known as electrowinning) has thus-far only been demonstrated at pilot scale[96].

One alternative to the BF/BOF steelmaking route is the DRI-EAF route, using the MIDREX direct reduction process. In this process, a reducing gas (pure hydrogen or a natural gas-based mix of CO, CO2, and hydrogen), is heated to around 900°C and fed into a shaft furnace where iron ore is reduced chemically to solid metallic iron. A gas heater is used as part of this process, which can be electrified. The solid metallic iron is then fed to an EAF. EAFs themselves produce steel from scrap metal (secondary steel production), which is already mainly electrified. EAFs can sometimes be used in conjunction with natural gas burners to ensure even heating. However, these burners can also be electrified. If green hydrogen is used for the DRI process, then indirect electrification can be achieved. Alternatives to the DRI route include MOE[97], MSE[98], and AHE[99]. However, these technologies are at early stages of development.

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[95] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

[96] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

[97] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

[98] Matthew Humbert and others (2024) 'Economics of Electrowinning Iron from Ore for Green Steel Production' Journal of Sustainable Metallurgy, Volume 10, 1679–1701

[99] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

After steel is created, it can be shaped into different forms using hot rolling mills. Within mills, heating is required for hot rolling (where metal is heated with natural gas burners to around 1,250 °C), and heat treatment (annealing). Within hot rolling, if the process is altered to occur after steel casting, this can then present the opportunity of replacing gas burners with induction heating (which has electrification potential). In the UK, Tata Steel has announced plans to introduce electric induction furnaces at its mill in Corby. Finally, the annealing processes (typically around 600-750 °C), can also be electrified with resistance or induction heating.

The UK government intends to publish a "Steel Strategy" in the spring of 2025. Details on an open consultation were published in February 2025[100]. UK Steel has noted that switching to EAFs could reduce the UK's total emissions by over 2%.

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[100] Department for Business and Trade (2025) 'The steel strategy: the plan for steel'

NZIP2

Table 29: Qualitative summary of baseline Iron & steel sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb. alternative	Insights from literature review & interview
Basic oxygen furnace, standard	BF-BOF	N/A	Electric Arc Furnace	2025 - 2035	No other interview insight bar the fact that one stakeholder participant explained how they were looking to move away from the BF-BOF (Blast Furnace – Basic Oxygen Furnace) approach. Integrated sites use a BF and a BOF. Literature review suggests BF-BOF costs typically reported together and not standalone.
Low-temperature heat technology	Boiler	5 - 25 MW		NA	A stakeholder participant said that they had transitioned away from combustion boilers that produce low pressure steam from waste gases. As such, all steam is now produced via combustion of natural gas. They are currently exploring how to generate heat going forward. Old boilers have been replaced with temporary package boilers for running pickle line and rolling mill. When EAFs are introduced, heat generation requirements will change – design plans include the EAF capturing and using waste process heat for scrap preheating. Interviewees were unable to comment on the cost of boilers without an NDA.
Blast furnace, standard	Same as NZIP2 technology	N/A	HISARNA, Direct reduced iron	NA	One stakeholder participant stated that they were changing their asset base for its blast furnace to EAF.
Sinter plant, standard	Same as NZIP2 technology	N/A			No clear applicable insight on sinter plants based on current interviews.
Caster & hot rolling mill, standard	Same as NZIP2 technology	N/A	Induction heating	Between 2030 - 2040	A stakeholder participant explained how they intend to decarbonise rolling and other finish furnaces with induction heating technology.

Table 30: Qualitative summary of decarbonisation Iron & steel sector technologies

NZIP2	Insights from interview and literature review
Electric arc furnace, standard	Interviews suggested that Guidehouse's EAF technology cost is accurate. EAFs do not require an integrated site but within this operation some iron inputs are likely needed depending upon the products being made. Varying by scope, an EAF can reduce site domestic emissions by 90% - for whole footprint: 50% reduction. EAF emissions depend on the use of raw materials – exploring biochar etc. There are plans to increase EAF use in the UK from 2027.
HISarna blast furnace CCS	HISarna technology is one option to make primary iron. A benefit is that this technology can use lower quality input material. It is also highly suited to CCS and thus a low-carbon solution. TRL level 7 has been reported in the literature[101].
Top-gas recovery blast furnace with CCS	Top gas recovery blast furnace is a relatively innovative solution (AKA the ULCOS Blast Furnace, this is deferent in operation to the top gas recovery turbine). Subtleties such as mixing with hydrogen etc. need to be explored and are being developed by some steel companies. This following statement refers to the top gas recovery turbine, utilising the furnace top pressure - Costs curves likely follow that of electrical generation i.e. £1million / 1MW.
ULCORED direct reduced iron CCS	A technology that produces DRI in a shaft furnace. A key difference with other direct-reduction-based technologies is the use of pure oxygen in the shaft furnace to produce flue gas with a higher concentration of CO2 for capture. After CO2 removal flue gas may be recycled to reduce demand for natural gas. The process may alternatively use different fuels other than natural gas[102].

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[101] Ahmed Gailani and others (2024) 'Assessing the potential of decarbonization options for industrial sectors' Joule, Volume 8, Issue 3, pages 576-603

[102] Bert Daniels, Marit van Hout & Andrew Keys (2019) 'Decarbonisation options for the Dutch steel industry', PBL Netherlands Environmental Assessment Agency

Table 31: Quantitative summary of Iron & Steel sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
Basic oxygen furnace, standard	Furnace	183	18.63	9/ 2011	3	Mt Liquid Steel
Biomass boiler	Boiler	11	0.83	9/ 2011	3	PJ
Biomass CHP	CHP	17	1.1	9/ 2011	3	PJ
Blast furnace gas boiler for low temperature heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Blast furnace gas boiler for low temperature heat	Boiler	2	0.03	9/ 2011	3	PJ
Blast furnace gas CHP	CHP	51	1.05	9/ 2011	3	PJ
Blast furnace, standard	Furnace	267	27.15	9/ 2011	3	Mt Pig Iron
Caster & hot rolling mill, standard	Iron & Steel	259	6.46	9/ 2011	2	Mt Hot Rolled Steel
Coke oven gas boiler for low temperature heat	Boiler	2	0.03	9/ 2011	3	PJ
Coke oven gas CHP	CHP	51	1.05	9/ 2011	3	PJ
Downstream process (energy use to produce finished steel from hot rolled steel)	Iron & Steel	184	52.93	9/ 2011	2	Mt Finished Steel
Electric arc furnace, standard	Furnace	255	23.93	9/ 2011	3	Mt Liquid Steel

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/Model Availability Date	Data confidence	Units
HISarna blast furnace	Furnace	868	97.36	7/ 2030	2	Mt Pig Iron
HISarna blast furnace CCS	CCS	908	142.73	7/ 2030	2	Mt Pig Iron
Hydrogen boiler for low temperature heat	Boiler	2	0.07	9/ 2011	3	PJ
Hydrogen Caster & hot rolling mill, standard	Iron & Steel	336	8.40	7/ 2025	2	Mt Hot Rolled Steel
Hydrogen CCGT CHP	CCGT CHP	85	1.9	8/ 2025	2	PJ
Hydrogen fuel cell CHP (lower cost)	CHP	263	2.9	9/ 2030	2	PJ
MIDREX direct reduced iron	Iron & Steel	289	7.23	9/ 2011	2	Mt Liquid Steel
Natural gas boiler for low temperature heat	Boiler - Hot water	5	0.09	9/ 2011	3	PJ
Natural gas CHP	CHP	37	0.7	9/ 2011	3	PJ
Sinter plant, standard	Iron & Steel	41	1.04	9/ 2011	2	Mt Sinter
Top-gas recovery blast furnace	Furnace	597	66.17	9/ 2025	2	Mt Pig Iron
Top-gas recovery blast furnace with CCS	CCS	797	66.48	8/ 2030	2	Mt Pig Iron
ULCORED direct reduced iron CCS	CCS	622	58.61	7/ 2030	2	Mt Liquid Steel

Demand Side Response

The DSR potential of the Iron & Steel industry is moderate and heavily site and product demand dependent. Most of the DSR potential comes from turning down the hot rolling mill and the electric arc furnaces. The stakeholder interviews revealed that they engage in load management activities on site. They do so by reducing the power of the hot rolling mill and the arc furnaces, not by completely switching them off.

EAFs run in batches that are typically scheduled closely to each other. So, while the batch nature of the process enables it to participate in DSR inherently, it can only shift its load by approximately quarter of an hour at a time[103].

The hot rolling mill comes after the electric arc furnace (or the blast furnace) and its DSR potential depends on the DSR potential of the process before. In theory, if the furnace’s demand is shifted by a quarter of an hour, the hot rolling can be shifted by a quarter of an hour. However, it is expected that this will not occur in practice, and that the hot rolling will continue to run in the background to keep the steel warm and prevent it from degrading. If this can be achieved through an alternative fuel e.g.: hydrogen, natural gas, biomass or waste heat from the other processes, then the hot rolling mill can offer DSR in line with the electric arc furnaces.

Table 32 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from the stakeholder interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked with the participants during the interviews. While they were unable to offer exact figures, they did not raise any objections to the values quoted.

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[103] Fraunhofer ISI/ TEP/ consentec/ r2b (2019) 'Definition and monitoring of security of supply on the European electricity markets' report for German Federal Ministry of Economics and Energy

Table 32: Demand side response potential summary of Iron & Steel sector

Process	Equipment	Practical DSR potential	Constraints
Iron and steel making	Electric Arc Furnace	Max peak demand reduction: Up to 100%, depending on the site's product demand Demand shift timing: Before and after peak window Demand shift duration: Up to 15 mins[104], with at least 8 hours between events[105] Ramping: <1 min[106]	Electric arc furnaces run in batches that are typically scheduled closely to each other.
Product rolling/casting	Hot rolling mills	Max peak demand reduction: Up to 100%, depending on availability of alt. fuel Demand shift timing: Before and after peak window Demand shift duration: Up to 15 mins Ramping: Information unavailable	The hot rolling mills cannot be completely shut down as the steel must always be kept warm to prevent it from degrading.

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[104] Stefan Estelmann, Dietrich Ralph-Uwe & Antje Seitz (2018) 'Flexibilitätsoptionen in der Grundstoffindustrie: Methodik, Potenziale, Hemmnisse'

[105] Alexander Kies, Bruno Schyska & Lueder von Bremen (2016) 'The Demand Side Management Potential to Balance a Highly Renewable European Power System' Energies, Volume 9

[106] Smart Energy Demand Coalition (2017) 'Explicit Demand Response In Europe – Mapping the Markets 2017'

Lime

While specific site processes may vary depending on product requirements, the main steps involved in lime manufacturing are:

Figure 15: Main production steps in Lime manufacturing

Crushing and grinding of the quarried limestone:

The quarried limestone goes through a series of crushers, where the rock is crushed and grinded to the desired size for the calcination process in a raw mill. The crushed limestone is then washed. This process is electrically powered. The stakeholder interviews revealed that this step accounts for ~12% of the total site's electricity demand.

Calcination:

In a parallel flow regenerative kiln the pre-heating of the limestone takes place in the upper section of the kiln shafts which are filled from the top. The limestone is pre-heated in the top of the kiln shafts using available heat from lower in the kiln shafts rising and being moved by pneumatic pumps between the kiln shafts through cross ducts. (Where rotary kilns are used to make dolime the limestone can be pre-heated by the waste heat). The limestone (calcium carbonate) is broken down, at temperatures of up to 1000°C into lime (calcium oxide) and carbon dioxide in the kiln, that operates continuously. Currently, PFRKs are powered by burning fossil fuels such as coal, natural gas or petroleum coke. This is the most energy intensive step in the process, however, electricity is only currently used to control the kiln. Even so, it makes up ~50% of current electricity consumption in the lime manufacturing process based on stakeholder interviews. The lime is then cooled by direct contact with air. Rotary kilns are only used in the UK for the manufacture of dolime and use coal and other solid fuels.

Post kiln milling and grinding:

The lime coming out of the kiln is crushed and ground in a mill. Based on stakeholder interviews, this step can account for up to ~14% of current site electricity consumption.

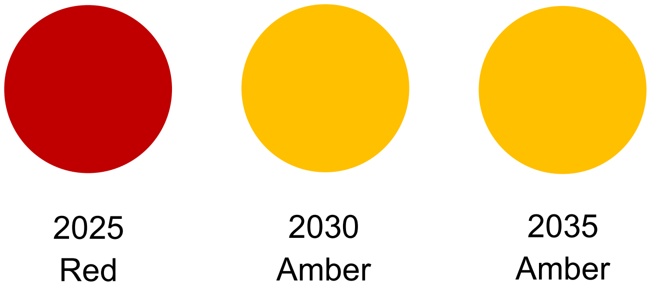
Hydration and drying/precipitation:

If the end product desired is hydrated lime, the lime is mixed with water in a lime hydrator, which is essentially a mixing vessel powered by a motor and dried carefully to meet customer specifications before it is packaged and transported. The hydration, drying and packaging steps account for ~11%, ~6% and ~3% of total site electricity consumption respectively.

In terms of NZIP2 technologies, entries for Lime are the same as those for Cement. Please refer therefore to the section on cement for further information.

Electrification Potential

Figure 16: Lime electrification potential (2025 - 2035)



For high-temperature processes in the Lime sector, a distinction can be made between hard-burnt lime and soft-burnt lime[107]. For hard-burnt lime, this is typically produced in ASKs, MFSKs, and other kilns with temperatures ranging between 1,2000 – 1,400 °C. For soft-burnt lime, this is typically produced in PFRKs at a slightly lower temperature range of 1,000 – 1,250 °C. Electrification of kilns is considered currently challenging for both hard-burnt lime and soft-burnt lime due to the high temperatures required. However, technologies in development such as plasma heating technologies (such as that being tested currently as part of the ELECTRA project), or resistance heating, might render electrification feasible here by 2030-2035[108].

In 2023, Mineral Products Association Lime published its “Net Negative 2040 Roadmap” for the UK where CCUS was expected to deliver the majority of emissions reductions[109]. Electrification was not directly cited in this report. The predominance of CCUS was also featured in the European Lime Association’s “A Pathway to Negative CO2 Emissions by 2050” report published in 2023[110], with the electrification of kilns providing the lowest emission reductions of the technologies cited.

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[107] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

[108] Another example is Salt X, which is developing an Electric Arc Calciner (EAC) that uses electric plasma technology.

[109] MPA Lime (2023) 'Net Negative 2040 Roadmap'

[110] European Lime Association (2023) 'A pathway to negative CO2 emissions by 2050'

NZIP2

Table 33: Quantitative summary of Lime sector technologies

NZIP2 Technology	CAPEX (m£/Mt)	OPEX (m£/Mt)	TRL/Model Availability Date	Data confidence
Advanced Amine (MDEA) - BAT KILN (Cormos 2017) (CCS)	480	9.13	9/ 2025	2
BAT kiln full oxyfuel (CCS)	408	4.55	8/ 2028	2
Calcium looping kiln	621	10.40	7/ 2030	2
Dry kiln with coal CHP and MEA CCS	674	16.84	9/ 2025	2
Dry kiln with natural gas CHP and MEA CCS	542	8.69	9/ 2025	2
Dry kiln, best available technology (BAT)	243	6.08	9/ 2011	3
Grinder and mixer with increased clinker substitution	28	1.14	9/ 2060	3
Grinding and mixing technology	28	1.14	9/ 2011	3
Partial oxyfuel dry kiln with CCS	464	11.60	8/ 2028	2

Demand Side Response

Just as in cement manufacturing, the lime manufacturing process has high potential for DSR with regards to the operation of the raw and post kiln mills, which account for over 25% of the site’s electricity consumption. The management of silo capacities, which if kept under optimal conditions can store the raw material and lime in a battery like fashion allows the site to shift mill electricity consumption away from peak network congestion times. However, the raw materials and lime cannot be stored for too long. The DSR potential from this is therefore limited by the size of the silos on site and the maximum duration for which the lime and raw materials can be stored in the silos.

Rotary kilns today are mainly powered by coal, natural gas or petroleum coke and only use electricity to turn the kiln, which accounts for 50% of total site electricity consumption. As part of their decarbonisation initiative, the lime industry is exploring technologies such as hydrogen powered kilns, electrified alternatives and kilns with bivalent heat generation (combination of hydrogen/biomass with electrical heat provision). If the electrified or bivalent technologies are adopted, on-site power consumption may increase significantly in the future. However, the rotary kilns must run 24 hours a day for its lifetime and are typically stopped only once every 7 years for a month for maintenance, which limits the DSR potential of this energy-intensive step. Furthermore, re-firing the kiln post shutdown is extremely energy intensive and can cause structural damage to the kiln. The only feasible DSR strategy would be to align the annual maintenance periods, which would occur in a winter month once every 7 years. The sites would need a notice period of at least a few months to plan their annual maintenance accordingly.

Table 34 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from the stakeholder interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked within the stakeholder interviews. While they were unable to offer exact figures, they did not raise any objections to the values quoted.

Table 34: Demand side response potential summary of Lime sector

Process	Equipment	Practical DSR potential	Constraints
Grinding and mixing (26%[111] of site current electricity demand)	Raw and post kiln mills	Max peak demand reduction: 100%, depending on silos size Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours Ramping: N/A	Typically limited by the silo's storage size. If the silos are large enough, they can provide up to 100% flexibility
Calcination (50% of site current electricity demand)	Electric rotary kilns	Max peak demand reduction: 0% during operation. 100% during maintenance. Demand shift timing: Before and after peak window Demand shift duration: Up to a month, depending on length on maintenance period Ramping: Up to 36 hours ramp up	The rotary kilns must run 24 hours a day for its lifetime and are typically stopped only every 7 years for maintenance. The only feasible DSR strategy would be to align the maintenance periods with the peak network congestion times.
Calcination (50% of site current electricity demand)	Kiln with bivalent heat generation	Max peak demand reduction: 100% of electrical demand. Demand shift timing: Before and after peak window Demand shift duration: Depends on availability of alternative fuels and design of kiln Ramping: <15 mins	Demand shift duration is limited by the amount of alternative fuel capacity that is available for kiln.

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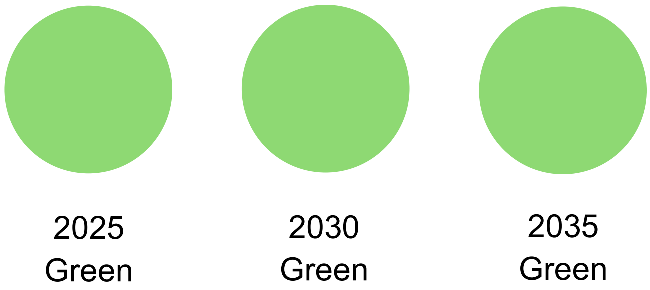
[111] Stakeholder Interviews

Mechanical Engineering

Mechanical Engineering is a very diverse industrial sector that covers the design, development, optimisation, and application of machinery used in various other industrial sectors such as (but not limited to): power, transport, agriculture, and manufacturing. This can include engines, turbines, agricultural and forestry machines, pumps, compressors, HVAC equipment (such as heat pumps), machinery for the textile industry, lifting and handling equipment and so on. Mechanical engineering can be understood as a supplier of machinery and equipment, but also as a service industry. Mechanical engineering has also been described as a predominantly small-batch and single-item production processes[112,113]. Major mechanical engineering companies in the UK include Rolls-Royce, Siemens, and BAE Systems.

Electrification Potential

Figure 17: Mechanical Engineering electrification potential (2025 - 2035)



Due to the heterogeneity of this industrial sector, it is difficult to identify specific industrial high-temperature heat processes and thus comment on electrification potential. The NZIP2 model references furnaces as the typical high-temperature heat technology in this sector, where direct electrification could be achieved using electric arc furnaces for example. Induction heating can also be applied in furnaces and is already being applied in certain industrial applications today[114].

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[112] Hans-Günther Vieweg and others (2012) 'An introduction to Mechanical Engineering: Study on the Competitiveness of the EU Mechanical Engineering Industry', Ecorys

[113] European Commission, Mechanical engineering

[114] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

NZIP2

Table 35: Qualitative summary of baseline Mechanical engineering sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
High-temperature heat technology (based on various fuels)	Furnace	Not determined, follow up call to be scheduled	Hydrogen/ Electrified Furnace	Post 2030s.	The interview participant confirmed that all furnaces in their operations operate on natural gas and that any transition to decarbonised solutions, such as hydrogen, can be limited by extensive multi-year process of re-validation for each furnace to produce components at customer and industry regulated specification. Interviews raised that across industry most sites, and companies, will not mix between electrified/hydrogen furnaces and it is likely that one solution will be adopted across all operations. The decision is equally challenging for each solution with the main risk being potential supply insecurity. Additionally, the decision to rely on an on-site hydrogen electrolyser brings an associated level of cost and risk than relying on national hydrogen infrastructure. Biogases (biomethane) is in consideration, but lack of clarity in greenhouse gas accounting principles for gas purchase agreements is prohibiting uptake Interviews indicate that the motivation to adopt decarbonised furnace technologies is purely informed by sustainability and net zero targets, and not economic benefits
Low-temperature heat technology (based on various fuels)	Boiler	< 1 MW	Heat Pump	Available	Interviews emphasised that heat pumps are the most likely to be adopted, and most viable, solution.

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Low-temperature space heat technology (based on various fuels)	Boiler	< 1 MW	Heat Pump	Available	Interviews emphasised that heat pumps are the most likely to be adopted, and most viable, solution.
CHP (Steam Turbine/CCGT based on various fuels)	-	1 – 5 MW	Hydrogen CHP	2035	Interviews indicated that gas engine-based CHP and battery technologies should be considered within NZIP2. These solutions are observed in industry and offer great potential for DSR and localised grid balancing, and, due to their longer operational profile, could have high efficiency as compared with 100% renewable system with shorter operational profile. Hydrogen CHP retrofit kits for gas CHP engines are observed in the market as informed by German publicly funded study. The hydrogen CHP retrofit kit allows for 100% hydrogen with minimal hardware changes to existing CHP and would be installed during major servicing windows. Additionally, some CHPs currently operational can run on up to 20% hydrogen without the retrofit kit applied. The interviews also highlighted that the earliest timeline for such a hydrogen CHP retrofit kit to be deployed at scale is earliest 2035, at which point significant investments should have materialised a large-scale hydrogen availability. The cost uplift for the hydrogen CHP retrofit kit would depreciate as technology TRL matures.

Table 36: Quantitative summary of Mechanical Engineering sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2
Electric motor technology	Motor	3	0.08	9/ 2011	3
Gas turbine CHP based on natural gas	CHP	81	0.3	9/ 2011	3
High-temperature heat technology based on coal	Furnace	10	0.27	9/ 2011	1
High-temperature heat technology based on electricity	Furnace	5	0.14	9/ 2011	1
High-temperature heat technology based on hydrogen	Furnace	6	0.16	8/ 2028	1
High-temperature heat technology based on LPG	Furnace	4	0.11	9/ 2011	1
High-temperature heat technology based on natural gas / biomethane	Furnace	4	0.11	9/ 2011	2
High-temperature heat technology based on solid biomass	Furnace	10	0.27	9/ 2011	1
Low-temperature heat technology based on coal	Boiler	17	1.26	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	6	0.02	9/ 2011	3

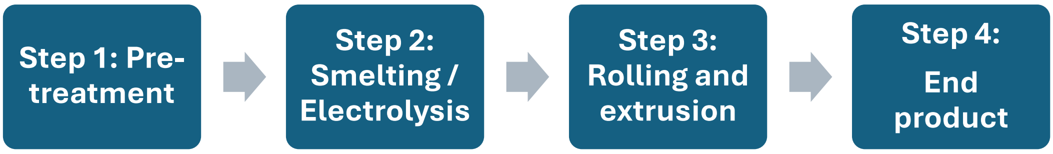
NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	6	0.20	9/ 2020	3
Low-temperature heat technology based on LPG	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on natural gas	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on solid biomass	Boiler	22	1.66	9/ 2011	3
Low-temperature space heat technology based on coal	Boiler - Hot water	9	0.65	9/ 2011	3
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature space heat technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3
Steam turbine CHP based on solid biomass	Biomass CHP	34	2.0	9/ 2011	3

Non-ferrous Metals

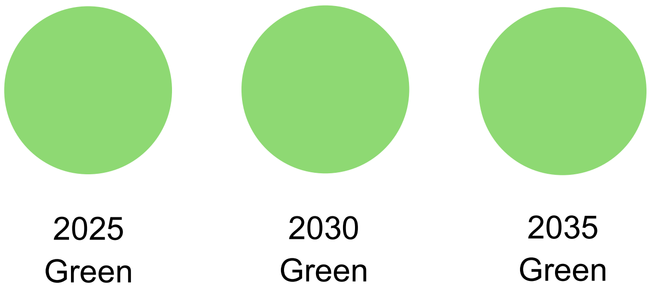
Non-ferrous metal production includes, among others, the production of the following materials: zinc, aluminium, tin, copper, lead, nickel, titanium, and copper alloys (brass or bronze). Typically, during the process, raw materials are smelted and purified, a process that involves high-temperature heat. The sector includes various processes across the production process (e.g. mining and extraction, electrolytic reduction, leaching, and alloying). Heat recovery is commonplace in the production and casting of non-ferrous metals, using regenerative burners, recuperative burners, heat exchangers, and boilers. That said, UK has limited primary metals production and therefore focus for this sector will be secondary metal production.

Figure 18: Main production steps in Non-ferrous Metals manufacturing



Electrification Potential

Figure 19: Non-ferrous Metals electrification potential (2025 - 2035)



The non-ferrous metals sector has a high electrification potential with existing technologies[115]. With a focus on non-ferrous metals processing (rather than primary metal production, which is less of a focus in the UK), several processes such as aluminium and copper melting, heat treatment, hot forming etc., can be electrified with the use of electric arcs, induction, or resistance heating. A 2023 report from DESNZ also noted that it was technically possible to electrify high-temperature processes in non-ferrous metals production.[116]

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[115] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

[116] Department for Energy Security and Net Zero (2023) 'Enabling industrial electrification: a call for evidence on fuel-switching to electricity'

NZIP2

Table 37: Qualitative summary of baseline Non-ferrous metals sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarbonisation alternative	Insights from literature review & interview
High-temp heat technology (based on various fuels)	Furnace	1 – 5 MW	Electric Furnace (EAF)	Available	Typical high temperature applications within the sector include re-heating and smelting furnace but UK has limited smelting operations.

Table 38: Quantitative summary of Non-ferrous metals sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/Model Availability Date	Data confidence
Electric motor technology	Motor	3	0.08	9/ 2011	3
High-temperature heat technology based on coal	Furnace	10	0.27	9/ 2011	1
High-temperature heat technology based on electricity	Furnace	5	0.14	9/ 2011	1
High-temperature heat technology based on hydrogen	Furnace	6	0.16	8/ 2028	1
High-temperature heat technology based on LPG	Furnace	4	0.11	9/ 2011	1
High-temperature heat technology based on natural gas / biomethane	Furnace	4	0.11	9/ 2011	2
High-temperature heat technology based on solid biomass	Furnace	10	0.27	9/ 2011	1

Demand Side Response

Because the non-ferrous metals manufacturing industry comprise of a large variety of subsectors using numerous different processes, the DSR potential of the sector is heavily process/subsector dependent. However, in general, the industry's DSR potential is moderate. Depending on the metal being manufactured, electricity consumption during smelting, electrolysis and casting/forming processes can be shifted/turned down in response to DSR signals.

Smelting can be electrified through the adoption of electric arc furnaces. Electric arc furnaces run in batches that are typically scheduled closely to each other. So, while the batch nature of the process enables it to participate in DSR inherently, it can only shift its load by approximately quarter of an hour at a time[117]. Furthermore, there is the risk of the liquid metal solidifying in the furnace if the power is turned off/down for too long, which could cause damage to the furnace.

The rolling and extrusion of non-ferrous metals is a batch process as well. Therefore, in principle, this step also can be operated flexibly by changes in production planning. However, depending on the schedule of the arc furnaces, this would require the liquid metal to be held/stored in a buffer holding furnace at a temperature high enough to prevent it from solidifying. This would be extremely energy intensive and expensive, negating a large portion of the benefits attainable from DSR.

The primary production of some non-ferrous metals such as aluminium and copper uses electrolysis. Flexible scheduling of aluminium electrolysis is state of the art and already in application at some sites. Therefore, these industries would offer greater potential for DSR than non-ferrous metal manufacturing using electric arc furnaces.

Table 39 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates from available literature and input from internal Guidehouse SMEs.

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[117] Fraunhofer ISI/ TEP/ consentec/ r2b (2019) 'Definition and monitoring of security of supply on the European electricity markets' report for German Federal Ministry of Economics and Energy

Table 39: Demand side response potential summary of Non-ferrous metals sector

Process	Equipment	Practical DSR potential	Constraints
Smelting	Electric Arc Furnace	Max peak demand reduction: Up to 100%, depending on the site's product demand Demand shift timing: Before and after peak window Demand shift duration: Up to 15 mins, with at least 8 hours between events[118] Ramping: <1 min[119]	Electric arc furnaces run in batches that are typically scheduled closely to each other.
Electrolysis (Aluminium) – Hall Heroult process	Electrolysers	Max peak demand reduction: Up to 95% Demand shift timing: Before and after peak window Demand shift duration: Up to 2 hours Ramping: Shutdown/Startup in 1 minute if warm, 10 minutes if cold.	
Rolling and extrusion	Rolling mill/Extrusion press	Max peak demand reduction: Up to 100% Demand shift timing: Before and after peak window Demand shift duration: Up to 2 hours Ramping: Information unavailable	Requires a buffer holding furnace for flex from this process to be unlocked, which can be extremely energy intensive.

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[118] Alexander Kies, Bruno Schyska & Lueder von Bremen (2016) 'The Demand Side Management Potential to Balance a Highly Renewable European Power System' Energies, Volume 9

[119] Smart Energy Demand Coalition (2017) 'Explicit Demand Response In Europe – Mapping the Markets 2017'

Paper & Pulp

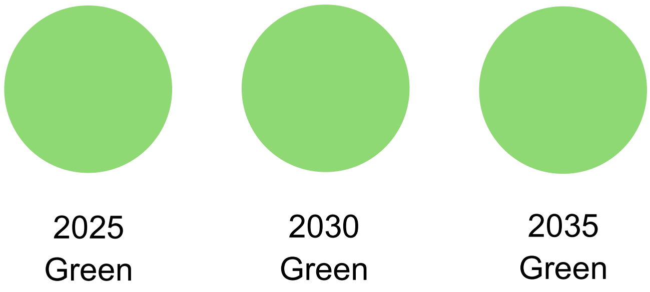
The paper production process can be divided into two main processes. In the first part, pulp is made from wood chips or recycled paper. In the second part, paper is made from pulp. Pulp and paper production is a very energy-intensive process, where one tonne of paper can require on average 11.5 GJ of primary energy, depending on factors such as the quality and grade of the paper manufactured, raw materials used, technologies involved[120].

Figure 20: Main production steps in Pulp & Paper manufacturing

The most important natural resource for the industry is biomass, with wood as the major fibre source, which generates biogenic CO2[121]. Operational CO2 emissions are mainly generated from fuel combustion to produce heat and power. There are no process emissions in pulp and paper, so the focus for decarbonisation is on fuel use in stationary equipment such as boilers and CHPs[122]. Due to the high heat and power requirements, the use of CHP is widespread in the industry. Heat, often in the form of high-pressure steam, is typically used to generate power in turbines. Steam extracted from the turbine as medium and low-pressure steam is used for various heating and drying applications. Electricity is used for various machinery such as: grinders and refiners, pulpers, machinery drives, vacuum pumps, compressors. Only low-temperature heat is needed in the paper industry which has the potential to be electrified with readily available technologies[123]. The primary thermal demand in the process is in the pressing and drying step which encompasses the wire section, press section, dryer section, and calendar[124].

Electrification Potential

Figure 21: Pulp & Paper electrification potential (2025 - 2035)



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[120] Michael Suhr and others (2015) 'Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board', EUR 27235, Publications Office of the European Union
[121] EU-BRITE, Production of Pulp, Paper and Board
[122] Ahmed Gailani and others (2024) 'Assessing the potential of decarbonization options for industrial sectors' Joule, Volume 8, Issue 3, pages 576-603
[123] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry
[124] Department of Energy and Climate Change (2015) 'Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Pulp and Paper'

Within Pulp & Paper, most of the sector's heat demand is below 200°C, and nearly all of this in the form of steam[125]. Existing electric boilers and heat pumps would be suitable technologies to achieve electrification. Electric IR dryers are also commercially available which could replace any natural gas impingement dryers[126].

One high-temperature process in pulp production that is regarded as difficult to electrify is the heating of lime kilns with typically involves furnaces that operate above 500 °C. This could potentially be electrified using resistance furnaces. As discussed in the Lime sector, the electrification of kilns is considered currently challenging for both hard-burnt lime and soft-burnt lime due to the high temperatures required. However, technologies in development such as plasma heating technologies or resistance heating, might render electrification feasible by 2030-2035[127].

Finally, the EU-funded ELECTRA project is investigating ways to substitute fossil fuel use, replace combustion technologies, and electrify high-temperature heat in the Cement, Lime, and Pulp industries[128]. This initiative involves investigating electrified rotary kiln technologies. However, it is unclear when technologies from this project will become commercially available.

In its position paper published in 2023, the UK Confederation of Paper Industries noted that the biggest barrier to electrification in the sector was not technological availability but high cost of electricity instead. Total electrification of fossil fuel heat in the sector would require 8 TWh of grid power and an additional electricity requirement of 2.5 TWh, representing a six-fold increase in import capacity. The paper estimated that electrification could possibly contribute 65% towards decarbonisation by 2050[129].

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[125] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

[126] CPI (2023) 'UK Paper Sector Decarbonisation Roadmap'

[127] Another example is Salt X which is developing an Electric Arc Calciner (EAC) that uses electric plasma technology.

[128] ELECTRA website

[129] CPI (2023) 'UK Paper Sector Decarbonisation Roadmap'

NZIP2

Table 40: Qualitative summary of baseline Paper sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Dryers (standard)	Same as NZIP2 technology	N/A	Reliant on decarbonisation of steam	Not determined	Interviews with stakeholders described how in a particular paper mill steam heated cylinders were used for drying, with around 0.85 tonnes of steam being used per tonne of paper, and around 1,000 tonnes of paper processed per day. For dryers, interviewees suggested temperatures of around 150 °C (3 barg steam) used in drying, and temperatures up to 230 °C for “improver” grades. Literature suggests that possible alternative technologies that could be explored include: Microwave Drying, Radio Frequency Drying (FR), Infrared Drying (IR), Refractance Window Drying (RW), Heat Pump Drying, Explosion Puffing Drying (EPD), Low-Pressure Superheated Steam Drying (LPSSD), together with technologies that combine processes (i.e. Microwave-Assisted Convective Drying (CD-MD)[130] [131].

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[130] Ángel Calín-Sánchez and others (2020) 'Comparison of Traditional and Novel Drying Techniques and Its Effect on Quality of Fruits, Vegetables and Aromatic Herbs', Foods, September 2020

[131] Ahmed Gailani and others (2024) 'Assessing the potential of decarbonization options for industrial sectors' Joule, Volume 8, Issue 3, pages 576-603

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
CHP (CCGT/ Steam Turbine based on various fuels)	N/A	5-25 MW	Grid connection and decarbonisation of heat with Heat Pump. Hydrogen Technologies	Dependent on Heat Pump COP improvement and reduced electricity cost. Hydrogen: mid-2030s, dependent on infrastructure development and access.	Interviews highlighted that heat pumps are technologically favourable and commercially available. Installation costs are high, but industry is willing to consider this technology. However current electricity prices, compared with natural gas, limit the business case and therefore adoption of heat pumps in the near term. Interviews highlighted that a CHP with on-site solar generation has been modelled in industry, but that this solution is only marginally favourable as compared with importing low carbon electricity and remains expensive (£1m/MW solar CAPEX figure). Interviews indicated that hydrogen adoption is likely and viable, but totally determined by geographical proximity. Transitioning to hydrogen supply would not alter existing site configurations – but for the paper specifically, any hydrogen adoption would require the price be guaranteed owing to low margin products. Interviewees also suggested installation of CHP generated a large emissions reduction but had also limited them in terms of future decarbonisation steps.

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
Low-temperature heat technology (based on various fuels)	Boilers	-	Heat Pump	Dependent on economics	For many but not all industrial sectors, the main decarbonisation pathway for boilers would likely be fuel-switching to alternative fuels such as hydrogen and biomass, electrifying, and using heat pumps which may be able to supply heat demand up to around 165°C[132]. Interviewees suggested that it's technically feasible to integrate heat pumps into a paper mill but requires considerations of the cost to run (ratio of gas to electricity prices) and integration with existing CHPs (whilst use of heat pumps improves electrical efficiency this reduction in power demand will impact the thermal efficiency of the CHP, making it more costly to operate).
Press section (standard)	Same as NZIP2 technology	-	-	-	Literature describes the press section as typically where water is mechanically removed to a degree from pulp, with the thermal removal of remaining water thereafter.

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[132] Ahmed Gailani and others (2024) 'Assessing the potential of decarbonization options for industrial sectors' Joule, Volume 8, Issue 3, pages 576-603

Table 41: Quantitative summary of Paper sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/ Start date	Data confidence	Units
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2	PJ
Coal boiler	Boiler	8	0.63	9/ 2011	3	PJ
Dryers (standard)	Paper	379	9.47	9/ 2011	1	Mt Basic Paper
Drying / separation technology based on electricity	Drying/ separation	4	0.02	9/ 2011	3	PJ
Drying / separation technology based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Drying / separation technology based on hydrogen	Drying/ separation	2	0.07	/ 2020	3	PJ
Drying / separation technology based on LPG	Drying/ separation	2	0.03	9/ 2011	3	PJ
Drying / separation technology based on natural gas	Drying/ separation	2	0.03	9/ 2011	3	PJ
Drying / separation technology based on solid biomass	Drying/ separation	11	0.83	9/ 2011	3	PJ
Electric motor technology	Motor	3	0.08	9/ 2011	3	PJ
Gas turbine CHP based on natural gas	CHP	36	0.7	9/ 2011	3	PJ
Gas turbine CHP based on natural gas	CHP	36	0.7	9/ 2011	3	PJ

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/ Start date	Data confidence	Units
Heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Low-temperature heat technology based on electricity	Boiler	4	0.02	9/ 2011	3	PJ
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Low-temperature heat space technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3	PJ
Low-temperature heat space technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3	PJ
Low-temperature heat space technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3	PJ
Low-temperature heat space technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3	PJ
Low-temperature heat space technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3	PJ
Low-temperature heat technology based on hydrogen	Boiler	2	0.07	9/ 2020	3	PJ
Low-temperature heat technology based on LPG	Boiler	2	0.03	9/ 2011	3	PJ
Low-temperature heat technology based on natural gas	Boiler	2	0.03	9/ 2011	3	PJ
Low-temperature heat technology based on solid biomass	Boiler	11	0.83	9/ 2011	3	PJ

NZIP2 Technology	Technology assumed	CAPEX (m£/unit)	OPEX (m£/unit)	TRL/ Start date	Data confidence	Units
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Natural gas boiler	Boiler - Hot water	5	0.09	9/ 2011	3	PJ
Press section (standard)	Paper	190	4.74	9/ 2011	1	Mt Paper before drying
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3	PJ
Steam turbine CHP based on solid biomass	Biomass CHP	17	1.1	9/ 2011	3	PJ
Steam turbine CHP based on solid biomass	Biomass CHP	17	1.1	9/ 2011	3	PJ
Technologies for the other production steps (standard)	Paper	190	4.74	9/ 2011	1	Mt Paper before pressing
Technologies for the production of the final paper products from basic paper	Paper	682	17.04	9/ 2011	1	Mt Final Paper

Demand Side Response

The pulp storage tower in between the de-inking/pulp production plant and the ‘paper machine’, where pressing and drying takes place, allows the paper manufacturing process to have a high potential for DSR[133]. Pressing and drying are continuous processes and require careful temperature control, which limits its DSR potential.

The pulp storage tower can be operated like a ‘pseudo battery’. During the stakeholder interview, participants revealed that their UK site has two large storage towers and two pulp lines feeding it. This allows them to turn off the pulp production process (i.e. the pulp lines) partially or fully in response to demand shift signals and feed the downstream pressing and drying processes with the pulp from the storage towers. The interview also revealed that these physical pulp storage towers are much less capital intensive than installing batteries or other energy storage technologies, suggesting that the paper manufacturing industry is a strong candidate for industrial DSR.

Table 42 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked within stakeholder interviews.

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[133] Stakeholder Interviews

Table 42: Demand side response potential summary of Paper sector

Process	Equipment	Practical DSR potential	Constraints
Paper machine - Mechanical pulping (67% of site electricity consumption)	Wood grinder	Max peak demand reduction: 100%, depending on pulp storage tower size Demand shift timing: Before and after peak window Demand shift duration: Up to 12 hours for 40% peak demand reduction. Up to 1.5 hours for 90% peak demand reduction Ramping: 15-30 mins ramp down. 30-60 mins ramp up	Typically limited by the size and number of pulp storage towers. If the pulp storage towers are large enough, they can provide up to 100% flexibility. However, the demand shift duration achievable reduces with peak demand reduction.
Pressing and drying (33% of site electricity consumption)	Heat pumps and/or electric boilers	Max peak demand reduction: 0% Demand shift timing: N/A Demand shift duration: N/A Ramping: 20-30 mins ramp down. 45 mins ramp up.	While this process can technically participate in DSR, the continuous nature of the process and the strict temperature requirements means site operators would never do so.

Vehicles

The vehicle manufacturing process is as follows:

Figure 22: Main production steps in vehicles manufacturing

Stamping: Involves shaping flat metal (carbide) sheets by deforming it with a punching product into the desired shape/parts for the car body. It is ideal for attaching parts to the car frame. Before starting this procedure, the metal alloys need to be prepared (casting), which can involve high temperatures (430-750 °C), limiting its electrification potential. It occurs in a press shop and accounts for 22% of energy consumption.

Welding: Involves heating the metal pieces and applying an electric current to join/attach the different pieces/parts to their distinct locations. It occurs in the body shop and accounts for 32% of energy consumption.

Painting: Involves painting and sealing operations for aesthetic and protection purposes. This is usually the most energy-intensive step in the process. It occurs in the paint shop and accounts for 36% of energy consumption.

Assembly: Involves putting together the manufactured parts to make a complete product. Automotive industries usually use technical machinery for assembly. Assembly includes component testing, installation, and test pressing and accounts for 10% of energy consumption.

Electricity consumption for facilities and systems common to the whole plant infrastructure is distributed among painting (27–50%), heating, ventilation, and air-conditioning (11–20%), lighting (14–15%), compressed air (9–14%), welding (9–11%), and materials handling/ tools (7–8%)[134].

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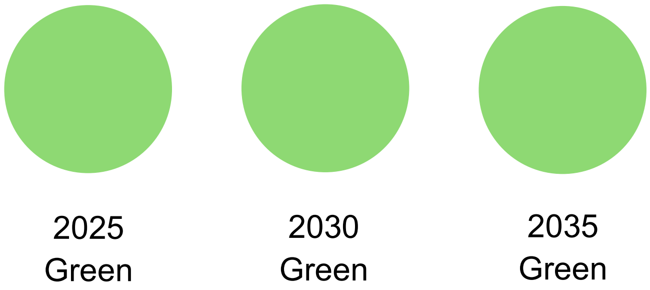
[134] Alessandro Giampieri and others (2019) 'A review of the current automotive manufacturing practice from an energy perspective', Applied Energy, Volume 261, March 2020

Electrification Potential

Figure 23: Vehicles electrification potential (2025 - 2035)



The NZIP2 model lists furnaces as the typical high-temperature heat technology for the Vehicles sector. Here direct electrification could be achieved using electric arc furnaces. Induction heating can also be applied in furnaces and is already being applied in certain industrial applications today.[135]

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[135] Fraunhofer ISI (2024) 'Direct electrification of industrial process heat', study on behalf of Agora Industry

NZIP2

Table 43: Qualitative summary of baseline Vehicle sector technologies

NZIP2 Technology	Technology assumed	Typical capacity	Decarbonisation alternatives	Timeline for decarb.	Insights from literature review & interview
CHP (Steam Turbine and CCGT)	CHP	1 – 5 MW	Hydrogen CHP	Contingent on H2 infrastructure (post 2035)	Interviews indicated 4 operational CHPs in the UK automotive industry and these all-gas engine-CHPs. No turbine CHPs currently operational in the UK.
High-temperature heat technology (based on various fuels)	Furnace	Not determined	Electrification	Not determined	Interviews indicated that high-temperature heat would not be commonplace across UK automotive industry, but that casting is the most representative category. Paint shop ovens are classified by the sector as high temperature however (operating at 350 °C).
Low-temperature heat technology (based on various fuels)	Ovens for paint curing	< 1 MW	Electrification	Not determined	Interviews indicated that all operational ovens in the UK automotive industry operate on direct-fired natural gas. 12 large paint shops, all using ovens, are operational in the UK. One production facility is considering electrification however electrified heated paint curing requires advancements in paint technologies for this to be viable.
Low-temperature space heat technology (based on various fuels)	Boilers	< 1 MW	Electrification through Heat pump	2025 - 2030	Interviews highlighted that trials of heat pumps for space heating have been run. For the larger production facilities, heat pumps are a possible and feasible solution, but there are additional ancillary costs that need to be considered in business-case decision.

Table 44: Quantitative summary of Vehicles sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2
Electric motor technology	Motor	3	0.08	9/ 2011	3
Gas turbine CHP based on natural gas	CHP	81	0.3	9/ 2011	3
High-temperature heat technology based on coal	Furnace	10	0.27	9/ 2011	1
High-temperature heat technology based on electricity	Furnace	5	0.14	9/ 2011	1
High-temperature heat technology based on hydrogen	Furnace	6	0.16	8/ 2028	1
High-temperature heat technology based on LPG	Furnace	4	0.11	9/ 2011	1
High-temperature heat technology based on natural gas / biomethane	Furnace	4	0.11	9/ 2011	1
High-temperature heat technology based on solid biomass	Furnace	10	0.27	9/ 2011	1
Low-temperature heat technology based on coal	Boiler	17	1.26	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	6	0.02	9/ 2011	3
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	6	0.20	9/ 2020	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
Low-temperature heat technology based on LPG	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on natural gas	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on solid biomass	Boiler	22	1.66	9/ 2011	3
Low-temperature space heat technology based on coal	Boiler - Hot water	9	0.65	9/ 2011	3
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature space heat technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3
Steam turbine CHP based on solid biomass	Biomass CHP	34	2.0	9/ 2011	3

Demand Side Response

The DSR potential of the vehicle manufacturing industry is moderate. Batch processes such as stamping, welding and assembly can offer DSR through aligning shift cycles to avoid peak network congestion periods. The continuous processes, such as those in the paint shop – paint curing and heat treatment – offer limited DSR potential as it would impact the site's production outputs. The paint shop tends to be the most energy-intensive step in the vehicle manufacturing process, accounting for 36% of current overall energy consumption and 27-50% of current electricity consumption.

The industry's overall DSR potential if further limited by the fact that the entire manufacturing process tends to be dispersed across multiple sites. This means that a particular process's ability to change its shift timings will depend on the ability of the preceding and succeeding steps' ability to do so, along with the individual site's buffer storage capacity.

Paint shops are considering moving away from continuous manufacturing towards a batch manufacturing system. If this happens, the overall DSR potential of the industry would improve significantly. However, this would require there to be sufficient buffer stores for the batches, which would be a major investment (money and space).

Space heating is another source of DSR from the Vehicle Manufacturing industry. Its potential would be dependent on building insulation levels and shift timings.

Table 45 below summarises the DSR potential of the different processes capable of flexing their electricity demand by current/future equipment. The figures quoted are estimates derived from input from stakeholder interviews and available literature. They have been verified by subject matter experts in Guidehouse and were sense-checked with the stakeholders during interviews.

The main constraint for DSR in this industry is that the entire manufacturing process tends to be dispersed across multiple sites, creating complexity in coordination across sites. This means that a particular process's ability to change its shift timings will depend on the ability of the preceding and succeeding steps' ability to also do so.

Table 45: Demand side response potential summary of Vehicle sector

Process	Equipment	Practical DSR potential[136]	Constraints
Stamping in the press shop (22% of current overall energy consumption)	Automotive stamping machine press	Max peak demand reduction: Up to 80% Demand shift timing: Before and after peak window Demand shift duration: Depends on shift patterns Ramping: Information unavailable	Coordination required across multiple sites
Welding in the body shop (32% of current overall energy consumption)	Electric welding technologies	Max peak demand reduction: Up to 90% Demand shift timing: Before and after peak window Demand shift duration: Depends on shift patterns Ramping: Information unavailable	Coordination required across multiple sites
Paint curing and heat treatment in the paint shop (36% of current overall energy consumption)	Heat pump/electric boilers	Max peak demand reduction: Up to 60% if operated as a batch process Demand shift timing: Before and after peak window Demand shift duration: Depends on shift patterns Ramping: <15 mins	Coordination required across multiple sites
Assembly (10% of current overall energy consumption)	Generic process technology	Max peak demand reduction: Up to 85% Demand shift timing: Before and after peak window Demand shift duration: Depends on shift patterns Ramping: Information unavailable	Coordination required across multiple sites
Space heating, ventilation and air condition (11-20% of current overall electricity consumption)	Heat pump/electric boilers	Max peak demand reduction: Up to 30% Demand shift timing: Before and after peak window Demand shift duration: Depends on shift patterns Ramping: <15 mins	Coordination required across multiple sites

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[136] Stakeholder Interviews

Refineries

Refineries are complex installations that fundamentally convert natural materials such as crude oil into more useful end-products. The combination and sequence of processes are usually adapted to the specific characteristics of the raw input materials and the desired end-use products. The production of fuels is the most important function of refineries, although some refiners will also produce valuable non-fuel products. Common processes in refineries include: crude and vacuum distillation, catalytic hydrotreatment, and catalytic cracking/reforming. European refineries have tended to adapt to local demands of middle distillates like diesel and jet fuel. Consequently, they have higher hydrotreating and hydrocracking capacities compared to catalytic cracking capacities, unlike refineries in other regions[137]. The main sources of CO2 emissions from refineries include:

- Process furnaces, boilers, and gas turbines
- Fluidised catalytic cracking regenerators
- CO boilers
- Flare systems
- Incinerators
- LNG plant CO2 separation

The NZIP2 database is primarily concerned with oil/petroleum refineries. The refining of crude oil can be conceived of in two phases. The first phase involves the desalting of crude oil and subsequent distillation into various fractions. The second phase involves downstream processes which serve to crack hydrocarbons (distillation fractions) into smaller molecules, to join them into larger molecules, or adapt them to higher-quality molecules.

The UK has seven oil refineries with a combined crude oil distillation capacity of 1.2 million barrels per day[138,139]. In 2024, it was announced that Petroineos would be closing its Grangemouth refinery (Scotland's only oil refinery and also the UK's oldest refinery), in the summer of 2025.

A number of these oil refineries are exploring carbon capture technology. Prax Lindsey has plans to retrofit its oil refinery with a post-combustion, amine-based carbon capture system[140,141]. Phillips 66 is also looking to install a post-combustion, amine-based carbon capture system at its FCC[142].

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[137] EU-BRITE, Refining of Mineral Oil and Gas

[138] US Department of Energy (2024) 'Country Analysis Brief: United Kingdom'

[139] Eastham (Nynas AB/Shell), Fawley (ExxonMobil), Grangemouth (Petroineos), Humber (Phillips 66), Lindsey (Prax Group), Pembroke (Valero), Stanlow (Essar Energy)

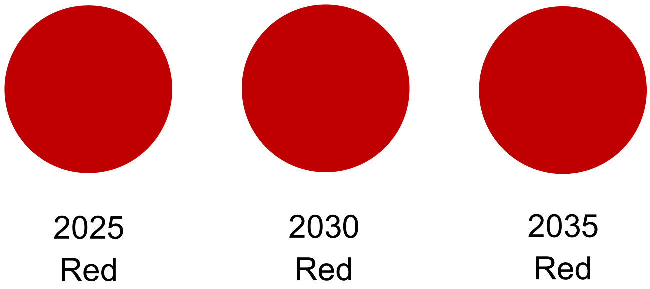
[140] Prax Group (2023) 'Prax Lindsey Oil Refinery Launches £300 Million Carbon Capture Project'

[141] HICP/UKRI (2023) 'Humber Industrial Cluster Plan'

[142] Phillips 66, Carbon Capture and Storage

Electrification Potential

Figure 24: Refineries electrification potential (2025 - 2035)



Key refinery heating processes that may be subject to future electrification include: Steam Methane Reforming (SMR), Catalytic Reforming, Hydrocracking, Thermal Cracking (Visbreaking), Vacuum Distillation Units (VDU), and Atmospheric Distillation Units (ADU)[143]. The ADU is the most emissions-intensive of these processes. Indirect resistance furnaces have been cited as the most feasibly electrification technology for refinery furnaces, with the technology reaching up to 3,000 °C. However, there seem to be no relevant industrial-scale demonstrations of this technology for the refining sector.

Demand Side Response

The dependence on on-site, behind-the-meter generation in most refineries means that any demand shifting offered by refineries would have minimal impact on grid congestion management. However, this may change in the future if/when refineries electricity demand increases should they decarbonise via electrification. Then, they may procure their electricity to power these from the grid.

The cracking/reforming processes offer some potential for DSR. Please refer to the chemicals demand side response section of this report for more information on this.

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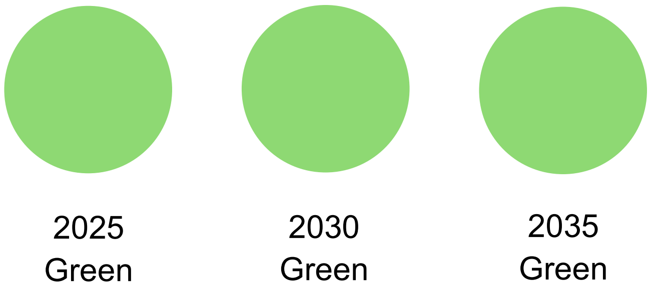
[143] ERM (2024) 'Future opportunities for electrification to decarbonise UK industry', A report for Department for Energy Security and Net Zero

Textiles

The textile industry is a complex manufacturing industry dominated by small and medium-sized enterprises, and driven by three main end-use groups: clothing, home furnishing, and industrial use. The production chain includes a wide range of sub-sectors, from the production of raw materials (man-made fibres) to semi-processed materials, and the final consumer products. Energy is primarily consumed to raise the temperature of baths (used in for example pre-treatment and dyeing operations), as well as drying and curing operations[144]. These processes can be regarded as part of what is broadly referred to as the “finishing process”, which are also part of what are referred to as “wet processes”. Dry processes primarily use electricity for machine drivers, and wet processing primarily uses thermal energy, often in the form of steam[145].

Electrification Potential

Figure 25: Textiles electrification potential (2025 – 2035)



Within the Textiles sector, the use of high-temperature heat applications above 400 °C are not expected, and the sector can be readily electrified using existing technologies[146].

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[144] EU-BRITE, Textiles Industry

[145] Minsuk Kim and others (2024) 'Reduction of greenhouse gas emissions by optimizing the textile dyeing process using digital twin technology', Fashion and Textiles, Volume 11, article 17

[146] Silvia Madeddu and others (2020) 'The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)' Environmental Research Letters, Volume 15, Number 12

NZIP2

Table 46: Quantitative summary of Textiles sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
CCGT CHP based on hydrogen	CCGT CHP	84	2.4	8/ 2025	2
Drying / separation technology based on coal	Drying/ separation	8	0.63	9/ 2011	3
Drying / separation technology based on electricity	Drying/ separation	4	0.02	9/ 2011	3
Drying / separation technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Drying / separation technology based on hydrogen	Drying/ separation	2	0.07	/ 2020	3
Drying / separation technology based on LPG	Drying/ separation	2	0.03	9/ 2011	3
Drying / separation technology based on natural gas	Drying/ separation	2	0.03	9/ 2011	3
Drying / separation technology based on solid biomass	Drying/ separation	11	0.83	9/ 2011	3
Electric motor technology	Motor	3	0.08	9/ 2011	3
Gas turbine CHP based on natural gas	CHP	34	0.9	9/ 2011	3
Low-temperature heat technology based on coal	Boiler	8	0.63	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	4	0.02	9/ 2011	3
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	2	0.07	9/ 2020	3
Low-temperature heat technology based on LPG	Boiler	2	0.03	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
Low-temperature heat technology based on natural gas	Boiler	2	0.03	9/ 2011	3
Low-temperature heat technology based on solid biomass	Boiler	11	0.83	9/ 2011	3
Low-temperature space heat technology based on coal	Boiler - Hot water	9	0.65	9/ 2011	3
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature space heat technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3
Steam turbine CHP based on heat pump	Heat pump	26	0.10	9/ 2020	3
Steam turbine CHP based on solid biomass	Biomass CHP	17	1.1	9/ 2011	3

Electrical Engineering

The Electrical Engineering sector covers the manufacture of electrical and electronic equipment. Technologies within NZIP2 include low temperature heat, low temperature space heating, and high temperature heating. Based on literature, typical capacity for low temperature heating is expected to be < 1 MW. Evidence on capacity ranges for high temperature applications is lacking within literature.

NZIP2

Table 47: Quantitative summary of Electrical Engineering sector technologies

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
Electric motor technology	Motor	3	0.08	9/ 2011	3
High-temperature heat technology based on coal	Furnace	10	0.27	9/ 2011	1
High-temperature heat technology based on electricity	Furnace	5	0.14	9/ 2011	1
High-temperature heat technology based on hydrogen	Furnace	6	0.16	8/ 2028	1
High-temperature heat technology based on LPG	Furnace	4	0.11	9/ 2011	1
High-temperature heat technology based on natural gas / biomethane	Furnace	4	0.11	9/ 2011	2
High-temperature heat technology based on solid biomass	Furnace	10	0.27	9/ 2011	1
Low-temperature heat technology based on coal	Boiler	17	1.26	9/ 2011	3
Low-temperature heat technology based on electricity	Boiler	6	0.02	9/ 2011	3
Low-temperature heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature heat technology based on hydrogen	Boiler	6	0.20	9/ 2020	3
Low-temperature heat technology based on LPG	Boiler	5	0.09	9/ 2011	3
Low-temperature heat technology based on natural gas	Boiler	5	0.09	9/ 2011	3

NZIP2 Technology	Technology assumed	CAPEX (m£/PJ)	OPEX (m£/PJ)	TRL/ Start date	Data confidence
Low-temperature heat technology based on solid biomass	Boiler	22	1.66	9/ 2011	3
Low-temperature space heat technology based on coal	Boiler - Hot water	9	0.65	9/ 2011	3
Low-temperature space heat technology based on electricity	Boiler - Hot water	4	0.04	9/ 2011	3
Low-temperature space heat technology based on hydrogen	Boiler - Hot water	2	0.08	9/ 2020	3
Low-temperature space heat technology based on heat pump	Heat pump	26	0.10	9/ 2020	3
Low-temperature space heat technology based on LPG	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on natural gas	Boiler - Hot water	2	0.04	9/ 2011	3
Low-temperature space heat technology based on solid biomass	Boiler - Hot water	11	0.85	9/ 2011	3

Recommendations for future work

NZIP2 technologies

Three key improvements were identified throughout the project to improve the accuracy of the model: 1) improving the granularity of energy use breakdown, 2) expanding the list of technologies to model the sector, and 3) updating the financial parameters.

On the first improvement, the model currently utilises ECUK energy consumption breakdown which does not provide sufficient granularity to map energy consumption and emissions to specific technologies. For example, low temperature heat within Food & Drink sector can be either steam generation (which is the assumption utilised in this scope of work) or direct heating applications in ovens and fryers. Sector specific energy mapping studies like the one cited in the footnote can be used as a starting point to build evidence.[147] This would need to be complemented by interviews with stakeholders to validate the breakdown of energy consumption and end use technologies corresponding to them. For sectors such as Food & Drink and Ceramics, this can be quite challenging to achieve due to the diversity of operations depending on the end products. In such cases, creating additional sectors to capture product diversity would be needed. Currently, the model also has baseline coal capacity in sectors where coal has been phased out (e.g. Food & Drink, Vehicles).

The second improvement identified is to expand the list of alternate technologies that can be adopted. Table 48: Alternative technologies to consider for NZIP2, below summarises some suggestions on additional CCS, electrification and CHP technologies that are TRL 7-9 that could be considered a part of future iterations of the database. However, to incorporate other electric technologies within NZIP2, the model would need to have the option between two different technologies of the same fuel type.

Table 48: Alternative technologies to consider for NZIP2

Technology group	Alternate technologies to consider
Cement	LEILAC, Indirect Calcination, Mineral Carbonation
CCS	Solid Adsorbents - Pressure Swing Adsorption/Vacuum Swing Adsorption, Non-amine based chemical solvents e.g. Hot Potassium Carbonate (HPC), Membranes, Cryogenic Separation with Membrane/ Pressure Swing Adsorption
High temperature heat - electricity	Induction heating, Di-electric heating, Infrared heating, Plasma torches
CHPs	Internal combustion engines, fuelled by natural gas, hydrogen or biogas

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[147] Benjamin Sovacool and others (2021) ‘Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options’ Renewable and Sustainable Energy Reviews, Volume 143

To action the last improvement opportunity, a framework has been developed to evaluate the need for future updates to the database. This utilises the current maturity of technologies (based on TRL/ expected start date), data confidence score, and a qualitative judgement of potential for cost reductions based on the nature of technology. Depending on where each technology grouping sits within the matrix, a parameter update strategy is defined as demonstrated in Table 49: Guidehouse's proposed framework for evaluating the need for future updates to the NZIP2 database.

Table 49: Guidehouse's proposed framework for evaluating the need for future updates to the NZIP2 database

Technologies / Processes	Future Disruption	Data Confidence
Drying – Ceramics	None	Low
Paper production, High temperature heat	None	Low-Moderate
Iron & Steel Furnaces	None	Moderate
Baseline Drying, Baseline CHPs	None	Moderate-High
Motors, Baseline – Low temperature heat	None	High
Crackers	Moderate	Moderate
MEA CCS	Moderate	Moderate-High
Electric low temp heat, Heat pumps	Moderate	High
Novel Iron & Steel Furnaces (e.g., HISARNA);	Moderate	Low-Moderate
Electric Cold Top Furnace	Moderate-High	Moderate
Oxyfuel CCS; H2 fired technologies	Moderate-High	Moderate-High
Hydrogen production – Electrolyzers	High	High

To support the application of the framework, literature review was performed to identify evidence on future developments for technologies that are expected to achieve cost reductions. The prevailing methodology for modelling future cost reductions is by applying learning rates. However, learning rates can be utilised as an input only if it is supplemented with additional evidence on the uptake of technology (number of units sold per year). Evidence on learning rates were also observed to vary. A summary of the literature review is provided below in Table 50.

Table 50: Literature review summary

Technology group	Evidence from literature
Heat pumps	Evidence on cost reductions of industrial heat pumps is limited. Global studies on learning curves residential heat pumps indicate wide range (-2% to 18%) and were observed to be heavily dependent on the policy environment and experience within market.[148] Interview with GEA suggested that the heat pump suggest that limited improvement in costs should be expected and pointed out factory layouts and source of waste heat are the biggest driving factor of cost. Danish Energy Agency's technology cost database on the other hand assumed 9%, 17% and 20% cost reduction with respect to 2020 prices by 2030, 2040, and 2050 respectively.[149]
MEA[150] CCS	MEA CCS is the most mature CCS technology. Evidence is conflicting on expected cost reductions. Global CCS institute suggest up to ~20% reduction in cost of capture projects to account for lessons relevant to plant design and non-proprietary learnings within the CCS community.[151] However, in ECRA's 2022 Technology Papers, they assume no future reduction in capital costs citing the technological maturity of MEA CCS.[152]
Oxyfuel, Calcium Looping CCS	ECRA's 2022 Technology Papers, assume a 1% year on year price reduction between 2020 – 2030 and forecast ~10% reduction in capital costs[153]
Hydrogen fueled technologies	Stakeholder interviews and literature point out that hydrogen-based industrials tend to be ~ 30% premium with respect to natural gas. This price differential could be expected to go down as the technology is mainstreamed. While there is limited evidence on learning rates for specific industrial applications, technologies (high temperature, low temperature applications) evidence from domestic and commercial applications for hydrogen-based boilers indicate that the technology should parity with natural gas in terms of capital costs as adoption scales up.[154] In the absence of evidence, assuming 2040 as the year of hydrogen fueled technologies to reach parity with natural gas baseline technologies would be reasonable.

In the absence of specific evidence, a rule of thumb can be applied for technologies with TRL<9 by assuming a 1% year on year reduction in capital costs.

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[148] Reinhard Haas and others (2022) 'Technological Learning: Lessons Learned on Energy Technologies', WIREs Energy and Environment, Volume 12

[149] Danish Energy Agency (2020) 'Technology Data for Industrial Process Heat'

[150] MEA: Monoethanolamine

[151] Global CSS Institute (2021) 'Technology Readiness and Costs of CCS'

[152] European Cement Research Academy (2022) 'State of the Art Cement Manufacturing: Current technologies and their future development'

[153] European Cement Research Academy (2022) 'State of the Art Cement Manufacturing: Current technologies and their future development'

[154] Element Energy Ltd (2018) 'Hydrogen supply chain evidence base', prepared for the Department for Business, Energy and Industrial Strategy

Demand Side Response

The sector specific insights on demand side response offered in this report have been obtained through 19 interviews with individual sites and trade associations representing certain sectors, academic papers and inputs from internal subject matter experts at Guidehouse. This research provides a strong starting point into understanding the amount of power flexibility that can be practically unlocked from industrial customers in the UK in a future, decarbonised world. However, given the relative nascency of electrified technologies for high temperature processes and the limited engagement in DSR today by industrial sites, with some exceptions, means that the results are mostly reliant on a qualitative understanding on the subject by the interviewees and learnings from a relatively small number of trials/schemes that have taken place internationally.

Table 51 below, summarises the relative knowledge gaps of this research, along with some recommendations on how these can be addressed going forward. For each of the DSR metrics included in the study, an overall confidence rating has been assigned on the following basis:

- **High** – high confidence in underlying literature and anecdotal experience, with validation by stakeholders.
- **Moderate** – Varying levels of confidence across sectors in underlying literature, anecdotal experience and stakeholder input. Needs more interviews per sector to improve confidence levels.
- **Low** – Available literature and anecdotal experience limited. Primarily driven by stakeholder input, which was process / context specific. Needs more interviews per sector to improve confidence levels.

Table 51: DSR summary - confidence rating and recommendations

DSR metric	Confidence rating	Explanation	Recommendations
Flex capability (yes or no, and duration of notice period)	High	Site operators and expert stakeholders interviewed were able to confidently direct the research team	N/A
Max peak demand reduction (%)	Moderate	Parameter is very context and process specific. Only 1-2 sites have been interviewed within the scope of this study which has limited the validation at a sector-level. Therefore, the max peak demand reduction achievable figures may be biased towards the site / the estimations of the interview participants.	DESNZ should commission additional research to engage with a greater sample size of industrial stakeholders and obtain a more representative view of each sector’s max peak demand reduction achievable. DESNZ could also look to engage with flexibility aggregators with industrial clients, who may have data on the amount of flex (MW) each of their clients can deliver.
Demand shift timing (before or after peak or both)	High	If a process’s electricity demand can be shifted, it should technically be able to shift to both before and after the peak windows. This assumption was verified by the stakeholders interviewed.	N/A

DSR metric	Confidence rating	Explanation	Recommendations
Demand shift duration (hours)	Low	The results presented are strongly biased towards the site / the estimations of the interviewee. There interviews revealed that there are many site-specific factors that impact demand shift duration, such as the shift operation schedules. Furthermore, certain sector definitions such as chemicals, food and drink and non-ferrous metals were too diverse to provide a reasonable estimate for demand shift duration.	DESNZ should continue their industrial engagement and look to engage with as many sites as possible per sector to obtain an unbiased, averaged view of the demand shift duration possible by sector. Additionally, sectors such as Chemicals, Food & Drink and Non-ferrous metals should be broken down into sub-sectors, and an average demand shift duration value should be assigned to each sub-sector due to the large variability across the wider sector. Examples of sub-sectors for the non-ferrous metals sector could include Aluminium manufacturing, Zinc manufacturing, Copper manufacturing, etc. Examples of sub-sectors for the chemicals sector could include refineries, ammonia production, ethanol production, pharmaceuticals, etc. Examples of sub-sectors for the food & drink sector could include sugar manufacturing, distilleries and breweries, soft drinks, etc. DESNZ could also look to engage with flexibility aggregators with industrial clients, who may have data on the amount of flex (MW) each of their clients can deliver.
Ramping (up and down – hours) (Additional scope)	Moderate	The electrified technologies for high temperature heat processes deemed capable of DSR are commercially immature and not very widespread, with low TRL. Additionally, only 2 OEMs were interviewed as part of this project.	DESNZ should continue their industrial engagement and look to engage with more OEMs on the potential ramp rates of high temperature electrified technologies.

Appendix A – NZIP2 methodology

Definition of technology parameters

Key parameters, their definitions, and key assumptions followed in the database included the following:

CAPEX – Capital costs per unit of capacity. This includes all costs of equipment and installation expressed in £'m/PJ or £'m/Mtonne. Key words such as "Investment Costs", "Installed Costs", "Indicative Cost" and "Direct Costs" are assumed to be synonymous with CAPEX. CAPEX costs will not include metrics such as "Owner's Cost" or process contingency costs. Where literature is unclear whether installation and ancillary equipment costs are included within reported figures, a judgement (based on factors such as reference capacity for the value) is made comparing scale of reported value with other sources for the technology to apply a scaling factor for installation costs. Literature where costs are mentioned as a range of maximum and minimum CAPEX values, average value is reported for the purposes of comparison with other sources, with the range captured documented qualitatively.

OPEX – Fixed operating costs for maintenance expressed in £'m/PJ or £'m/Mtonne. In the absence of reliable data on OPEX, the parameter may be taken as % of CAPEX. Where applicable this will be technology specific. Sometimes O&M costs are reported with fuel costs stated separately, so it is assumed in such a case that the first metric is fixed O&M specifically despite it not explicitly saying so.

Technology Readiness Level (TRL) – TRL level definitions taken from EU Horizon 2020 programme literature available here: Technology readiness levels (TRL) (Annex G). Where TRL is not specified explicitly technology, an assessment of technology application and maturity based on qualitative statements in literature has been used to align with TRL definitions.

Lifetime – Years expected to be in service. Lifetime taken as reported, usually a whole number in years and not number of operating hours. Where multiple lifetime figures are reported, the most-reported value (mode) is used.

Efficiency – Output activity/input activity. Thermal and electrical efficiency values encountered with technologies such as CHPs. Electrical efficiency reported in the database (MWe). Thermal efficiency values noted for reference. Ratings may be based on a particular fuel for multi-fuel technologies. For example, a turbine may be multi-fuel, but vendor specification sheets may report efficiency when using natural gas.

Start Date – Year in which technology is expected to be available. Start year can be defined in two different ways: First interpretation focuses on commercial availability of a technology and TRL is used as an indication of start date. For example, technologies with TRL 9, start year is assumed to be current day. This can be established based on literature reviews. Second interpretation focuses on expected adoption timelines within industry. This will be indicated through sector interviews.

Emissions Capture Rate – For CCS, gross CO2 capture efficiency. Maximum steady-state gross carbon capture efficiency (%); max. gross quantity of CO2 the capture system is designed to capture expressed as a percentage of the total CO2 processed through it (i.e. a post-combustion flue gas stream passed through a capture system).

Availability – % of year technology is available to run. Availability factor is typically expressed in hours of operation. This is converted to % by dividing with 8,760 h/year.

Transformation of financial data – Financial values in literature are reported across a wide range of parameters and time periods. To ensure consistency across the parameters in NZIP2, all financial values are based upon the transformations shown below in Figure 26.

Figure 26: Transformation of financial data

Exchange Rate Based on average exchange rate for 2024

X

Price correction Chemical Engineering Plant Cost Index (CEPCI) used to account for inflation for target year (2021)

X

Installation costs Where CAPEX doesn't include installation costs, a technology specific scaling factor will be used.

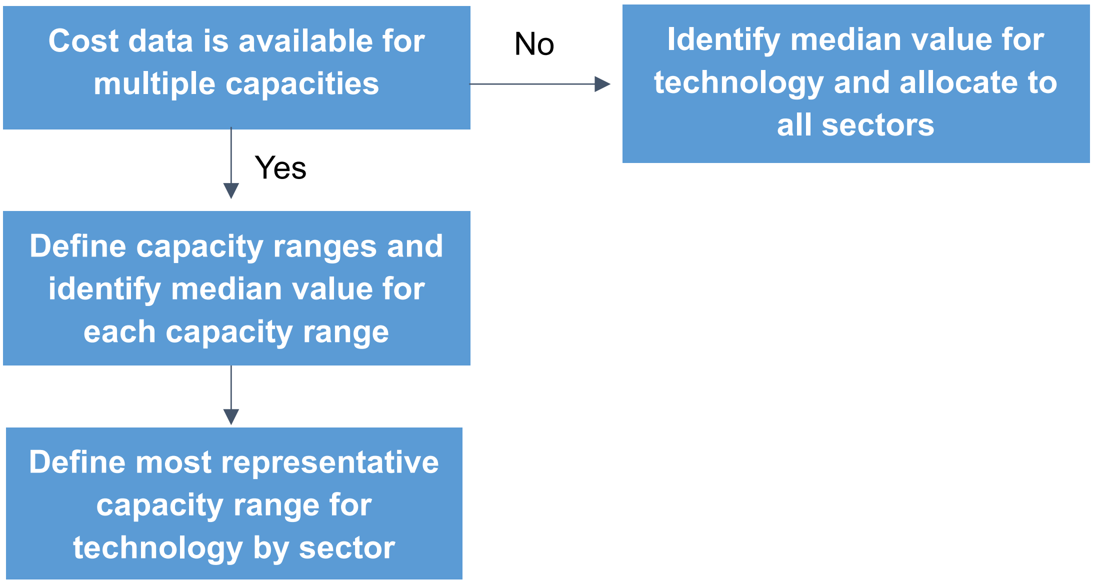
X

Capacity units £'m/MWe, £'m/MWth, or £'m/Mt to be converted to £'m/PJ

Determining a single value per sector and technology – NZIP2 model requires a single financial estimate for each sector technology combination. To determine the most representative value for a sector technology combination the following rules are applied:

- Eliminate outliers
- Eliminate data with poor data quality score and lack of traceability of estimate
- Identify median values based on the flowchart shown Figure 27

Figure 27: Determination of single value



Appendix B – Scoping of Stakeholder Engagement Process

Initial Stakeholder Engagement Plan

In accordance with the ITT response, the initial stakeholder engagement plan consisted of two engagement methods: 1) sector-specific interviews and 2) focus groups. Guidehouse proposed conducting 13 sector-specific interviews for the purpose of validating the technology parameters identified via the literature review research; and 5 focus groups, for the purpose of consensus-building among industry in the development of updated technology parameter inputs for each of the NZIP2 sectors.

The proposed groupings for sector interviews were:

- Cement and Lime
- Mechanical Engineering
- Electrical Engineering and Vehicles
- Chemicals and Refining
- Food and Drink
- Glass
- Hydrogen Production
- Iron & Steel
- Non-Ferrous Metals
- Paper
- Ceramics

For focus groups, participants would be grouped based on the similarity of their technological processes. Therefore, the proposed focus groups were:

- Cement and Lime
- Chemicals, Refining, Hydrogen Production
- Iron & Steel, Non-Ferrous Metals
- Paper, Ceramics, Glass
- Food and Drink, Vehicles, Electrical Engineering, Mechanical Engineering, Textiles, Construction and Other industry

Identified Engagement Challenges

Guidehouse was provided the opportunity to engage colleagues from the DESNZ team responsible for the delivery of DESNZ's 2023 Energy Efficiency (EE) study to discuss the initial stakeholder engagement plan. Based on past learnings from a similar stakeholder consultation exercise conducted within the 2023 EE study, DESNZ identified several engagement challenges with Guidehouse's proposed stakeholder engagement plan. These learnings indicated that focus group engagement would not be a suitable method for use in this study based on the following factors.

Firstly, focus groups consisting of multiple stakeholders, some of whom are commercial competitors, would not provide a forum for open information sharing. This challenge was cited for the 2023 EE study, where participants demonstrated reluctance to disclose potentially commercially sensitive data within focus group forums. Using focus groups for this study would therefore have limited the quality of insights gathered and would potentially undermine the accuracy of the NZIP2 technology parameter validation exercise.

Secondly, conducting focus groups would have required the engagement of sector associations within each of the NZIP sectors and for each focus group. Learnings from the 2023 EE study highlighted that the engagement of sector associations across the NZIP2 industries would present logistical and scheduling constraints that were not possible to accommodate within the condensed timeline of this research.

Based on these past learnings, and through alignment with DESNZ, the initial stakeholder engagement plan was adjusted to reflect the engagement challenges identified and to prioritise the accurate validation of updated technology parameters for the NZIP2 database through additional stakeholder interviews.

Adjusted Stakeholder Engagement Plan

Guidehouse and DESNZ are aligned in an adjusted stakeholder engagement plan. This is consisted of the following adjustments to the initial stakeholder engagement plan:

- Removal of focus groups
- Conducting multiple interviews per industrial sector where applicable
- Extension of the stakeholder participant base to include Original Equipment Manufacturers (OEMs)
- Engagement of sector associations only in those sectors of high heterogeneity or where an industrial contact is not available to Guidehouse or DESNZ.

Therefore, for the adjusted stakeholder engagement plan, Guidehouse is conducting:

- At least 15 interviews across each of the NZIP2 sectors
- At least 4 interviews with OEMs who supply core NZIP2 technologies.

Guidehouse is confident that the above adjustments proportionately reflect the challenges raised in discussion with DESNZ and provide a more suitable approach to achieve the intended objectives of the stakeholder consultation. The engagement of both OEMs and industrial contacts, as representatives of their sectors, will ensure the stakeholder consultation remains inclusive and representative in the validation of technology parameter inputs. This will also enhance the accuracy of the parameter validation exercise through the addition of OEMs who directly supply the NZIP2 technologies.

Interview Process overview

Interview guides are distributed to confirmed participants prior to the interview being conducted. The interview guide details the objectives of the stakeholder consultation, and of the study, and provides contextual pre-read material on the NZIP2 model and topic of Demand Side Response (DSR). This material is intended to ensure participants are fully familiarized with the interviews objectives before each interview is conducted and that the appropriate personnel are in attendance.

The interview guide contains an NZIP2 technology profile and a DSR sector profile for the respective sector of each participant. The NZIP2 technology profile presents NZIP2 technologies and their sub-technologies with their corresponding data values as identified via the literature review research. These include, but have not been limited to, the following categories: energy vector, typical capacity range, CAPEX, lifetime, temperature ranges, TRL, and efficiency. Where data values are not available from the literature review, unknown data fields are clearly labelled to ensure these are covered in the interview. The DSR sector profile provides an indicative process flow diagram for the sector as informed by the NZIP2 production pathway documents. Using this diagram, each process step is highlighted for its practical DSR potential across the following categories: maximum of peak demand reduction, demand shift duration, and ramping time.

Each sector profile (NZIP2 technology and DSR) is accompanied by a list of validation topics, including but not limited to potentially omitted technologies from the NZIP2 database, inaccurate technology labels, CAPEX, OPEX, lifetime, and efficiency. During the interview, the validation topics are used in conjunction with the material presented to formulate a semi-structured discussion. Participants are invited to comment on the accuracy of each of the data categories presented and, where able, validate the technology parameter values, provide values for unpopulated categories, or provide qualitative responses to the validation topics.

All interview responses are captured and recorded in an interview minutes log. This captures the qualitative and quantitative data provided by participants in response to each of the validation topics and sector profiles. Follow up items and further validation questions not answered in the interview are recorded. Participants are provided a complete set of interview minutes post-interview, summarising their responses and with clear communication of remaining follow up items and timelines for providing further response.

Key focus areas by interview type

Across the participant types (NZIP2 sector stakeholders and OEMs), interviews were structured into two focus areas as informed by the sector profiles presented. These are: NZIP2 technology parameter validation and Demand Side Response (DSR) discussion. While the interview process remains broadly similar and all participants are invited to validate the accuracy of data values presented in both the NZIP2 technology and DSR sector profiles, the different focuses for each interview type are detailed below.

For interviews with NZIP2 sector stakeholders, participants have been invited to provide feedback on the technology and DSR sector profiles, from a sector level, and identify any omitted process steps, technologies, or additional considerations. NZIP2 sector stakeholders are also invited to provide comment on the technology parameters for each of the relevant technologies across the following categories: energy vector, typical capacity range, CAPEX, lifetime, temperature ranges, TRL, and efficiency. NZIP2 sector stakeholders are also invited to describe the breakdown of electrical and thermal demand consumed in each process step or by each NZIP technology within their operations, detailing common applications of low and high-temperature heat. For DSR, NZIP2 sector stakeholders are asked to describe the DSR potential of their site/sector processes in terms of practical and technical potential. In this description, participants are invited to identify current or future constraints and enablers of DSR capability, and comment on the changes required to see DSR uptake across their sector.

For interviews with OEM stakeholders, the interview primarily focuses on technology parameter validation. Here, participants are invited to validate or provide feedback on the data presented within each of the categories of the NZIP2 technology sector profile. Participants are invited to describe the industries they supply and any key insights on CAPEX and OPEX costs of their technologies within each known end-use application. Installation and potential ancillary costs are captured also. DSR is discussed in terms of the technical potential of the technologies which the OEM supplies/manufactures with examples of existing DSR application of their technologies from within industry being captured.