UK Government

RAF018/2324: Updating evidence on energy efficiency potential for UK industry

Department for Energy Security and Net Zero (2026)

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Executive summary

1.1 Aims and objectives

This work updates the evidence relating to the potential for improvements in energy efficiency (EE) in UK industrial sectors. In this context, EE reduces the delivered energy consumed per unit of production of industrial output.

This report updates the 2015 Industrial Decarbonisation and EE Roadmaps to 2050[1], which considered energy-related levers available to decarbonise industry, including EE, fuel switching and carbon capture, utilisation and storage (CCUS) technologies. This research relates to **EE measures available within the industrial process only and** does not include building level or behavioural EE measures.

Throughout this report, the previous 2015 study is referred to as Roadmaps 2015 (RM2015) and the new study is referred to as Roadmaps 2024 (RM2024),

The evidence updated includes, but is not limited to, the following:

- Measures available to industry to improve EE
- Suitability of the measures to the industrial sectors considered (see below)
- Characteristics of the measures, e.g. capital expenditure (CapEx) and energy savings
- Barriers to implementation of the measures
- Current adoption of measures
- Ultimate applicability of measures for a sector
- Plausible scenarios for the future adoption of the measures

The work has concentrated on the manufacturing sectors contained within SIC2007 10-33. A focussed approach has been taken for seven of the eight most energy intensive industrial sectors in line with the 2015 research - that is, Iron & Steel (I & S), Cement, Chemicals, Food & Drink (F&D), Paper & Pulp (P&P), Glass, and Ceramics. To note, updated evidence for EE in oil refining is not included in this research but has been updated in a separate report.

In addition to updating the evidence related to the above seven sectors, this work includes an evidenced based analysis of the EE potential available in the rest of industry, which we refer to here as “Other Manufacturing” (OM).

Evidence gathering used a structured approach involving the following main steps:

- Literature reviews for the seven main sectors, plus targeted literature review for some significant sub-sectors within Other Manufacturing.
- Data gap analysis relating to literature evidence.
- 66 structured stakeholder interviews to validate data and fill gaps from the literature review.

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[1] DECC (2015) ‘Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050’

- Targeted questionnaires to identify and prioritise the most significant EE measures to discuss in stakeholder workshops and fill gaps from the literature review.
- Seven stakeholder workshops, to fill gaps in data, validate existing data and gain stakeholder consensus on EE measure adoption rates.
- Adaptation of an existing model, constructed to estimate EE potential in 2015, and the use of this model to run a number of updated scenarios relating to the potential to reduce industrial energy consumption.

1.2 Findings

Energy efficiency (EE) measures have long been recognised as a practical way for businesses to reduce energy use and lower manufacturing costs. As such, they have been considered a cost-effective first step towards industrial decarbonisation and are typically adopted earlier than other decarbonisation technologies such as electrification, hydrogen, and carbon capture, usage and storage (CCUS) as they can be more expensive and complex to install and operate.

While EE measures often remain cost-effective and beneficial for reducing production costs for manufacturing sectors, the findings from this report highlight that EE investments are being considered alongside other decarbonisation technologies and that EE measures in the most energy intensive sectors are increasingly viewed in the context of long-term industrial equipment replacement cycles and wider energy investment decisions. As a result, the adoption of EE measures is seen to be more gradual than suggested in the 2015 report[2].

The quantitative findings of the research are summarised in Table 1 and 2 below. Potential to improve EE is evaluated in relative terms and is expressed as a percentage reduction of baseline energy consumption for each sector[3]. When analysing energy saving potential, this is done by considering separately the potential to save electricity and fuel consumed for the generation of heat, or Fuel for heat (FFH). The energy savings potential for these two energy streams by 2050 is presented separately for two scenarios: business-as-usual (BAU) and Maximum Technical Potential (Max Tech). Max Tech represents what is technically possible after all non-technical barriers are removed, whilst BAU represents what is predicted to happen under the assumption that current investment preferences, policy landscape and economic outlook remain unchanged to the context at the time of the study. The difference between Max Tech and BAU potential is, therefore, the scale of additional savings that may be achieved if non-technical barriers are addressed, for example, through policy.

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[2] To note, there are some differences between the two reports as the 2024 study narrows the focus to EE measures for industrial processes, excluding buildings-related measures and those that relate more to fuel switching or resource efficiency, in which there were a few overlaps found in the 2015 report.

[3] Energy baseline applied aligns with the CCC's Carbon Budget 7 (CB7) industrial decarbonisation analysis: CCC (2025) 'The Seventh Carbon Budget'

Table 1: Roadmaps 2024 energy savings in 2050 by sector (percentage saving compared to baseline energy consumption)

Sector	Scenario	FFH (%)	Elec (%)
Ceramics	BAU	6	<1
	Max Tech	9	<1
Food & Drink	BAU	7	8
	Max Tech	8	11
Pulp & Paper	BAU	13	6
	Max Tech	26	8
Chemicals	BAU	2	2
	Max Tech	3	2
Iron & Steel[4]	BAU	<1	4
	Max Tech	3	9
Glass	BAU	7	4
	Max Tech	12	4
Cement	BAU	0	4
	Max Tech	1	11
Other Manufacturing	BAU	5	5
	Max Tech	7	6

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[4] Note: the scope of this sector in 2024 is different to 2015. Blast furnaces processes materially affected by electrification are excluded from the 2024 scope.

Table 2: Roadmaps 2015 energy savings in 2050 by sector (percentage saving compared to baseline energy consumption)

Sector	Scenario	FFH (%)	Elec (%)
Ceramics[5]	BAU	9	<1
	Max Tech	5	<1
Food & Drink	BAU	4	7
	Max Tech	20	25
Pulp & Paper	BAU	5	3
	Max Tech	35	3
Chemicals	BAU	7	4
	Max Tech	9	4
Iron & Steel[6]	BAU	4	5
	Max Tech	6	6
Glass	BAU	8	2
	Max Tech	20	3
Cement	BAU	<1	1
	Max Tech	10	-11
Other Manufacturing	BAU	N/A	N/A
	Max Tech	N/A	N/A

Whilst the tables above shows that there is remaining potential for energy efficiency savings in all sectors out to 2050, it also shows that the potential has diminished since 2015. The Max Tech levels of EE potential that could be achieved by 2050 are lower than estimated in 2015 for all sectors except ceramics. This reflects the implementation of many industrial EE upgrades since 2015 due to industry's strong ambition and motivation to decarbonise. There have also been some notable reductions in the energy saving potential considered from certain technologies in certain sectors, which contribute to the reduction in EE potential – some of these are described in the sector specific bullets below.

For some sectors' electricity and Fuel for heat use, the levels of EE that will be achieved under BAU is considered higher in 2024 than in 2015. This higher level of adoption is intuitive given increased Emissions Trading Scheme (ETS) carbon prices and the tightening of the UK's legally binding commitment to Net Zero.

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[5] Ceramics BAU Fuel for heat savings for the 2015 Roadmaps study are higher than Max Tech savings due to the Max Tech scenario assuming greater adoption of electric kilns out to 2050, reducing scope for EE.

[6] Note: the scope of this sector in 2024 is different to 2015. Blast furnaces processes materially affected by electrification are excluded from the 2024 scope.

All sectors are shown to have a gap between the BAU and Max Tech level that could be achieved. The gap between BAU and Max Tech differs by sector but is broadly lower than in 2015.

The energy savings results are interpreted in detail in each sector’s chapter. However, the following key differences between the RM2024 and RM2015 results are described here as examples of how industry’s interpretation of EE potential has evolved:

- The Fuel for heat (FFH) savings potential in the Glass sector under the Max Tech scenario is appreciably lower under RM2024 (12%) than under RM2015 (20%). This is primarily due to the sector’s updated view that electrification of furnaces will be more prevalent than was believed back in 2015.Electric furnaces have more limited scope to implement EE measures to recover and reuse of heat since there is no waste stream of combustion products passing out of the furnace from which heat can be recovered.
- Within the Food & Drink sector, there is a notable decrease in projected savings for both FFH and electricity between RM2024 and RM2015, under the Max Tech scenario. RM2015 projected 20% FFH savings compared to 8% for RM2024 and, 25% electricity savings, compared to 11%. While may partly be attributed to the view by stakeholders that opportunities have already been taken and so less potential remains, this finding may be influenced by a greater portion of the consulted stakeholders representing larger organisations than during the 2015 project. Larger organisations tend to have more resource / drivers to implement EE measures than smaller organisations.
- FFH savings in the Paper & Pulp sector are considerably higher in the RM2015 study compared with RM2024 (35% compared to 26%). This reflects this study’s revised view of adoption rates of certain measures, as well as the exclusion of early-stage technologies that related more closely with fuel switching. The expectation that that the sector will replace direct fuel boilers with electric boilers saves significant quantities of FFH and therefore savings are notably lower for RM2024 due to electrification being outside the scope of EE measures considered in this report.
- The same trend can be seen in the Chemicals sector, with FFH savings in RM2024 of 2.5% compared to 9% with RM2015. This is due to the sector having already implemented, directly or indirectly, EE measures to limit their running costs, especially after the spike in energy prices after the start of the conflict in Ukraine.
- Cement also sees a large divergence in savings, across both FFH and electricity, under the Max Tech scenario. Peak FFH savings are 8% lower in the RM2024 study, due to stakeholder feedback indicating limited expectation of further adoption of measures as CCUS is increasingly seen as the means of decarbonising heat generation in the sector. Conversely, RM2024 shows 10.5% electricity savings compared to minus 11% in RM2015. This difference is explained by the assumptions in the RM2015 Max Tech scenario about the adoption of oxygen enrichment technology which involves an increase in electricity consumption.

The following key differences between Max Tech and BAU for RM2024 are described here as examples of how non-technical barriers can influence the realisation of EE potential:

- In the Paper & Pulp sector, the Max Tech scenario shows a significantly more rapid increase in FFH savings up to 2030, reaching 13% compared to 3% for BAU, peaking at 26% in 2050 compared to 13%. The difference in the savings profile between BAU and Max Tech is mainly due to earlier adoption of these mature EE techniques in the Max Tech scenario.
- Differences in FFH savings between Max Tech and BAU trends in the glass sector stem from the additional savings contributed by the batch pelletisation and batch reformulation measures. According to stakeholder engagement, these measures would see much higher levels of penetration under Max Tech, as the high investment costs associated with these measures are overcome under this scenario but continue to affect uptake under the BAU scenario.
- The Iron and Steel sector, which only considers processes downstream of hot metal casting, shows a notable difference between the Max Tech and BAU scenarios in terms of projected electricity savings. The Max Tech scenario shows a more rapid increase in savings, and a considerably higher peak of 8.5% compared to 4% under BAU. The Max Tech savings could be realised with rapid adoption of improved automation and process control, improved planning and throughput optimisation in downstream processes and replacement with premium efficiency motors, achieving up to 5.5% energy savings by 2030, followed by additional uptake of these measures. The main difference between BAU and Max Tech is due to investment constraints in the sector, including feedback that investment usually only takes place when the payback is short (6-12 months). For RM2024 electricity savings results, the main contributor is variable speed drives.
- Max Tech and BAU scenarios also differ considerably in the Cement sector, in terms of electricity savings. Max Tech rapidly reaches its highest savings of 12% by 2030, before lowering to 10.5% by 2040 and remaining flat out to 2050. This is due to the expected up take of CCUS resulting in less available recovered heat to use for electricity generation, since this heat would be needed for carbon capture solvent regeneration. Conversely, the BAU scenario shows a steady increase out to 2050, with a saving of 4%. The difference between BAU and Max Tech scenarios is due to BAU assuming that mills are upgraded as and when they come to the end of their lives, while Max Tech brings forward in time these replacements. Max Tech also includes additional take up of other measures (electrical efficiency improvements and electricity generation from recovered heat) resulting in a greater overall electricity saving.

As well as updating the existing estimates of potential for EE improvement, this work has also gathered evidence on the barriers to the implementation of EE measures.

Barriers to implementation are discussed both in terms of those which are generally applicable across industry and those that are specific to a particular sector. However, it is instructive to acknowledge the following barriers, widely cited by stakeholders, which are applicable across the board:

- Risk of disruption to production associated with EE implementation which, if it appears significant and cannot be mitigated against, will disrupt the implementation of EE measures.

- A general trend of loss of available and capable expertise to identify, work up and champion EE projects, which makes it difficult for project to get off the drawing board.
- Lack of capital available means that EE projects are crowded out by other projects which appear to have greater rates of return.
- In the case of multinational operations, difficulty of attracting capital for investment in EE projects at UK sites, because investments overseas are perceived as better long-term bets. Uncertainty with wider decarbonisation policy (e.g. the availability of hydrogen) making the future landscape unclear and delaying decisions on EE investments, e.g. whether or not to proceed with heat recovery projects.

While there was a view at the time of the field work that the existing Government funding to support EE investments was difficult to apply for, since then this sentiment is likely to have changed, as the Government has announced that there will be no further application windows under the Industrial Energy Transformation Fund (IETF).

When the Max Tech and BAU scenarios were developed with stakeholders the significance of the barriers to EE improvement are taken into consideration.

1.3 Notable challenges for the work

A number of challenges were encountered, and these are discussed in more detail in the main sections of this report. However, there are two which are notable and should be taken into consideration when interpreting and using the results.

The first significant challenge was managing the scope of the work. There are many EE measures applicable to industry and updating the evidence for all of these was a challenge. Consequently, it was necessary to take a prioritised approach, concentrating on the EE measures which available evidence indicated had the greatest potential to save energy and which stakeholders indicated were the most relevant to their operations. In respect of these ‘prioritised measures’, all relevant characteristics were updated. For the other ‘non-prioritised’ measures, just the CapEx was updated. Consequently, not all measures feeding into the estimates of energy savings have been comprehensively updated from the 2015 Roadmaps project.

The second significant challenge related to a shortage of useable data on implementation costs from the literature and, where data were available, framing the costs at a scale of application suitable for the sites making up each industrial sector. As a result of this, some of the measures contributing the most potential should be scrutinised further from a cost point of view when considering using the data for a particular measure at a particular site.

2 Introduction

2.1 Background and policy context

In the autumn of 2023, Ricardo Energy & Environment was commissioned by the Department for Energy Security and Net Zero (DESNZ) to update the evidence base related to the potential for industrial EE improvements in the United Kingdom. Thinks Insights were a subcontractor to facilitate workshops/interviews.

This work builds upon work carried out in 2015 under the project: Industrial Decarbonisation & EE Roadmaps to 2050. This project considered all of the energy-related levers for reducing industrial carbon emissions[7], including EE, Carbon Capture Utilisation and Storage (CCUS) and fuel switching.

This project is concerned only with updating the evidence base relating to the potential for EE to reduce carbon emissions in industrial processes. The potential for the other decarbonisation levers applying to industry, i.e. CCUS, fuel switching and resource efficiency, are considered separately in DESNZ modelling of industrial decarbonisation pathways.

There are interactions between the different industrial decarbonisation levers which have implications for the accurate estimation of the overall carbon reduction potential from EE measures, i.e., measures may be less or more viable depending on wider fuel switching scenarios/ decarbonisation pathways. For example, heat recovery EE measures become less relevant as process heat is increasingly generated using electricity instead of fuel combustion. These interactions were acknowledged so adjustments could be made when applied to the modelling.

The quantitative results of this work have been provided by DESNZ to the Climate Change Committee (CCC) and were used by the latter in its work to advise government on the setting of the 7th Carbon Budget (CB7) which runs from 2038-2042. The qualitative results, especially those relating to barriers to and enablers of the adoption of EE measures, are being closely considered by DESNZ in its review of the industrial EE policy landscape and future policy development.

2.2 Research purpose and research objectives

The aim of this research is to update data and information currently held by government relating to EE potential in UK industry. The evidence updated relates to those factors which need to be known to quantity the potential for EE to reduce industrial energy consumption out into the future, to understand the costs of doing this and the barriers facing the implementation of EE improvements to be realised. Consequently, this research has sought new data and information to allow the following to be achieved:

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[7] Carbon emissions measures as carbon dioxide equivalents (CO2e) – converting the climate impact of different greenhouse gases into the equivalent amount of carbon dioxide.

1. **To update and improve the list of EE measures available to the seven main industrial sectors**. This means, where necessary, identifying new measures which have become available since the 2015 roadmaps work. Moreover, it means, for the full schedule of measures, sourcing updated estimates for capital expenditure (CapEx), operating expenditure (OpEx) and installation costs as well as estimates of electricity and Fuel for heat savings achievable. In order for the measures to align with DESNZ wider decarbonisation modelling, the measures have been further characterised:
    - Mapping the measures to existing industrial processes observed.
    - Identifying cases of mutual exclusivity between measures, so that potential is not overestimated.
    - Identifying which measures overlap with deeper decarbonisation options such as fuel switching and, for those not overlapping, whether and how their adoption might be affected by these deeper decarbonisation actions.
    - Identifying which measures effectively constitute measures already taken into consideration by DESNZ via earlier studies into the potential for energy reduction via resource efficiency.
2. **To update information on the current adoption of the updated EE measures, the maximum technical potential for each measure to be adopted and a range of scenarios for the future adoption of the measures.** This means obtaining information which effectively sets upper bounds on the energy savings deliverable by each measure and allows savings to be estimated for more realistic outturn scenarios.
3. **To update and augment evidence relating to the barriers to the uptake of the identified EE measures**. This is important as it informs DESNZ of policy interventions that could lead to higher EE measure uptake and also forms the basis for defining EE adoption scenarios based on continued operation or alleviation of the barriers.
4. **Gather evidence related to the potential for EE in the parts of industry not included in the 8 main sectors from 2015. This part of industry is known in this study as “Other Manufacturing” (OM).** This means, for Other Manufacturing, gathering evidence, with the same structure as that gathered for the 8 main sectors, but disaggregated in a way which reflects the diversity of processes within Other Manufacturing, whilst still allowing an evidenced based estimation of the EE potential in this part of industry. An evidence-based approach to estimating the potential for EE in OM has not previously been undertaken.

2.3 Research scope and definitions

The scope of this research relates to the technical and economic potential for EE improvements in the manufacturing sectors contained within SIC2007 10-33. Measures considered were focussed on industrial processes and technologies that reduce energy per unit of throughput. As such, measures do not include building EE measures (i.e. smart building management systems or upgrades to building fabric) or behavioural measures. The time horizon adopted is for potential out to 2050.

A focussed approach for potential has been taken for the seven most energy intensive industrial sectors, in line with the 2015 research. These sectors are: Iron & Steel, Cement, Chemicals, Food & Drink, Paper, Glass and Ceramics. It should be noted that, due to the unique challenges of undertaking this research in the UK Refining sector, the EE potential at refineries is covered in a separate report facilitated by Fuels Industries UK (FIUK). For the part of manufacturing not covered by the seven main sectors (plus Refineries) – known here as Other Manufacturing, OM - we have undertaken a higher-level analysis. For some sectors in OM, we have analysed the EE potential for cross-cutting EE measures, widely applicable across industry. For some of the larger sub-sectors in OM, we have taken a more bottom-up approach to identifying EE potential, which is justified by the presence of very specific processes in these sub-sectors.

Table 3: SIC codes applied to each sector

Sector	SIC code (2007)
Ceramics	23.2 to 23.4
Food & Drink	10 to 12
Paper & Pulp	17.1
Chemicals	20 to 21
Iron & Steel	24.1 to 24.3
Glass	23.1
Cement	23.51
Lime	23.52
Other Manufacturing	12 to 16, 18, 22, 24.4 to 24.5 (excluding 24.46), 25 to 33

Detailed SIC codes applying to each sector are given in the specific sector chapters.

Various definitions need to be understood in order to follow the modelling methodology and to accurately interpret the modelling results. These are listed below:

- **Adoption in 2024 –** This refers to the extent to which an EE measure is currently taken up. In the model this is expressed as an estimated percentage of the throughput passing through a process to which the measure has already been applied.
- **Adoption in 2030/ 2040/ 2050 –** This refers to estimates of the uptake of the EE measure in the future for different scenarios. As with adoption in 2024, this is expressed in the model as an estimated percentage of the throughput passing through a process to which the measure would be applied for the scenario under consideration. Estimates were provided in 10-year increments for 2030, 2040 and 2050.
- **Applicability –** This is the maximum extent to which an EE measure can be applied to a process across a given sector at the time of the study. The applicability rate takes into consideration technical barriers for adopting EE measures. This is expressed as an estimated percentage of the throughput passing through a process to which the EE measure could be applied.
- **Category** – This is a sub-set of total sector energy use and describes the energy consumed within either a specific process carried out within the sector, or a sub-sector contained within the main sector, for example dryers in the paper & pulp sector. Each category has a baseline energy consumption which is in turn resolved into electricity and Fuel for heat generation. EE measures (see below) are applied to categories.
- **EE Measure** – This is a physical intervention which, when applied to a category, reduces the category's electricity consumption, Fuel for heat consumption or both.

Percentage electricity saving – This only applies to certain EE measures and categories and is the percentage of the category's electricity consumption that can be saved by the application of the EE measure in question.

Percentage Fuel for heat Saving – This only applies to certain EE measures and categories and is the percentage of the category's Fuel for heat consumption that can be saved by the application of the EE measure in question. The percentage saving is compared to baseline energy consumption for the category of energy consumption within the sector process.

Dependent Measure – Dependent measures are EE measures whose adoption would be affected by action taken to make progress towards deep decarbonisation, such as fuel switching or CCUS. An example of a dependent measure would be a measure related to recovery and reuse of heat from combustion against a background where deep decarbonisation may be pursued via the electrification of process heat – electrified heat consuming processes, by their nature, produce less waste heat than processes heated via the combustion of a fuel.

Independent measure – An independent measure is an EE measure whose adoption is not expected to be affected by progress made towards deep decarbonisation, such as fuel switching or CCUS. Examples of independent measures are those associated with processes which are already driven by electricity, such as compressed air and other processes driven by motors.

Business-as-Usual (BAU) – This is the name given to one of the adoption scenarios and describes future adoption of EE measures under an assumption that current investment preferences and criteria are maintained, and the policy landscape and economic outlook in which those investments take place also remains unchanged.

Maximum Technical Potential (Max Tech) - This is the name given to one of the adoption scenarios and describes future adoption of EE measures under an assumption that all non-technical barriers to its adoption are removed.

Non-Technical Barriers – These are barriers to the implementation of EE measures which are not technical in origin. They are predominantly barriers obstructing the implementation of EE measures which relate to payback or the difficulty with accessing finance to implement EE measures.

2.4 Methodology

The approach taken involved carrying out literature reviews for each sector, followed by interviews with stakeholders to test findings and evidence gaps from the literature reviews. At this point, to manage the scope of the work, a prioritised approach towards the EE measures was adopted, whereby EE measures with the greatest relevance and potential to save energy within each sector were identified and carried forward for detailed examination during stakeholder workshops. In order to identify these ‘prioritised’ measures, questionnaires were circulated to stakeholders soliciting information relevant to EE measure prioritisation and other information to fill gaps in EE measure characterisation. The literature review, interviews and questionnaires were all used to produce a list of ‘prioritised’ measures with preliminary characteristics for discussion during the workshops. Workshop discussions resulted in a consensus being reached on the prioritised EE measure characteristics and other parameters used in a model to estimate EE potential for industry. ‘Non-prioritised’ measures, which were included in the 2015 study, were carried forward to modelling but were only updated in respect of CapEx.

2.4.1 Literature review

2.4.1.1 Literature review methodology

A structured literature review was carried out for the seven main sectors plus some targeted sub-sectors for Other Manufacturing. A data collection template was developed to capture the characteristics of the data sources selected and the EE measures identified. The research questions this work sets out to answer were analysed and data and information needed to answer these questions were defined and installed in the data collection template.

Taking into consideration the types of data and information needed to answer the research questions, experts from the Ricardo team proposed search terms to apply to literature sources. These were subsequently refined following consultation with DESNZ.

The literature consulted comprised both documents already known to Ricardo experts and DESNZ, and documents uncovered from a search of established academic databases using the agreed search terms. The academic databases used included: Google Scholar, ISI Web of Science, and Science Direct. Uncovered sources were filtered using quality criteria including currency (how recent the paper was), geographical relevance and credentials of the institution producing the paper. Papers meeting the quality thresholds were then carried forward for detailed review. Data and information that was relevant to the research were recorded in the relevant fields of the data collection template.

To be consistent with the scope of this work, measures identified from the literature were filtered to remove those that relate to fuel switching, resource efficiency and CCUS.

The process of identifying EE measures from the literature produced many results for essentially the same measure, but which had different names. In order to manage the volume of data, measures were individually rationalised into groups using expert judgement, with measures in a group representing essentially the same physical intervention in the same sector. For example, two measures that appear different but are rationalised into the same group are motors and drives, and VSDs. Energy savings and, where available, CapEx and OpEx for these measures were collated according to group.

Finally, the rationalised measures were analysed against the EE measures identified in the 2015 study and measures deemed qualitatively different for those in the earlier study were carried forward as new measures.

2.4.1.2 Main findings

The salient findings from this exercise were:

- In most cases, information relating to costs to implement the measure were missing, thus placing a reliance on later stakeholder engagement stages to fill these gaps.
- The was a near universal absence of data and information relating to the current adoption of the EE measures in UK industry, again placing heavy reliance on later stakeholder engagement to provide these inputs for the modelling.
- While there is data available on the savings that could be delivered by the measures, information on whether this was electricity or related to heat was often missing, and so expert judgement was required to make this distinction.
- Careful consideration of the measures was necessary in order not to cut across earlier DESNZ projects related to industrial decarbonisation derived from fuel switching, CCUS and resource efficiency. Expert judgement therefore had to be applied to establish whether the measure in question was essentially related to these deep decarbonisation levers and, where this was found to be the case, removed from further consideration.
- To manage the volume of measures identified in the literature, it was necessary to go through a rationalisation process which grouped together measures representing essentially the same physical intervention.

2.4.1.3 Outputs per sector

After passing through the filtration and rationalisation steps discussed above, the table below presents the main findings from the literature review for each sector in terms of number of sources identified, the quality of these sources, the geographical origin of the sources and number of rationalised EE measures carried forward after filtration.

Table 4: Summary of results from literature review for each sector

Sector	Sources Identified	Source Quality	Geography of Source	No. of Rationalised EE Measures	New EE Measures
Food & Drink	126	High: 22 Medium: 76 Low: 28	UK: 12 EU: 38 OECD:45 North America:15 China:11 Total: 121	11	4
Paper & Pulp	28	High: 2 Medium: 12 Low: 14	UK: 4 China: 24	36	8
Chemicals	32	High: 5 Medium: 26 Low: 1	UK: 3 EU: 28 OECD: 1	7	2
Ceramics	67	High: 31 Medium: 21 Low: 15	UK: 15 EU: 25 OECD: 27	32	7
Iron & Steel	60	High: 20 Medium:28 Low:12	UK: 7 EU: 31 OECD:22	26	12
Glass	17	High: 2 Medium: 3 Low: 12	UK: 11 EU:2 OECD: 4 Total: 18	24	16
Cement	15	High: 8 Medium:7	UK: 4 EU: 3 Worldwide: 9 Total: 16	20	16

2.4.2 Interviews

2.4.2.1 Key Stakeholders Selected

Despite the extensive literature review undertaken, there were still substantial gaps in the data and information that was needed to answer the key research questions. This put more emphasis on the subsequent interview stage to fill gaps in data.

The gaps from the literature reviews informed the development of specific questions which were implemented in interview scripts, aimed at a diversity of stakeholder type. The nature of these gaps was varied and so to cover the gaps and access a range of perspectives, a wide range of stakeholder types were selected for interview. The types of stakeholders interviewed included: sector associations, operators within the sector of interest, consultants and academics working in the field of industrial EE and equipment suppliers.

For each stakeholder type and sector under consideration, a bespoke interview script was constructed, concentrating on the technical areas where the stakeholder was most likely to add value. Consequently, numerous unique interview scripts were generated.

2.4.2.2 Interviews Carried Out

Table 5 summarises the number of interviews of each stakeholder type carried out for each sector.

Table 5: Summary of interview participants per sector

Sector	Sector Association	Operators	Academics/ Consultants/ Suppliers/ Other
Food & Drink	Food and Drink Federation Cold Chain Federation	Dale Farm Diageo Long Clawson Dairy Ltd Devro British Sugar	Evonic
Paper & Pulp	Confederation of Paper Industries	Northwood Tissue WEPA Smurfit Kappa Palm Paper DS Smith	Suez
Chemicals	Chemical Industries Association	Solenis Ineos Acetyls Victrex Dow Silicones Syngenta CF Fertilisers GEO Specialty Chemicals Tronox	Loughborough University University of Cambridge Green Alliance Centre for Process Innovation
Ceramics	Ceramics UK	None (SA preference)	None
Iron & Steel	UK Steel	Liberty Steel Celsa UK British Steel Tata Steel	Zushu Li (Warwick University) Jon Bolton (Materials Processing Institute)
Glass	British Glass Manufacturers' Confederation	Encirc St Gobain	Glass Futures Glass Technology Services
Cement	Mineral Products Association	Breedon Cemcor CEMEX Aggregate Industries	University College London University of Cambridge Carbon Upcycling Expedition Engineering
OM - Plastics	British Plastics Federation	None	None

Sector	Sector Association	Operators	Academics/ Consultants/ Suppliers/ Other
OM - Rubber	British Tyre Manufactures' Association	None	None
OM - Gypsum	Gypsum Products Development Association	British Gypsum	None
OM - Lime	Mineral Products Association	None	None

2.4.2.3 Thematic Analysis

In order to extract findings from the interviews to inform the prioritisation of EE measures, important considerations for modelling, interpretation of the results and findings relating to barriers and enablers to EE implementation, a thematic analysis of the interviews was carried out. This exercise provided more detailed information on why particular stakeholders may or may not consider implementing certain EE measures.

The main themes with a bearing on interpreting the results and understanding the nature of barriers at play within each sector were logged in tables. The importance of any given theme was determined by a combination of the frequency with which it was mentioned, the expertise of the stakeholders who mentioned it, and the relevance of the theme to the modelling. Any knowledge gaps, unexpected insights and key barriers/enablers were also recorded in the thematic analysis for a comparison against evidence/evidence gaps from the literature review.

These themes were used to inform the design and areas of emphasis for the Questionnaire and Workshops.

2.4.3 Questionnaire

Questionnaires were developed and distributed to a wide number of stakeholders to help fill gaps remaining after the literature review and interview stages and to assist with workshop design and prioritisation of content and EE measures for discussion during workshops. Questionnaires were developed using Qualtrics software, which allowed the collation of results.

Working with project partners, Thinks Insight & Strategy, the questionnaires were tailored to allow specific areas of uncertainty to be explored. This meant that the questionnaires differed from each other. Nevertheless, the common areas consulted upon via the Questionnaires were:

- The main energy consuming processes within the sector and the approximate apportionment of electricity and Fuel for heat across these processes
- The relevance of the EE measures, as identified during the literature review and refined following the interview stage

- Whether there were any EE measures missing of importance to the sector under consideration
- The dependency of the EE measures on deep decarbonisation
- The reasonableness of the estimates of energy savings for each EE measure that the literature and interviews had uncovered
- The reasonableness of the estimates of CapEx for each EE measure that the literature and interviews had uncovered
- The maximum energy saving that stakeholders considered possible from each process (Category)
- The current adoption of each EE measure (see Research scope and definitions)
- The current applicability of each EE measure (see Research scope and definitions)
- Feedback on fuel prices, which is used to assess payback information

The response to these questionnaires was low. Nevertheless, responses allowed for the most important EE measures to be identified and prioritised for consideration during the workshops, the revision of existing energy savings and CapEx estimates for individual EE measures and proposed estimates of adoption and applicability of measures.

Overall, the research up to this stage established a proposal for each parameter of each measure, which were then tested in the workshops.

2.4.4 Workshops

Seven interactive 3 hour[8] workshops were held online. Attendees included sector association representatives, operators in each sector and some consultants.

Workshops were facilitated by Thinks Insight & Strategy using interactive boards on Mural software. Mural allows the same content to be seen by workshop attendees and for them to interact with this content by leaving comments in the form of virtual Post-it Notes. In agreement with stakeholders, all workshops were recorded and Post-it Note comments stored for later reference.

Interactive content was tailored to each sector to reflect important distinctions highlighted in earlier stages of the research. Therefore, the workshops varied slightly for different sectors. Nevertheless, the following exercises were common across all workshops:

- Validation of proposed main energy consuming processes and proposed split of electricity and Fuel for heat across these processes
- Validation of proposed prioritised EE measures
- Discussion of proposed CapEx and energy savings values for the prioritised EE measures
- Discussion of proposed payback categories for each EE measure
- Discussion of proposed adoption and applicability values for individual EE measures

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[8] The Ceramics workshop was only 2 hours, and was split into three parallel sessions for its respective sub-sectors

- Discussion of the relevance of key barriers to EE measure adoption uncovered during earlier stages of the work and other barriers deemed important by the stakeholders
- Development of adoption scenarios for the EE measures under BAU and Max Tech scenarios.

Comments received from stakeholders via the mural board and workshop recordings were analysed in detail to extract the values of key variables needed for the modelling of EE potential. These values represent the consensus arrived at during the workshop or the average value of responses. In some cases, where consensus could not be achieved, the same stakeholders were consulted later to obtain clarifications. The confidence level of responses was also accounted for, i.e. whether a response was a ‘best guess’, or based on first-hand knowledge, with the latter afforded greater consideration. Whether a response was site-specific, or sector wide and therefore more broadly applicable, was also considered.

Final variable values were recorded against each sector’s EE measures in an Excel workbook . This document contains written justifications for the variable values recorded and red-amber-green (RAG) ratings of the values according to the level of agreement achieved across stakeholders, the level of confidence in the response, and the number of data points on which the recorded value is based.

2.4.5 Handling of large number of EE measures

The large number of EE measures identified during the literature review and the need to create a short-list of EE measures was discussed previously. Nevertheless, in some sectors, the short-list of EE measures remained large, therefore a process of prioritisation was necessary to manage scope when working with stakeholders during the workshops. Prioritised measures were those which, according to pre-workshop information, were likely to have the largest potential for energy savings and which feedback from stakeholders indicated were the most relevant in the UK context. It is in respect of prioritised measures that updated values for adoption in 2024, future adoption in 10-year increments for 2030, 2040 and 2050, as well as applicability and costs were sought during the Workshops. Those measures which were not prioritised are primarily informed by the 2015 research findings.

2.4.6 Handling Interaction of EE with Deep Decarbonisation (DD)

As emphasised throughout this report, the focus of this study is to estimate the potential for reductions in industrial energy consumption purely from EE measures. However, industry is also embarking on actions to make cuts in carbon emissions via fuel switching and CCUS. These will eventually have a far more significant impact on industrial carbon emissions than EE measures and so must not be discounted when thinking about how EE measures could be adopted in the future.

Fuel switching and CCUS have the potential to affect the adoption of EE measures identified in this work. An illustration of this is the attitude towards investment in the recovery and reuse of heat from a process where the heat is generated by the combustion of a fuel. Electrification of heat for the process produces significantly less waste heat and would, therefore, make any heat recovery asset a stranded asset. This will affect the attitude of a site contemplating heat recovery now if it believes that it will electrify heat in the future.

To capture this interaction between EE and DD, EE measures are categorised according to whether they are “Dependent” or “Independent”. Dependent measures are those whose adoption has the potential to be affected by fuel switching and CCUS, while Independent measures are those for which, all other things being equal, the adoption can be assumed to be the same with or without DD being pursued in the background.

We captured the impact of DD on dependent measures during the workshops by asking stakeholders to frame their estimates of the EE measure adoption under BAU and Max Tech in light of what they believe will be the DD trajectory of their sector.. The assessment on which EE measures were Dependent or Independent are listed in the respective sector chapters.

3 Challenges and limitations of the work

Throughout the work we encountered challenges and certain limitations of the approach taken have come to light, which have mostly overcome by adopting a flexible approach. These challenges and limitations essentially fall into the categories presented in Table 6, which also details how the issues were overcome or mitigated.

Table 6: An assessment of the challenges and limitations associated with the work, impact and mitigation

No.	Theme	Issue	How was this addressed?
1	Availability of evidence from literature	a) Limited quantitative data available (particularly CapEx) and data on Applicability and Adoption of EE measures in UK industry b) Varied quality of literature across the sectors.	CapEx was updated where literature allowed, otherwise 2015 estimates were relied on (inflated to 2024 prices, in the case of CapEx) and checked with stakeholders. Suppliers were contacted but very limited response was received. Applicability and adoption of EE measures was checked with stakeholders during workshops. Literature Review sources were ranked according to currency, author credibility and geographical relevance. Highest ranking sources were used.
2	Industry engagement	a) Data, information and insights needed spread across different stakeholder types b) Lack of stakeholder availability/time available. c) Confidentiality concerns.	A wide range of stakeholder types were identified and engaged, including industry Sector Associations, operators of industrial sites, consultants and academics working in the field of industrial EE and equipment suppliers. Efficient, focussed and very carefully designed interview, questionnaire and workshop material used. Maximum flexibility and perseverance on part of researchers in following-up with stakeholders and accommodating the latter’s availability. Written assurance given at the outset on anonymity and that findings would be presented in a non-attributable form. This assurance was repeated at the start of interviews and Workshops.

No.	Theme	Issue	How was this addressed?
3	Complexity of capturing EE potential in a form that can be modelled.	a) Specific parameters are needed to describe EE potential in a way that reflects its size and applicability so that it can be modelled. These parameters need to have very specific meanings to avoid ambiguity among stakeholders and appropriately capture EE potential. Examples of these include: Adoption in 2024, Adoption out to 2050, Applicability, percentage electricity savings, percentage Fuel for heat savings and CapEx for representative site.	A sense of workability of parameter definitions was tested during interviews and amendments made where necessary. Definitions were clearly spelt out in Glossary of terms provided for questionnaires and during workshops. It should be noted that these amendments could not always perfectly address the issue, as it was a challenge for stakeholders to adjust their responses to an artificial 'average' scale, when they are familiar only with the scale of their own site. A preferred method would have been to frame savings/ CapEx per scalable unit, but literature didn't allow for this.
4	Heterogeneity of sectors	a) Chemicals and Food & Drink sectors are very heterogeneous in terms of process, product and, therefore, relevant EE measures.	Interviews with sector associations were carried out first to gauge and understand the scale of the heterogeneity issue. Interviewees and workshop attendees were selected to capture, in the best way possible, the heterogeneity issues within the confines of the project timescale. EE measures were aggregated to have the maximum possible relevance to the sector as a whole.
5	Scope of research	a) Scope of the work is wide, but time and resources limited.	EE measures were rationalised down using expert judgement. The significance and relevance of rationalised measures was established through testing with stakeholders. Prioritised measures (those with the greatest EE potential and of most relevance to the sector) were identified and carried forward for detailed discussion during Workshops. Focussed stakeholder material was prepared.

No.	Theme	Issue	How was this addressed?
6	Interactions of EE measures with other deep decarbonisation levers, such as fuel switching and CCUS.	a) Wider moves towards deep decarbonisation influence the uptake of EE measures. These interactions are sometimes significant and difficult for stakeholders to conceptualise.	Prior analysis carried out to identify which EE measures are susceptible to interaction with deep decarbonisation, i.e. which EE measures' adoption could be influenced by deep decarbonisation. Explanation of the interactions issued to stakeholders and presentation of interacting measures during Questionnaires and Workshops. Stakeholders asked to consider the deep decarbonisation backdrop when estimating EE adoption rates.

4 Overall results - Qualitative

4.1 Availability and usefulness of evidence from literature

The literature relating to opportunities for EE in the main sectors examined is extensive and is often provided in the context of wider decarbonisation, such as fuel switching and resource efficiency. It has therefore been necessary to carefully separate the effects of EE from those of deeper decarbonisation when identifying EE measures and extracting from the literature characteristics of EE measures, such as energy savings. The methodology and results of the literature review, including number of sources and the quality of these sources, is presented in 2.4 Methodology.

4.2 Literature Review

The literature review produced a great many EE measures which on first assessment appeared to be distinct from each other. This posed a challenge in terms of the volume of data that had to be handled. However, when viewed in the round, it was clear that the EE measures could be rationalised into a much smaller number of measures, with each individual rationalised measure representing a distinct physical intervention in an industrial process. This made the handling of data easier. Rationalisation of EE measures also allowed a meaningful mapping against EE measures identified in 2015 to be undertaken, which in turn made it possible to identify EE measures that were genuinely new to those modelled in 2015.

Even when considered in their detailed, unrationalised form, a very common finding from the literature review was that costs of measures were not provided in the literature. In such cases, we were reliant on stakeholder engagement at the Questionnaire and Workshop stages of the work to either provide views on how existing costs (identified in 2015) had changed in the intervening period or offer estimates of the costs of new measures identified in this work.

A lack of information in the literature on current levels of uptake of EE measures (Adoption) and the extent to which measures could eventually be adopted across the sector (Applicability) was almost universal. This meant that the research was entirely reliant on stakeholder input to source primary data on the values for these necessary modelling variables.

Information from the literature relating to energy saving from a particular EE measure expressed these measures on a variety of bases, including at the site and individual process levels and also per unit production. This necessitated careful consideration and translation into units used in modelling in order to be useful.

4.3 New EE measures identified

As well as updating the evidence relating to existing EE measures (i.e. those identified in the 2015 research project), an aim of this work has been to identify EE measures which were not considered then.

EE measure rationalisation, necessary to allow measure characteristics to be extracted from the literature allowed what appeared to be genuinely new EE measures to be identified. The numbers of such measures are provided in 2.4 Methodology.

The relevance of these new measures to UK industry was subsequently tested with stakeholders at interview and Questionnaire stages, including their suitability to the UK specific context and commercial availability. Those identified as relevant on these two grounds were shortlisted for discussion at the workshops and for inclusion when modelling sector EE potential.

4.4 Cross-cutting barriers to Adoption

Barriers to Adoption have been elicited at various stages of the research, including at the literature review stage, interviews and questionnaires. They have also been discussed during the workshops in the context of making distinctions between the BAU and Max Tech adoption scenarios (see above).

There are some specific barriers at the individual sector level that have been frequently cited, and these are listed in each sector’s specific section below. However, certain barriers have been cited frequently and across different sectors. These findings are valuable to Government in that they give an indication of where policy intervention could be most effectively targeted and, when taken together with the modelling output for different adoption scenarios, allow some quantified estimate of the benefit of the intervention to be made.

These common barriers (known as cross-cutting barriers) are listed below.

Technical

- Space constraints at older, urban situated sites hindering the development of EE measures requiring space (e.g. heat recovery projects).
- Significant risk if implementation of a measure causes disruption to the production line. This risk cannot always be mitigated against, with many measures often causing disruption outside of scheduled maintenance windows.
- Difficulties with sourcing external expertise, with trusted credentials relating to specific site processes, to identify and develop EE projects which site management has confidence in.

Organisational

- Lack of and decreasing supply of internal technical expertise (within organisations) necessary to identify, work up and champion individual EE projects is making it difficult to get EE measures off the drawing board and progressed.
- Additional time associated with information and data gathering to understand whether an EE measure is viable, and the management time required to interpret these data and information, often gets in the way of pursuing a perceived opportunity.
- Competition between EE projects and non-EE projects and (in the case of multi-national companies) competition between EE-projects across different countries, where the competing project is considered more profitable, is crowding out EE investments in the UK.

- Investment in EE measures can be especially difficult to justify when competing against strategic projects with longer term returns, such as increases in production capacity or improvements in product quality. This can crowd out EE projects with longer payback periods, resulting in only short payback period EE projects being considered for implementation.
- Long lead times and sudden changes in cost associated with components for EE measures creates risk with EE project planning and implementation.

Funding/Policy

- Combination of high investment costs and limited budget availability making it difficult to find capital for investment in larger EE measures.
- Uncertainty about future energy prices complicating the process of making the financial case for EE project implementation.
- Policy uncertainty making it difficult to make significant decisions regarding large EE investments, e.g. uncertainty about timing of availability of hydrogen complicating decisions relating to heat recovery projects. Specifically, where process heat is electrified in the future instead of being produced by low or zero carbon fuels (such as green hydrogen), heat recovery projects invested in now could become stranded assets and this makes sites reluctant to invest.
- Grant funding available from Government to reduce EE project payback from the operator’s point of view is too onerous to apply for. The suggestion has been made that grant funding schemes should be more collaborative and less competitive[9].

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[9] Since this project completed the Government has announced that there will be no further phases of the Industrial Energy Transformation Fund (IETF) and so the salience of this barrier has recently increased

5 Results by Sector

Below are the results of the modelling for each of the 7 main industrial sectors, as well as the collection of sectors contained within Other Manufacturing (OM). Percentage energy savings, both electricity and Fuel for heat, are measured against the baseline year 2024.

5.1 Sector 1 (Ceramics)

5.1.1 Definition and context

The Ceramics sector analysed in this work covers activities included in the following SIC (2007) codes:

23.2 Manufacture of refractory products

23.3 Manufacture of clay building materials (e.g. bricks and tiles)

23.4. Manufacture of other porcelain and ceramic products (e.g. sanitaryware, household ware and technical ceramics)

The ceramics industry in the UK uses approximately 4.5 TWh annually, with gas representing about 87% of the required fuel.[10] The manufacture of ceramics requires several energy-intensive processes, most notably firing which requires high temperatures between 1,000 to 1,500°C, sometimes up to 2,500 °C. Five processes have been targeted for the review of potential EE measures in this report:

- Compressed Air Generation
- Powder preparation (e.g. milling)
- Green component forming (i.e. extrusion)
- Green component drying
- Component firing

Ceramics UK is the trade association representing approximately 90% of the sectors emissions in the UK. According to the Ceramics UK decarbonisation Roadmap, the UK ceramics sector has £1.6bn of product sales, £600 million of which are export sales. Between 2003 and 2019, the sector reduced its Scope 1 and Scope 2 emissions by 47% to a value of approximately 1.25 MtCO2. In 2023 approximately 61% of all emissions were associated with fuels firing, 28% from process (from clays and additives) and 11% from electricity. Over 90% of ceramics installation in the UK are small or ultra small emitters, meaning that they emit less than 25ktCO2 per annum. The preponderance of relatively small-scale operations in the sector has implications for the availability of skills to identify and implement EE opportunities in the sector.[11]

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[10] Data supplied by CeramicsUK

[11] Ceramics Uk decarbonisation roadmap: Decarbonising UK Ceramic Manufacturing Roadmap - Technical Appendix — Ceramics UK

5.1.2 Literature Review

5.1.2.1 Salient Sector Specific Points

The ceramics sector is diverse, but is frequently separated out into the following sub-sectors:

- Heavy clay products (e.g. bricks, tiles and pipes)
- Whitewares (e.g. Sanitaryware and tableware)
- Refractories (insulating materials)
- Technical ceramics (a wide variety of speciality materials e.g. piezoelectric materials, dielectric materials and cutting tools)

Note: For the purposes of modelling EE savings we have considered refractories and technical ceramics together and heavy clay and whitewares separately. This is due to a current lack of separate information relating to refractories and technical ceramics.

The literature review has identified measures which imply that the main energy consuming processes across the sector can be considered to fall under the following broad categories:

- Powder preparation (process specifics will depend upon the end product)
- Green component formation (again, process will depend upon the end product)
- Green component drying (which may or may not use waste heat from component firing)
- Firing (which may be carried out in continuous or batch (intermittent) kilns)
- Finishing
- Utilities (e.g. hot water and compressed air generation)

However, many of the common processes have important differences, depending upon the sub-sector of the end product. This means that the applicability of specific EE measures identified are limited to a particular subsector.

5.1.2.2 Sources identified and their relevance

The literature review for ceramics yielded 67 sources of various degrees of usefulness, sorted into high, medium and low relevance. Sources were rated based on a combination of factors, geographical relevance, author credibility, recency of the publication and availability of statistics on cost and energy savings potential. 31 out of the 67 sources were rated high, 21 were rated medium and 15 were rated low quality. The majority of the sources were from the European and British context, 25 and 15 sources respectively, whilst the rest were from other OECD countries. The literature was mostly taken from peer-reviewed sources published between 2006 and 2025, usually from academic institutions, equating to 53 sources. The rest of the literature was taken from expert authors, including industry associations and product manufacturers. The Ceramics UK decarbonisation roadmap has been a valuable resource in understanding the scale and distribution of operations across the sector, including the distribution of numbers of sites across the sub-sectors, their relative sizes in terms of emissions and the relative sizes of emission types (combustion, indirect and process).

The sources collectively present an understanding of the challenges and opportunities in achieving EE savings across the sector. Although most sources were targeted on specific decarbonisation technologies for ceramics, or cross-cutting techniques such as drying, there were some sources which provided information on barriers and drivers.

5.1.2.3 Conclusions from Literature Review – Gaps and Limitations

The main gaps identified during the literature review related to specific costs of EE measures and other quantitative data such as adoption and applicability of the EE measures. Consequently, the fieldwork was reliant on later engagement with stakeholders (questionnaires and workshops) to derive values for the modelling inputs.

Regarding identification of EE measures relevant to the sector, the literature revealed a large number of very specific measures which had to be resolved down into broader categories constituting the same physical intervention in order to manage scope. The literature review identified a number of EE measures which were distinct from those modelled in 2015, but feedback from stakeholders indicated that these were not of sufficiently salient relevance to warrant their inclusion in the schedule of measures that were eventually modelled. These measures were:

- Roller kilns
- Tower mills for powder preparation
- Spray drying (various, e.g. increasing feed concentration/preheating feed)
- Hybrid powder mills
- Vertical kilns with microwave combustion

5.1.3Engagement

Engagement with Ceramics UK resulted in agreement to examine EE potential within the sector using the structures established during the 2015 project. A categorisation of sub-sectors was pursued that focused on products produced:

- Heavy Clays
- Whitewares
- Refractories and Technical Ceramics

Refractories and technical ceramics were considered together owing to a current lack of separate information relating to these two sub-sectors. Ceramics UK also provided sector energy consumption split by sub-sector which was adopted in the modelling.

Other engagement with the sector took the following forms:

- One interview and several meetings with the sector association (Ceramics UK) during which we discussed an agreed the most appropriate way to engage with the sector
- Questionnaires, with responses received from 7 stakeholders
- One 2-hour workshop attended by Ceramics UK and 11 operators across building materials, refractories, sanitaryware and household ware. Parallel stakeholder sessions were run for heavy clay, whitewares and refractories/technical ceramics.

5.1.4 Main categories of Energy Use

For the purposes of modelling energy savings, the Ceramics sector has been resolved into the following sub-sectors: Heavy clay, whitewares and refractories/technical ceramics. The proportion of sector energy consumed across these sub-sectors is as shown in Table and is based on data provided by Ceramics UK. Heavy clays is the largest consumer, accounting for around 80% of gas use and 50% of electricity use. Refractories/Technical ceramics accounts for the second largest share of electricity usage, at around 30% but a marginally lower proportion of gas use compared with White Wares.

5.1.5 Prioritised measures

As discussed in 2.4.5, in order to handle scope, EE measures have been split into Prioritised and Non-Prioritised measures, with the former receiving increased scrutiny during Workshops to update the variables needed for modelling.

Information was obtained on prioritised measures for each of the three ceramics subsectors separately in breakout groups from the main workshop. All participants contributed to discussions relating to measures applicable across all sub-sectors. Sub-sector breakout groups discussed those measures applying only to the sub-sector under consideration.

Table 7: Share of each fuel type in the baseline attributed to each category in the ceramics sector

Category	Percentage of Total Sector Energy Use (%)*				
	Electricity	Gas	Coal	Oil	Biomass
Heavy Clays (Brick) (GWh)	53%	79%	100%	90%	100%
Refractories/Technical Ceramics	30%	9%	0%	10%	0%
White Wares	18%	12%	0%	0%	0%
Total Sector Energy	**100%**	**100%**	**100%**	**100%**	**100%**

*Values have been rounded and may not sum to 100%

One of the prioritised EE measures - Adopt available lowest carbon process (BAT, new kilns) - has the effect of precluding the adoption of some of the other measures because the BAT kiln measure is assumed to incorporate, by default, some of these other measures. This means that the number of cases where the other measures are applicable is less in the wake of adoption of the BAT measure than before it. Consequently, the adoption of these other measures is adjusted down in proportion to the adoption of the BAT measure at the year under consideration. The other measures whose adoption is adjusted down in this way are known as “BAT kiln dependent measures”. This dependency is indicated in the table below.

Table 8 lists the prioritised measures, the categories of energy consumption to which they apply, their dependency on Deep Decarbonisation scenarios and their dependency on the adoption of the BAT kiln measure. Measures that are dependent on the BAT kiln measure are that all adoption rates are affected (reduced) when implemented after the BAT kiln.

Table 8: EE measures prioritised for the Ceramics sector and dependency on deep decarbonisation scenarios

Measure Name	Measure Description	Ceramics sub-sector relevance	Deep Decarbonisation Dependency	BAT Kiln Dependency
Reduce radiant, convective and hot gas losses and leakage	Improving the quality of insulation and ensuring that kiln walls and gaps are properly sealed	All sub-sectors	Independent	Dependent
Improve control of process	Closer monitoring and control of heat-using processes to reduce energy consumption in all subsectors	All sub-sectors	Independent	Dependent
Improve combustion efficiency	Adoption of new burner technology, burner optimisation and burner control technology to enhance fuel efficiency	All sub-sectors	Dependent (electrification)	Dependent
Adopt available lowest carbon process (BAT, new kilns)	The replacement of older kilns with BAT kilns at the time of replacement.	All sub-sectors	Dependent (electrification)	N/A
Improve heat use by regenerative processes	Capture of waste heat and storage in a high heat capacity medium for later reuse	Heavy clays	Dependent (electrification)	Dependent
Improve heat capture	Capture of waste heat and storage in a high heat capacity medium for later reuse	Whitewares	Independent	Dependent
Optimisation of kiln circulation	Optimisation of flow of air through kilns	Whitewares	Dependent (electrification)	Dependent
Oxy-fuel firing/ oxygen enrichment	Reduction in the quantity of heat released by fuel combustions that is lost through the stack	Refractories and Technical Ceramics	Dependent (electrification)	Dependent

Measure Name	Measure Description	Ceramics sub-sector relevance	Deep Decarbonisation Dependency	BAT Kiln Dependency
Low mass kiln furniture	Reduces the amount of fuel required by reducing the amount of heat need to raise the temperature of the furniture to the required sintering temperature	Refractories and Technical Ceramics	Independent	Independent

5.1.6 Non-prioritised measures

The non-prioritised measures are listed in Table 9. For the purposes of modelling, none of these measures are treated as dependent on BAT kiln adoption.

Table 9: EE measures prioritised for the Ceramics sector and dependency on deep decarbonisation scenarios

Measure Name	Measure Description	Ceramics sub-sector relevance	Deep Decarbonisation Dependency
Apply VSD to variable duty pumps/ fans	Avoidance of energy wastage through throttling for variable loads	All sub-sectors	Independent
Organic Rankine Cycle (ORC) on heat recovery	Generation of electricity using waste heat	All sub-sectors	Dependent (electrification)
Low mass refractory for kiln cars	Reduces the amount of fuel required by reducing the amount of heat need to raise the temperature of the kiln cars	Heavy clays	Independent
Preheat water added for forming	Promoting formability and reducing heat demand for drying	Heavy clays	Independent

Measure Name	Measure Description	Ceramics sub-sector relevance	Deep Decarbonisation Dependency
Reduce air/product mass ratio	Increases the productive output of heat and hence reduces fuel consumption per tonne of product.	Heavy clays	Dependent (electrification)
Pulse firing of kilns	Maximises proportion of time burners firing at full power, where efficiency is optimised.	Refractories	Dependent (electrification)
Re-use heat regeneratively	Capture of waste heat and storage in a high heat capacity medium for later reuse	Refractories	Dependent (electrification)
Extreme condition refractory	Kiln insulation maintained in good condition for longer, thereby reducing heat losses	Technical	Independent
Re-use heat regeneratively	Capture of waste heat and storage in a high heat capacity medium for later reuse	Technical	Dependent (electrification)
Low mass refractory for kiln cars	Reduces the amount of fuel required by reducing the amount of heat need to raise the temperature of the kiln cars	Whitewares	Independent
Re-use heat regeneratively	Capture of waste heat and storage in a high heat capacity medium for later reuse	Whitewares	Dependent (electrification)

5.1.7 Key assumptions

As explained above, it is assumed that the BAT kiln measure is a major undertaking that would only be implemented at times of major kiln refurbishment. Some other EE measures would cease to be relevant in the immediate wake of implementation of the BAT kiln measure, because these other measures would be implemented by default as part of the BAT kiln measure.

5.1.8 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in Cross-cutting barriers to adoption. However, some barriers specific to the circumstances faced by operators in the ceramics sector came to light and these are listed below.

The following barriers were identified during the literature review:

1. Manufacturing, Managerial, and Infrastructural Concerns:

- Long investment cycles and operational lifespans of production assets (kilns) places limits on the opportunities for equipment improvements, which in turn pushes back in time when savings can be made.

2. Lack of Information, Knowledge, and Skills:

- Limited awareness and information about energy-efficient practices and opportunities, while a cross-cutting barrier not limited just to ceramics, was particularly acute at smaller ceramics sites.

3. Financial and Economic Disincentives:

- Reluctance to invest in energy-efficient measures with payback times above 3–5 years.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- The is a lack of knowledge and awareness of support available in the supply chain to identify and progress EE projects, especially for the smaller operators in the sector.
- Strict planning requirements can inhibit the implementation of EE measures which lead to significant alteration of infrastructure of plants.

5.1.9 Results

The tables and graphs below show the inputs and results of the modelling for the Ceramics sector. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an ‘average’ site within a sector. Broadly, the RAG ratings associated with the parameters can be interpreted as below:

- A red rating signifies low confidence, with limited or uncertain input from stakeholders and available data sources.
    - Parameters given a red rating should be viewed with caution and may have a large range.
- Amber ratings signify medium confidence where a small number of stakeholders may have given similar input, or some input was provided from a reputable source and there was a broad consensus from stakeholders, insofar as this was possible with the information available. Alternatively, there may have been some disagreement between stakeholders, and in such cases a midpoint was selected based on the assessment of the sector expert.
    - Amber rated parameters should still be viewed with some caution and uncertainty.
- Agreen rating signifies high confidence in the data presented with multiple stakeholders giving similar responses or agreeing that the data looked sensible, indicating a clear consensus.
    - Green rated parameters can be viewed as well-grounded estimates, however still carry uncertainties.

5.1.9.1 Key parameters derived

5.1.9.2

Table 10: Energy savings and CapEx

Measures	Energy Savings applied to	Elec Savings (%) (range) *RAG*	Fuel for heat savings (%) (range) *RAG*	CapEx for ‘average’ site (£, 2024 prices) (range) *RAG*
Reduce radiant, convective and hot gas losses and leakage	Cross Sub-Sector (Generic) Measure	0% (0%) *Green*	8% (6-10%) *Green*	£7,100,000 (£5,900,000 to £8,000,000) *Amber*
Improve control of process	Cross Sub-Sector (Generic) Measure	-1% (-2-0%) *Green*	2% (0-4%) *Green*	£390,000 (+/- 20%) *Amber*
Improve combustion efficiency	Cross Sub-Sector (Generic) Measure	0% (0%) *Green*	4% (3-5%) *Green*	£320,000 (£170,000 - £580,000) *Amber*
Adopt available lowest carbon process (BAT, new kilns)	Technical Ceramics	0% (0%) *Green*	15% (11-30%) *Red*	£1,300,000 (+/- 20%) *Amber*
	Heavy Clay			£3,500,000 (+/- 20%) *Amber*
	Whitewares			£2,700,000 (+/- 20%) *Amber*
Improve heat use by regenerative processes	Heavy Clay	0% (0%) *Green*	15% (10-20%) *Green*	£4,000,000 (+/- 20%) *Amber*

Measures	**Energy Savings applied to**	**Elec Savings (%) (range) *RAG***	**Fuel for heat savings (%) (range) *RAG***	**CapEx for 'average' site (£, 2024 prices) (range) *RAG***
Low mass refractory for kiln cars	Heavy Clay	0% (0%) *Green*	8% (6-10%) *Green*	£2,800,000 (+/- 20%) *Red*
Preheat water added for forming	Heavy Clay	0% (0%) *Green*	3% (2-4%) *Green*	£160,000 (+/- 20%) *Red*
Reduce air/product mass ratio	Heavy Clay	0% (0%) *Green*	8% (6-10%) *Amber*	£160,000 (+/- 20%) *Red*
Oxy-fuel firing/ oxygen enrichment	Technical Ceramics	0% (0%) *Green*	13% (11-15%) *Green*	£130,000 (+/- 20%) *Green*
Low mass kiln furniture	Technical Ceramics	0% (0%) *Green*	8% (6-10%) *Amber*	£130,000 (+/- 20%) *Green*
Improve heat capture	Whitewares	-2% (not provided) *Green*	7% (not provided) *Amber*	£100,000 (+/- 20%) *Green*
Optimisation of kiln circulation	Whitewares	0% (0%) *Green*	5% (not provided) *Amber*	£60,000 (+/- 20%) *Green*

Table 11: Applicability and adoption rates for the BAU and Max Tech scenarios

Measure	Subsector	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050	Max Tech 2030	Max Tech 2040	Max Tech 2050
Reduce radiant, convective and hot gas losses and leakage	Technical	90%	36%	40%	51%	44%	53%	43%	25%
	Heavy Clay			56%	60%	57%	69%	48%	27%
	Whiteware			38%	44%	33%	39%	39%	23%
Improve control of process	Technical	100%	80%	70%	67%	52%	53%	47%	28%
	Heavy Clay			71%	65%	63%	74%	48%	30%
	Whiteware			76%	64%	41%	72%	50%	26%
Improve combustion efficiency	Technical	85%	80%	71%	60%	47%	66%	44%	25%
	Heavy Clay			69%	65%	54%	74%	45%	26%
	Whiteware			67%	57%	37%	60%	45%	25%
Adopt available lowest carbon process (BAT, new kilns)	Technical	95%	10%	15%	28%	48%	21%	49%	72%
	Heavy Clay			14%	23%	37%	14%	47%	70%
	Whiteware			16%	33%	59%	28%	50%	74%

Measure	Subsector	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050	Max Tech 2030	Max Tech 2040	Max Tech 2050
Improve heat use by regenerative processes	Heavy Clay	100%	60%	56%	62%	63%	56%	48%	30%
Low mass refractory for kiln cars	Heavy Clay	90%	16%	No value provided	No value provided	No value provided	No value provided	No value provided	No value provided
Preheat water added for forming	Heavy Clay	40%	2.50%	No value provided	No value provided	No value provided	No value provided	No value provided	No value provided
Reduce air/product mass ratio	Heavy Clay	50%	20%	No value provided	No value provided	No value provided	No value provided	No value provided	No value provided
Oxy-fuel firing/ oxygen enrichment	Technical	70%	7%	31%	36%	26%	70%	20%	20%
Low mass kiln furniture	Technical	70%	21%	50%	0%	0%	70%	20%	20%
Improve heat capture	Whiteware	70%	40%	36%	36%	23%	25%	31%	18%

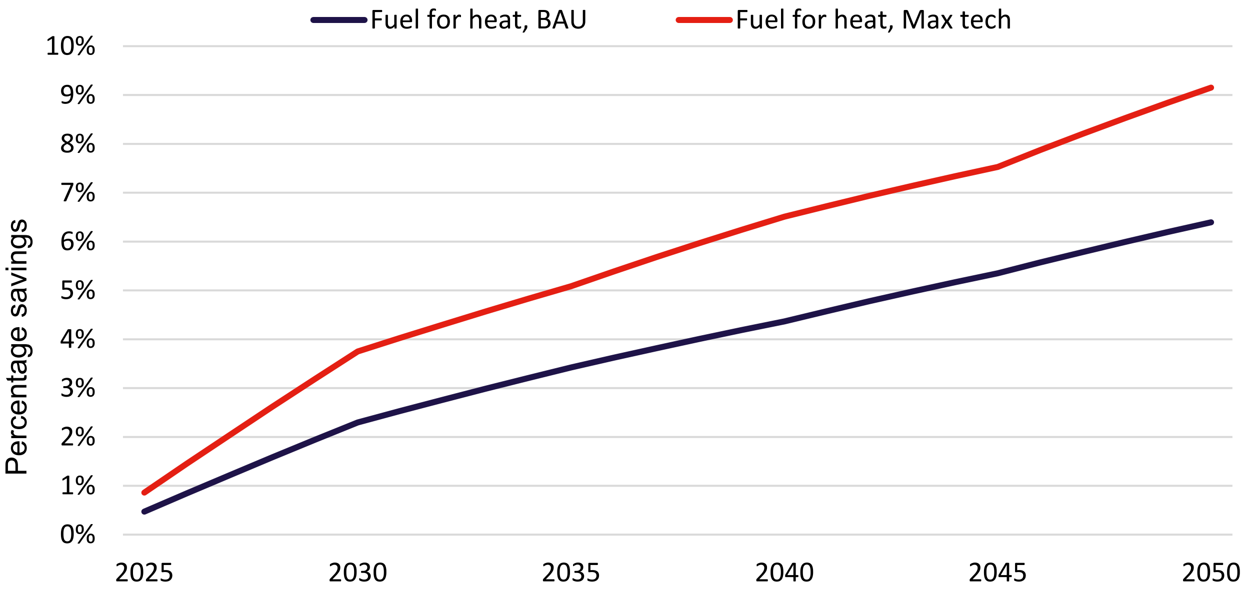
Measure	Subsector	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050	Max Tech 2030	Max Tech 2040	Max Tech 2050
Optimisation of kiln circulation	Whiteware	60%	5%	17%	27%	25%	29%	25%	16%

The data on adoption rates, percentage energy savings and the sector's baseline energy consumption by sub-sector were multiplied together to yield the results for Fuel for heat and electricity savings set out in the sections below.

5.1.9.3 RM2024 Fuel for heat Savings

Figure 1 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 1: Ceramics sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



Both scenarios show a comparative trend, with the rate of savings increases slowing after 2030 though Max Tech shows a greater increase up until this point. The Max Tech scenario hits a high of 9% in 2050 after a slight increase in the rate of savings, compared to 6.5% for BAU.

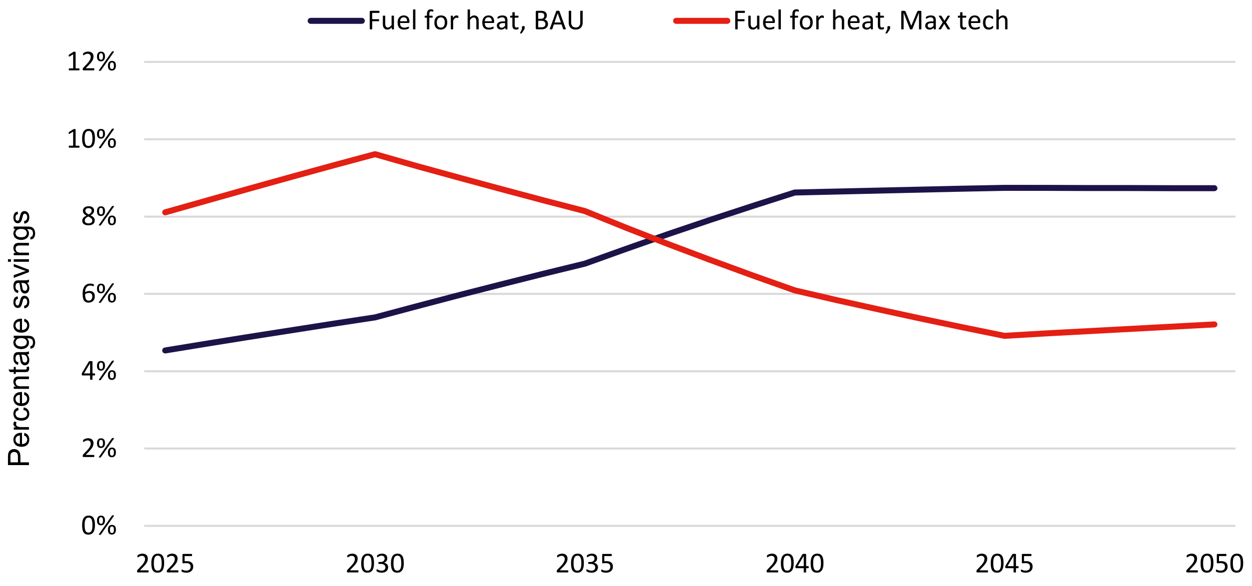
Adoption of BAT kiln at the time of kiln rebuild accounts for the largest direct savings in both BAU and Max Tech scenarios. Many other measures are technically linked to the BAT kiln measure and so are assumed to occur naturally when BAT kiln replacement takes place. Therefore, adoption of BAT kiln drives RM2024 emissions savings in the sector related to EE. The main difference between BAU and Max Tech trajectories for RM2024 Fuel for heat savings is due to costs and, therefore, payback of BAT kiln. Payback is long (5-10 years) and would therefore not be undertaken outside of normal kiln rebuild cycle. Under Max Tech these considerations are removed, and the rate of heat savings improvement would be accelerated. The linear trajectory of both BAU and Max Tech scenarios reflects the steady rate at which kilns age and become available for rebuilding, at which point the BAT kiln option becomes applicable.

Savings from other heat saving measures are secondary when compared against BAT kiln adoption.

5.1.9.4 RM2015 Fuel for heat Savings

Figure 2 shows the Fuel for heat savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 2: Ceramics sector (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



The trend lines shown are almost converse, with the Max Tech scenario showing higher savings initially, but reducing significantly out to 2050, from a peak of just below 10% down to around 5%. Whereas, the BAU scenario shows lower savings between 2025 and 2035, but higher savings of just under 9% by 2040, out to 2050.

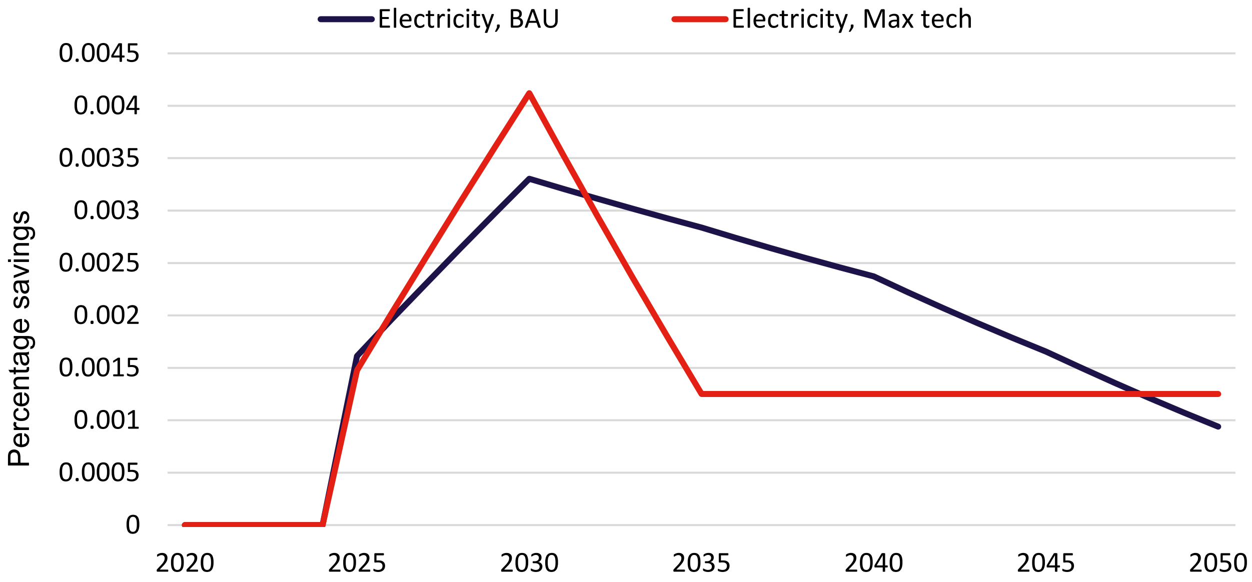
The Fuel for heat savings for RM2024 and RM2015 peak at broadly similar values. For example, under Max Tech, they both peak in the range at about 9-10%, but the time taken for this peak to be reached in RM2024 is longer, due to updated data from stakeholders on the rate of adoption of the EE measures, most notably the BAT kiln measure, for which the Fuel for heat savings percentage is also lower in RM2024 than in RM2015 (15% versus 20%). Under BAU, the max savings are slightly different with RM2024 peaking at just above 6% and RM2015 just below 9%. These differences, and the time taken for the maximum values to be reached, are again the result of updated adoption data from stakeholders and estimates of energy savings (especially for the BAT kiln measure).

The Fuel for heat savings trajectory is linear for RM2024 but for RM2015 it is irregular in shape. During this project, when gathering evidence on the future adoption of EE measures, we explicitly asked stakeholders to consider the deep decarbonisation (e.g. fuel switching) futures likely to unfold in their sectors and consider the effect of this upon the adoption of the EE measures under consideration. The savings trajectory presented in this project are reflections of these considerations. It is possible that the irregular shape of the trajectories in RM2015 are the result of a different approach to accounting for the interaction between EE measures and deep decarbonisation scenarios.

5.1.9.5 RM2024 Electricity Saving

Figure 3 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 3: Ceramics sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios

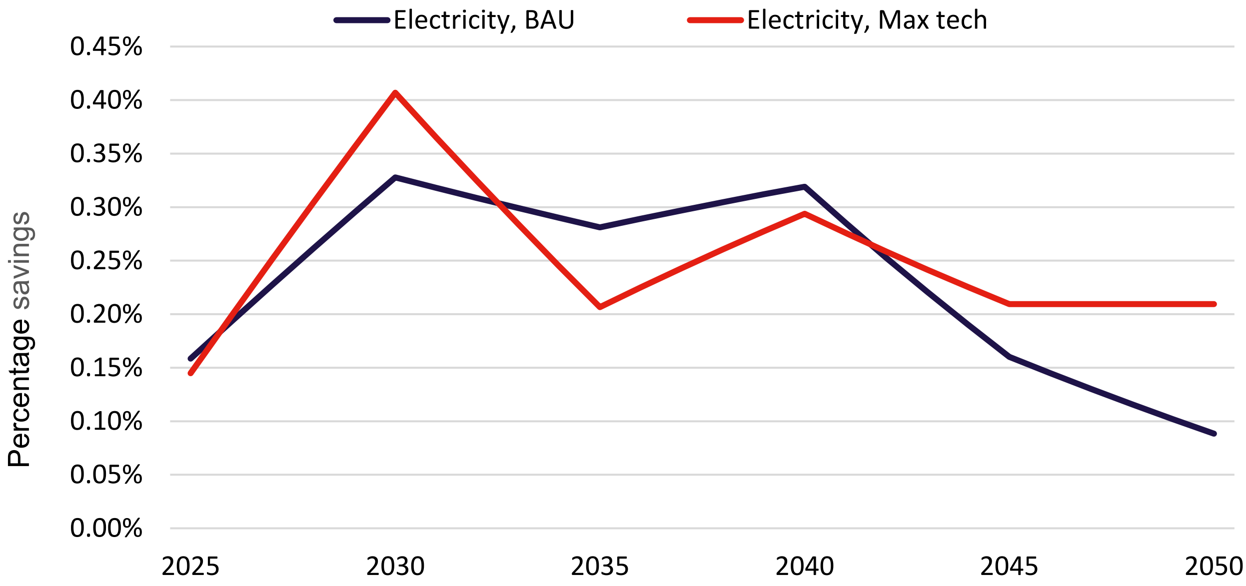


The electricity savings are modest (<1%) due to the fact that the overwhelming majority of energy saving potential associated with the measures is Fuel for heat. Some other measures which address the heat consumption (such as process control) are considered to consume more electricity in order to make possible the saving of heat, and this produces a reduction on electricity savings in later years as these negative electricity savings measures are increasingly adoption.

5.1.9.6 RM2015 Electricity Savings

Figure 4 shows the electricity savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 4: Ceramics sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The difference in the electricity savings between RM2024 and RM2015 is minimal, with both Max Tech peaking at 0.4%. Under the BAU scenario, the RM2015 results show a peak of 0.33% electricity savings, again the same as under RM2024. This is largely due to the small number of EE measures contributing to electricity savings in both studies.

5.1.10 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 12: High and Low scenario definitions

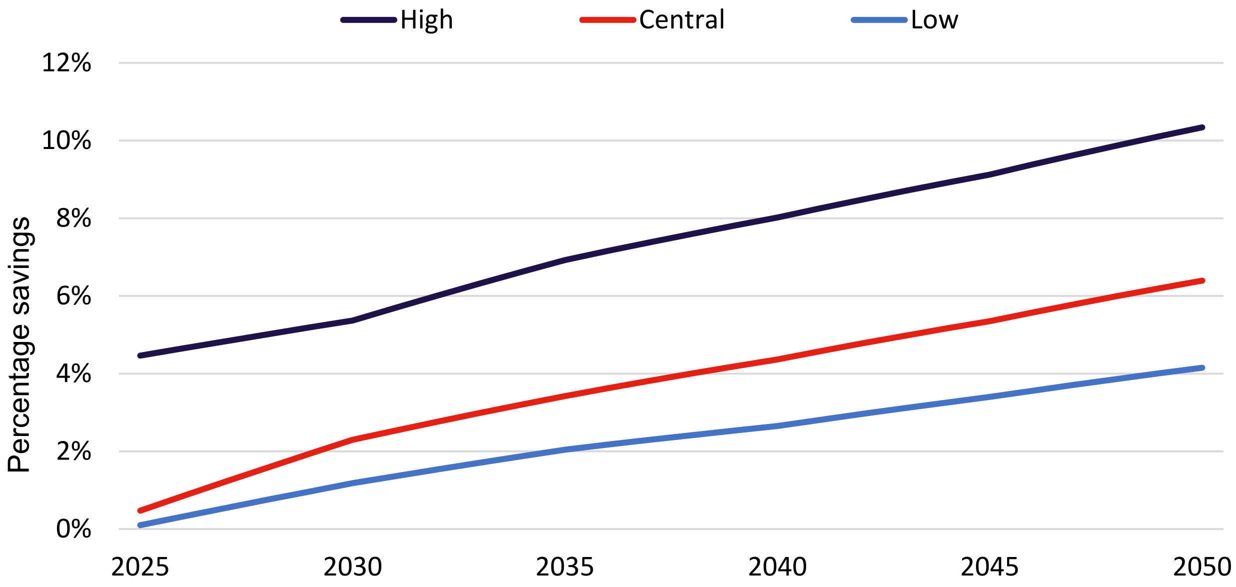
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.1.10.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 4.2%-10.4%.

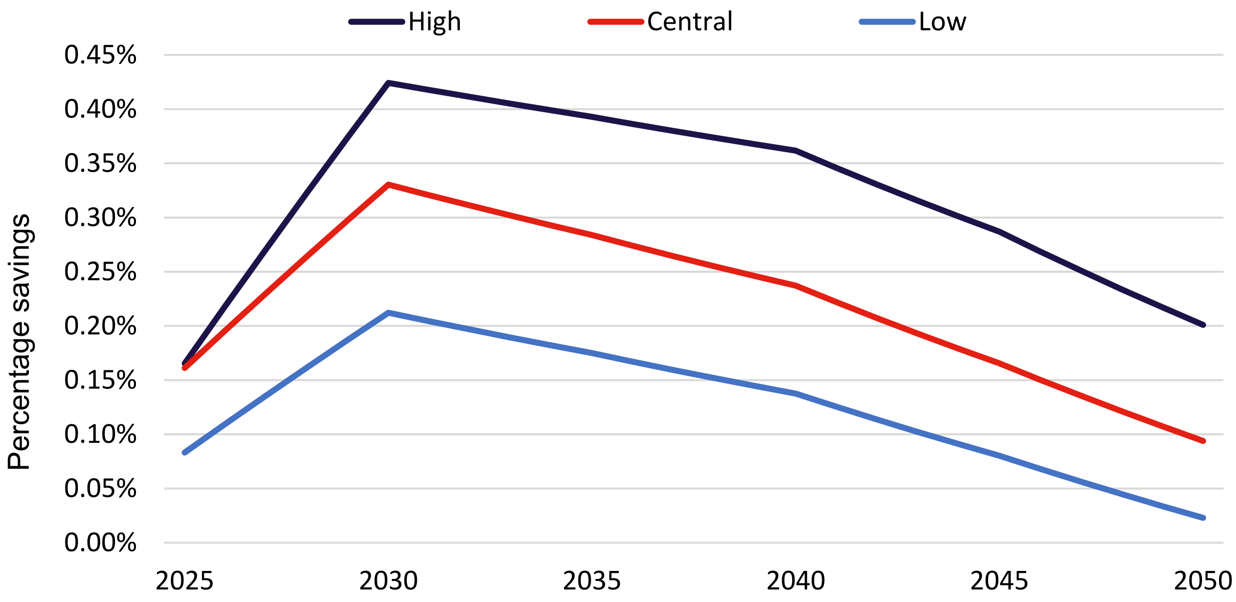
Figure 5: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.1.10.2 BAU Electricity

The range of BAU fuel for electricity by 2050 is <0.1 - 0.2%.

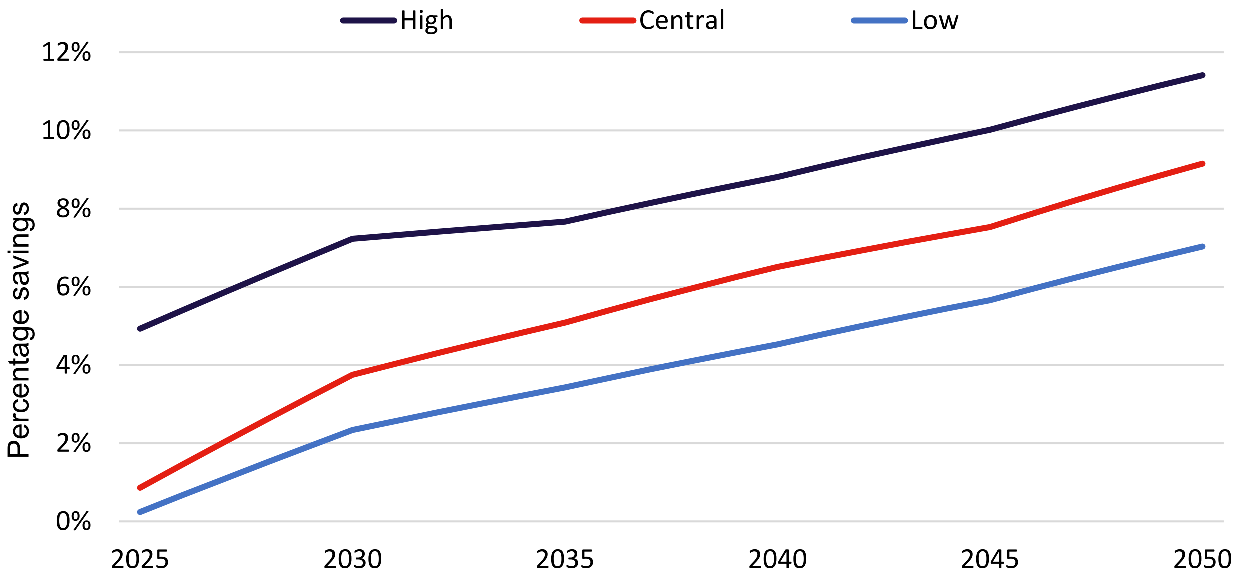
Figure 6: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.1.10.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 7.4%-11.5%.

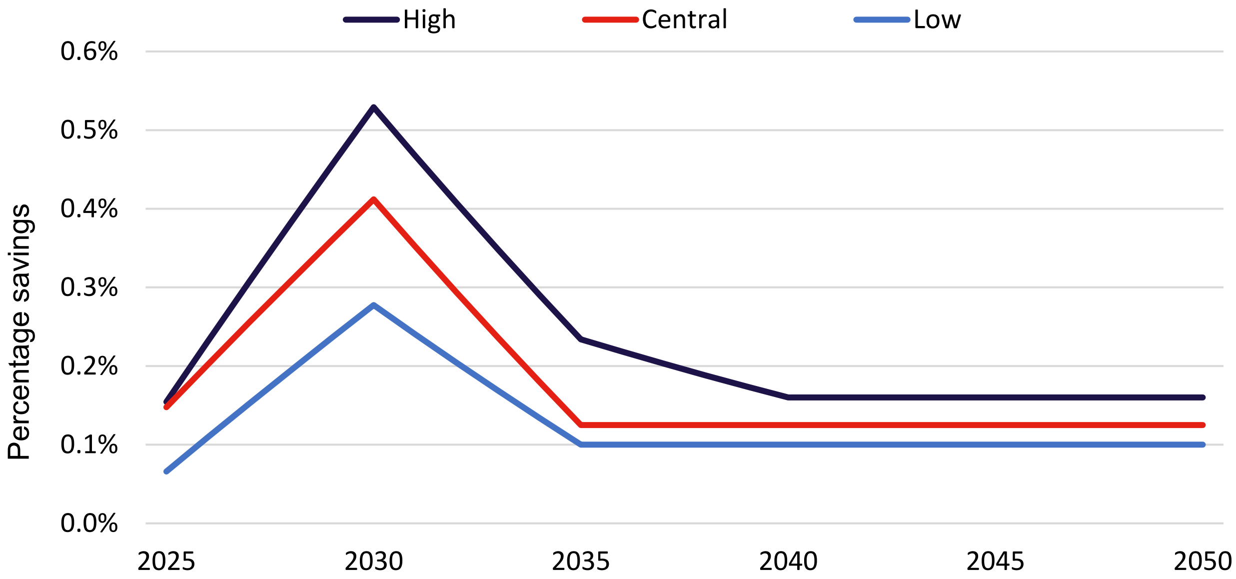
Figure 7: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.1.10.4 Max Tech Electricity

The range of BAU electricity savings by 2050 is 0.1 - 0.2%.

Figure 8: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.1.11 Limitations

The following limitations are applicable to the analysis carried out for the ceramics sector and should, therefore, be kept in mind when considering the results presented here:

- Engagement with sector was confined to a Questionnaire and Workshop. Sector was unable to engage in interviews.
- While this should not be an issue for EE measure applicability (which is a technical issue where a view at the site level is likely to be representative at the sector level), stakeholders had to take a view on sector level Adoption in 2024 and in future of measures when, naturally, knowledge of this is likely confined to their own operations.
- To manage scope for the workshop, prioritised measures were selected for discussion. While the EE measures selected were those identified as most relevant in the Questionnaire, and which were likely to have the highest saving potential, some of the potential included in these plots has not been updated since the original project in 2015.
- It is difficult for stakeholders to conceptualise adoption of some EE measures in the context of deeper decarbonisation in the sector (e.g. fuel switching). This is especially the case for EE measures related to waste heat recovery, which will be less relevant when all electric kilns begin to be adopted.
- When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category’s energy use for a ‘representative site’ within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of “percentage energy savings”.

5.2 Sector 2 (Food & Drink)

5.2.1 Definition and context

The Food & Drink (F&D) sector analysed in this work covers activities included in the following SIC codes:

10 Manufacture of food products

11 Manufacture of beverages

12 Manufacture of tobacco products

5.2.2 Literature Review

5.2.2.1 Sources Identified and their relevance

The literature review for the Food & Drink sector yielded 126 sources of various usefulness to the research, sorted into high, medium, and low relevance. Sources were rated based on a combination of factors, geographical relevance, author credibility, recency of the publication and availability of statistics on cost and energy savings potential. 22 out of the 126 sources were rated high, 76 were rated medium and 28 were rated low. The majority of sources were taken from the other OECD countries and European content - 45 and 38 sources respectively - while other papers were quite evenly split between the North American, Chinese and British contexts. The remaining papers were dedicated to an Australian and a global context. The literature was mostly taken from peer-reviewed sources, usually from academic institutions, equating to 115 sources. The rest of the literature was taken from expert authors, including industry associations and product manufacturers. There was one paper which was classed as unverified, which was in turn ranked as a low priority source.

The assessed sources collectively present an understanding of the challenges and opportunities in achieving EE and carbon emissions reduction within the Food and Drinks industry.

5.2.2.2 Conclusions from Literature Review – Gap and Limitations

There was a lack of information in the literature detailing how EE measures interact with one another.

Among the EE measures identified from the literature review, most lack specifics on implementation costs and only refer to typical payback periods rather than detailing capital expenditure, operational costs, and installation costs. Only one measure includes a complete set of costs.

The literature does not clearly detail whether the efficiency measures preclude fuel switching to electricity, hydrogen or biofuel or the adoption of CCUS, highlighting the importance of the work done in this project to classify EE measures as dependent or independent, depending on their interaction with fuel switching and CCUS.

The literature lacked data on the energy savings associated with a number of EE measures commonly adopted across the sector.

5.2.3 Engagement

Engagement with the sector took the following forms:

- 2 interviews with relevant sector associations - Food & Drink Federation, Cold Chain Federation

  Interviews with 5 operators (Dale Farm, Diageo, Long Clawson Dairy Ltd, Devro, British Sugar) and 1 supplier (Evonic)
- Questionnaires, with responses received from 4 stakeholders
- One 3-hour workshop attended by the Food & Drink Federation, 15 operators, 2 consultancies (Carbon Architecture and SLR) and 1 supplier

5.2.4Main categories of Energy Use

For the purposes of modelling energy savings, the F&D sector has been resolved into the following categories against which EE measures have been applied (including baseline energy consumption):

The ‘Other Heating’ category accounts for the large majority of fuel consumed for the generation of heat in Food & Drink. This refers to the generation of steam and hot water which is the main medium for carrying heat to process in this sector, as opposed to the generation of heat sent direct to process which accounts for a smaller share of Fuel for heat. Fuel for steam and hot water are grouped in this way because the EE measures applying to this category are similar across the large number of sub-sectors in the main Food & Drink sector.

Table 13: Share of each fuel type in the baseline attributed to each category in the food and drink sector

Category	Percentage of Total Sector Energy Use (%)				
	Electricity	Gas	Coal	Oil	Biomass
Direct Fired Ovens	0%	13%	13%	13%	13%
Direct Fired Drying	<1%	3%	3%	3%	3%
Other Heating	0%	85%	85%	85%	85%
Total Cooling	32%	0%	0%	0%	0%
Other Electricity	67%	0%	0%	0%	0%
Total Sector Energy	**100%**	**100%**	**100%**	**100%**	**100%**

*Values have been rounded and might not sum to 100%

Other notable categories of energy consumption include the consumption of electricity for cooling, which is significant in this sector and, therefore, warrants a category in its own right which is separated out from other electricity.

5.2.5 Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and adoption out to 2050. Applicability and adoption were discussed during the workshop in the context of whether the EE measures were dependent or independent (deep decarbonisation dependency).

Table 14 lists the prioritised measures and their dependency on deep decarbonisation scenarios.

Table 14 EE measures prioritised for the F&D sector and dependency on deep decarbonisation scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Process Design (Total sector)	A wide-ranging measure covering many different types of improvement to the operation of processes and their flow. To help simplify the discussion the measure was split into ‘continuous improvement’ measures and ‘significant redesign’, as continuous improvement is incremental and less costly. **2015 measure.**	Independent
Energy Management and Good Manufacturing Practice (GMP) (Total sector)	Measures relating to management behaviour including energy monitoring and targeting and behaviours to improve control, scheduling, setpoints, running hours, operating intensity, process optimisation and similar. **2015 measure.**	Independent
New Refrigeration Technologies (Total cooling)	Includes higher efficiency equipment, alternate refrigeration technologies, improved design and layouts and improved control equipment and methods of control. It also includes retrofit and new design / plant. **2015 measure.**	Independent
New Drying Technologies (Direct fired drying)	Measures relating to drying technologies including higher efficiency techniques, drying ovens and component equipment, alternate drying technologies, improved design and layouts and improved control equipment and methods of control. Includes retrofit and new design / plant. **2015 measure.**	Independent
Waste Heat Recovery/CHP/No Heat Losses (Total heating)	Includes all activities to reduce heat losses including insulation through heat recovery and use of heat pumps. **2015 measure.**	Dependent
Use of High Temperature Heat Pump Technology (to generate steam) (Total sector)	Application of heat pumps with working temperatures above 80°C, typically 120°C and higher to generate steam and / or to serve higher temperature applications. Most typically applied where there is an abundant mid-grade heat source that can be uplifted. **RM2024 measure.**	Independent

5.2.6 Non prioritised measures

The non-prioritised measures are listed in Table 15.

Table 15 EE measures non-prioritised for the F&D sector and dependency on deep decarbonisation scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Advanced oven technologies (Direct fired ovens)	Examples: water bath oven (cooking water or using water instead of brine), shower oven, steam oven, hot-air oven, and microwave oven, optimise damper settings, balance oven airflows, direct-drive or no-slip-drive on fans, improved (integrated) oven controls in all, circumstances, improved combustion efficiency in ovens (direct- and indirect-fired), oven burner fire, rate modulation, high-efficiency ovens, reduction of the baking tin thermal mass, heat recovery from oven, and gas-fired proving	Dependent
Supply chain collaboration (Total sector)	Avoiding unnecessary handling, treatment, transport through improved collaboration with third parties such as clients, suppliers, etc	Independent

5.2.7 Key assumptions

When updating the characteristics of the 2015 measure ‘Process Design’, in order to allow stakeholders to conceptualise this in physical terms, the measure was split into two sub-measures: significant redesign and continuous improvement.

5.2.8 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.4 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the food & drink sector came to light and these are listed below.

The following barriers were identified during the literature review:

Organisational and behavioural related barriers:

- In the case of smaller food and drink producers, the implementation of some more complex efficiency measures can demand complex decision-making which the site may not be comfortable with because of lack of experience.
- Internal factors, like a lack of interest in EE or time constraints, might impede implementation of measures at smaller food and drink operators.

- Divergent interests within the organisation, where one department bears costs but others benefit, can stall progress on measure implementation.

Policy barriers:

- The time gap between making an EE decision, implementing it, and witnessing benefits can interrupt the dissemination of information and hinder replication elsewhere.

Process barriers:

- Unless other measures like continuous power quality monitoring and the installation of harmonic filters and oversized transformers and cabling is undertaken, frequency-converter-driven (e.g. VSD) motors may have to be limited to less than approximately 60% of the total energy use of the installation, otherwise the site's power quality may deteriorate in the form of voltage harmonics and fluctuations[12].
- The wall temperature of a boiler economiser must not drop below the dew point of acids contained in the flue gas; otherwise, corrosive condensate will attack the economiser structure. Concern about this may lead to reticence about installing economisers in the first place or being overly conservative with the design of the economiser[13].
- Mechanical Vapour Recompression (MVR) plant may be perceived as too noisy in some applications, especially when located close to packaging areas.
- There are limits to the extent to which the discharge pressure of an air compressor can be reduced (and electricity saved), since too low a pressure may cause end users of compressed air to malfunction. General unease about this may make sites reluctant to consider any action to reduce compressed air pressure even when there is technical scope to do so.
- Reducing boiler pressures can save fuel. However, boiler owners should consult their boiler supplier when reducing steam pressures as boilers are designed to operate under rated conditions and pressure reductions may produce undesirable effects such as the carryover of moisture in the steam or unwanted changes to feedwater flow or deaerator operation. Worried about this can lead to no further action being taken.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- Lack of granular data on energy consumption by process makes it difficult to identify and evaluate EE projects, which is especially the case at the sector's smaller sites.

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[12] Therkelsen et al (2014), 'Energy efficiency opportunities in the U.S. commercial baking industry': Energy efficiency opportunities in the U.S. commercial baking industry - ScienceDirect

[13] Ekezie et al (2017), 'Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments': [Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments - ScienceDirect]

5.2.9 Results

The tables and graphs below show the inputs and results of the modelling for the Food & Drink sector. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an ‘average’ site within a sector.

5.2.9.1 Key parameters derived

Table 16 Energy savings and CapEx

Measures (Sector energy use category)	**Site size**	**Elec Savings (%) (range)** ***RAG***	**Fuel for heat savings (%) (range)** ***RAG***	**CapEx for ‘average’ site (£, 2024 prices) (range)** ***RAG***
Process Design (Total sector)	Small	20% (5-30%) *Amber*	20% (5-30%) *Amber*	£180,000 (£130,000 - £200,000) *Red*
	Large			£9,800,000 (£7,000,000 - £11,000,000) *Red*
Waste heat recovery / CHP / no heat losses (Total sector)	Small	5% (2-15%) *Amber*	30% (20-50%) *Amber*	£300,000 (£100,000 - £500,000) *Red*
Waste heat recovery / CHP / no heat losses (Total sector)	Large	5% (2-15%) Amber	30% (20-50%) Amber	£13,800,000 (£11,500,000 - £16,100,000) *Red*

Measures (Sector energy use category)	**Site size**	**Elec Savings (%) (range) *RAG***	**Fuel for heat savings (%) (range) *RAG***	**CapEx for 'average' site (£, 2024 prices) (range) *RAG***
New refrigeration technologies (Total cooling)	Small	35% (10-50%) *Red*	2% (1-5%) *Red*	£200,000 (£100,000 - £400,000) *Red*
	Large			£3,000,000 (£1,000,000 - £5,000,000) *Red*
Energy management & GMP (Total sector)	Small	10% (5-15%) *Red*	10% (5-15%) *Red*	£50,000 (£10,000 - £50,000) *Red*
	Large	5% (2-10%) *Red*	5% (5-10%) *Red*	£240,000 (£50,000 - £250,000) *Red*
New drying technologies (Direct fired drying)	Small	-10% (not provided) *Red*	35% (not provided) *Red*	£324,000 (£162,000 - £810,000) *Red*
	Large			£2,900,000 (£584,000 - £5,840,000) *Red*
Use of high temperature heat pump technology to generate steam (Total sector)	Small	-15% (-5%- -20%) *Red*	37.5% (25-50%) *Red*	£1,000,000 (£500,000 - £4,000,000) *Red*
	Large			£6,000,000 (£4,000,000 - £10,000,000) *Red*

Table 17 Applicability and adoption rates for BAU and Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Process Design	95%	15%	24%	35%	50%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			27%	40%	55%
Waste heat recovery / CHP / no heat losses	90%	20%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			25%	35%	50%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			30%	40%	50%
New refrigeration technologies	70%	20%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			20%	25%	30%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			20%	30%	50%
Energy management & GMP	95%	50%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			60%	75%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			70%	80%	85%

<table>
<tr><td rowspan="4">New drying technologies</td><td rowspan="4">50%</td><td rowspan="4">10%</td><td>BAU 2030</td><td>BAU 2040</td><td>BAU 2050</td></tr>
<tr><td>18%</td><td>28%</td><td>45%</td></tr>
<tr><td>Max Tech 2030</td><td>Max Tech 2040</td><td>Max Tech 2050</td></tr>
<tr><td>23%</td><td>30%</td><td>45%</td></tr>
<tr><td rowspan="4">Use of high temperature heat pump technology to generate steam (independent)</td><td rowspan="4">30%</td><td rowspan="4">3%</td><td>BAU 2030</td><td>BAU 2040</td><td>BAU 2050</td></tr>
<tr><td>15%</td><td>20%</td><td>25%</td></tr>
<tr><td>Max Tech 2030</td><td>Max Tech 2040</td><td>Max Tech 2050</td></tr>
<tr><td>25%</td><td>28%</td><td>30%</td></tr>
</table>

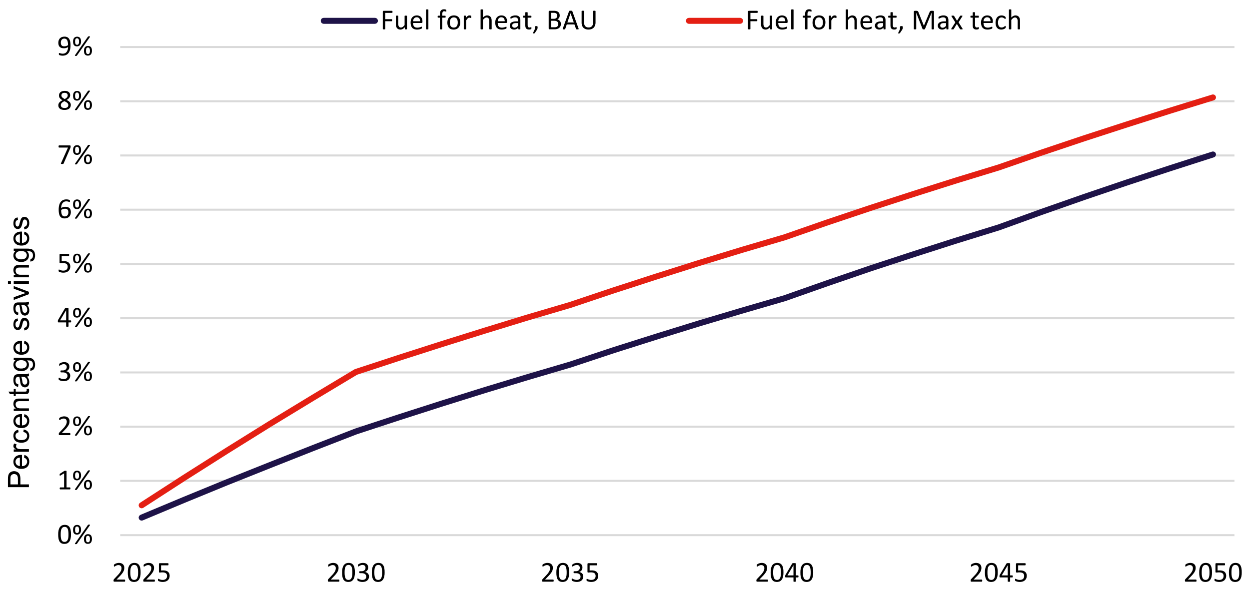
Note format change in table compared to the same table presented in the Ceramics chapter.

These measures were entered into the DESNZ model yielding the detailed results set out in the sections below.

5.2.9.2 RM2024 Fuel for heat Savings

Figure 9 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 9: F&D sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



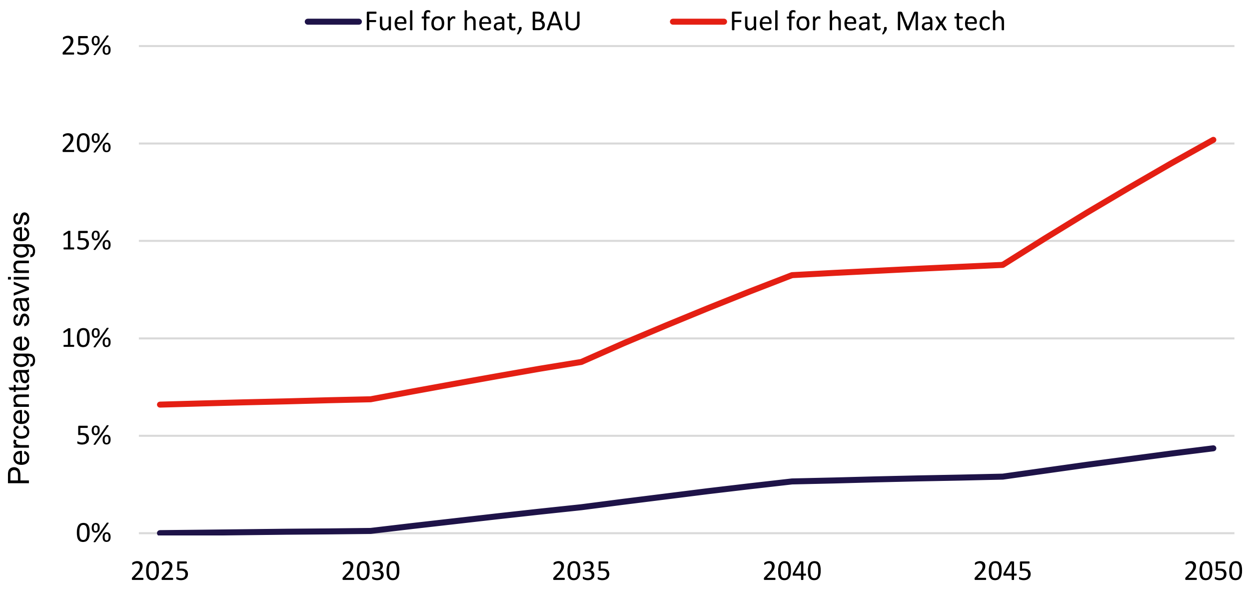
Similar trends can be observed under both scenarios. Savings increase more rapidly under Max Tech until 2030, at which point both trajectories become nearly identical. The Max Tech scenario peaks at savings of 8% in 2050, compared to 7% for BAU.

The measures “Energy Management & GMP”, “Process design” and “Waste heat recovery / CHP / no heat losses” account for the largest direct savings in both BAU and Max Tech scenarios. Savings due to Energy Management & GMP are anticipated to reduce over time as the low hanging fruit are taken and this is in turn superseded by increased application of the two measures: “Process Design” and “Waste heat recovery / CHP / no heat losses”. This is the case across both scenarios. The main differences between BAU and Max Tech trajectories for RM2024 Fuel for heat savings are explained by the more difficult implementation and higher costs of the measures: Process Design and Waste heat recovery / CHP / no heat losses. which are more likely to be implemented as part of wider upgrades to processes.

5.2.9.3 RM2015 Fuel for heat Savings

Figure 10 shows the Fuel for heat savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat.

Figure 10: F&D sector (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



The trends between the BAU and Max Tech scenarios for the RM2015 results are quite divergent, compared with the RM2024 results. Savings start and peak considerably higher under the Max Tech scenario, reaching a high of 20% by 2050, compared to a high of around4% under BAU. Further, BAU savings only start from 2030 with RM2015, whereas they both start from similar points in RM2024.

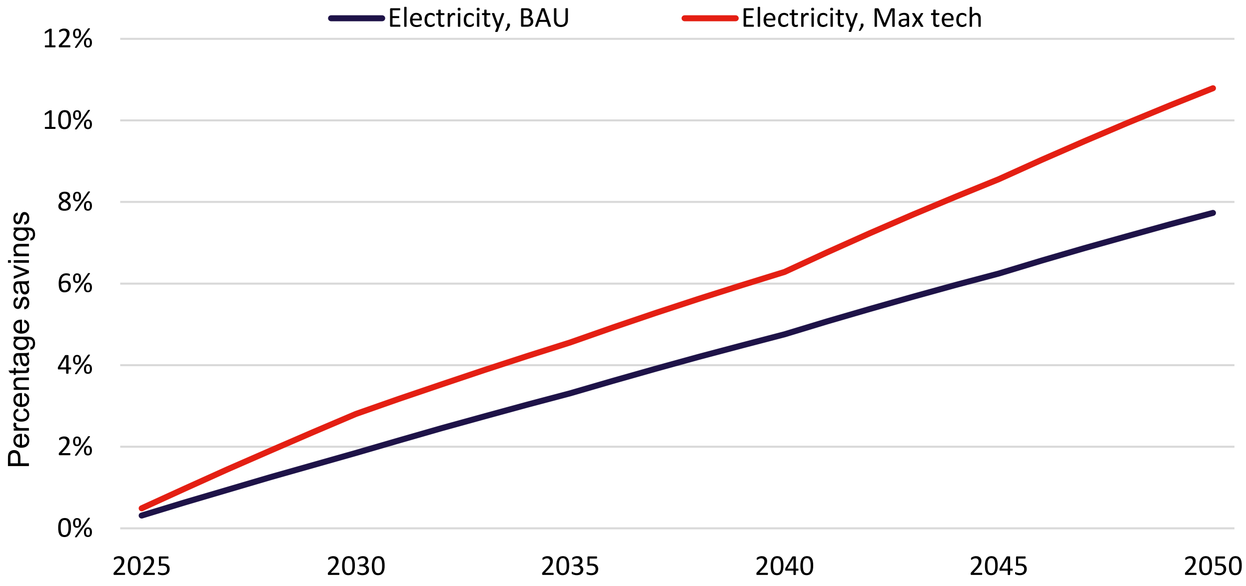
In terms of direct savings in Fuel for heat, the Max Tech savings potential by 2050 has decreased from around 20% in RM2015 to around 8% in RM2024, whereas the BAU savings have increased from just under 5% to 7% by 2050. The decrease in Max Tech savings may partly be attributed to the view by stakeholders that opportunities have already been taken and so less potential remains; this view however may be influenced by a greater portion of stakeholders representing larger organizations being engaged with during this project than during the 2015 project. Larger organisations tend to have more resource / drivers to implement EE measures than smaller organisations. For example, larger processes are more likely to have implemented heat recovery measures. The increase in BAU savings for RM2024 compared to RM2015 is likely due to stakeholders taking a view that adoption rates will be higher in the former than in the latter – feedback from workshops suggested there is large appetite in the sector for less disruptive EE measures with reasonable paybacks. Moreover, real terms increases in energy prices since RM2015 are likely to have brought a greater quantum of energy savings into the BAU category, as project paybacks reduce.

The gap between the Max Tech and BAU scenarios between RM2015 and RM2024 for savings at 2050 has narrowed from around 16 to around 1 percentage points, due to the decrease in remaining potential Max Tech savings and the optimistic BAU adoption profiles returned by stakeholders, as discussed above.

5.2.9.4 RM2024 Electricity Savings

Figure 11 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 11: F&D sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios

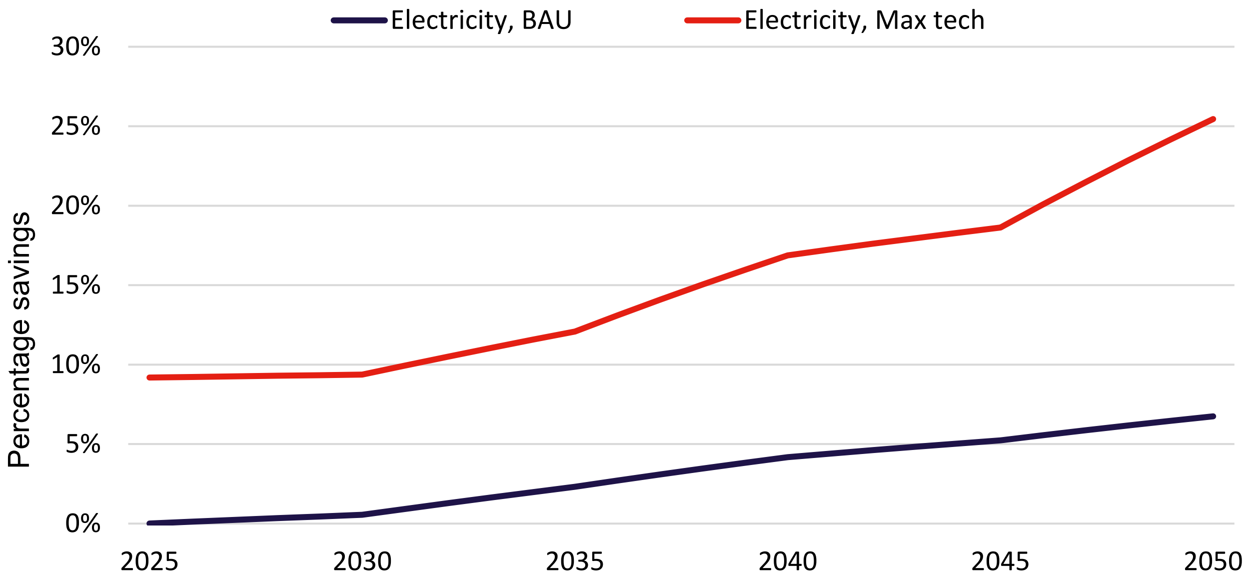


The measures and factors influencing the electricity savings are similar to those affecting Fuel for heat savings, as described above. Here, the gap between BAU and Max Tech is slightly larger at around 3%, with Max Tech peaking at around11% compared to almost 8% for BAU.

5.2.9.5 RM2015 Electricity Savings

Figure 12 shows the electricity savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity.

Figure 12: F&D (2015 Roadmaps) – Electricity Savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



In terms of indirect electricity savings, the Max Tech savings potential by 2050 has decreased from 26% in RM2015 to 11% in RM2024, whereas the BAU savings are little changed at around 7% by 2050. As with Fuel for heat, the decrease in Max Tech savings may partly be attributed to the view by stakeholders that opportunities have already been taken and so less potential remains. As noted above, this view may be skewed in the RM2024 project due to there being a greater portion of stakeholders representing larger organizations that have more resource / drivers to implement EE measures.

The gap between the Max Tech and BAU scenarios between RM2015 and RM2024 has narrowed from around 19% to around 3% by 2050, comparable to the changes in the Fuel for heat scenario.

5.2.10 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 18 High and Low scenario definitions

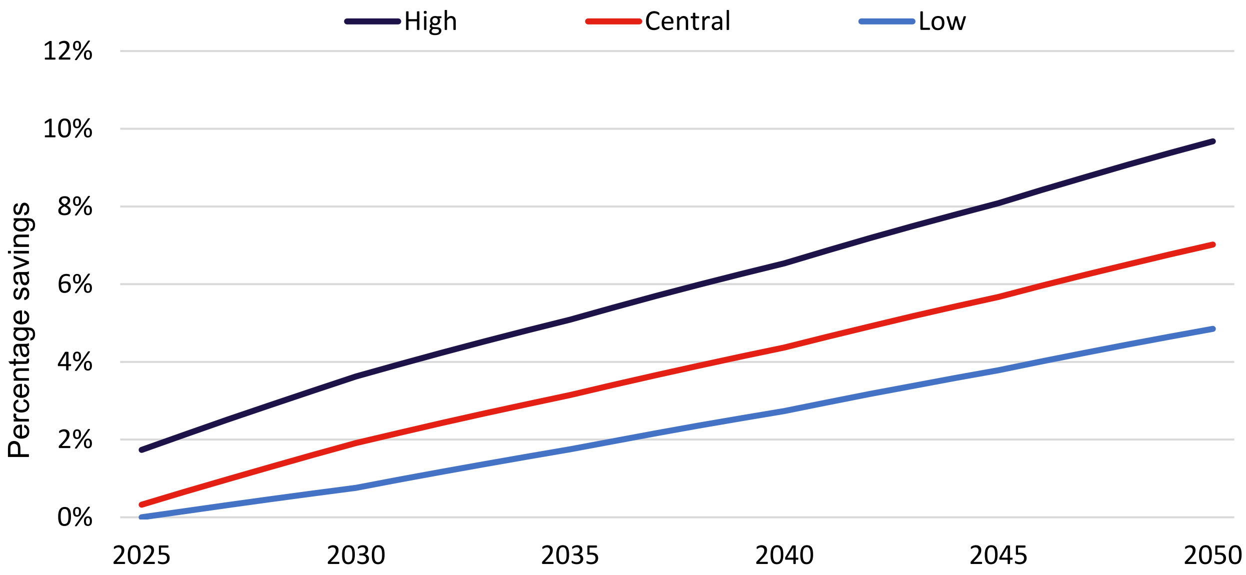
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.2.10.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 4.9%-9.7%.

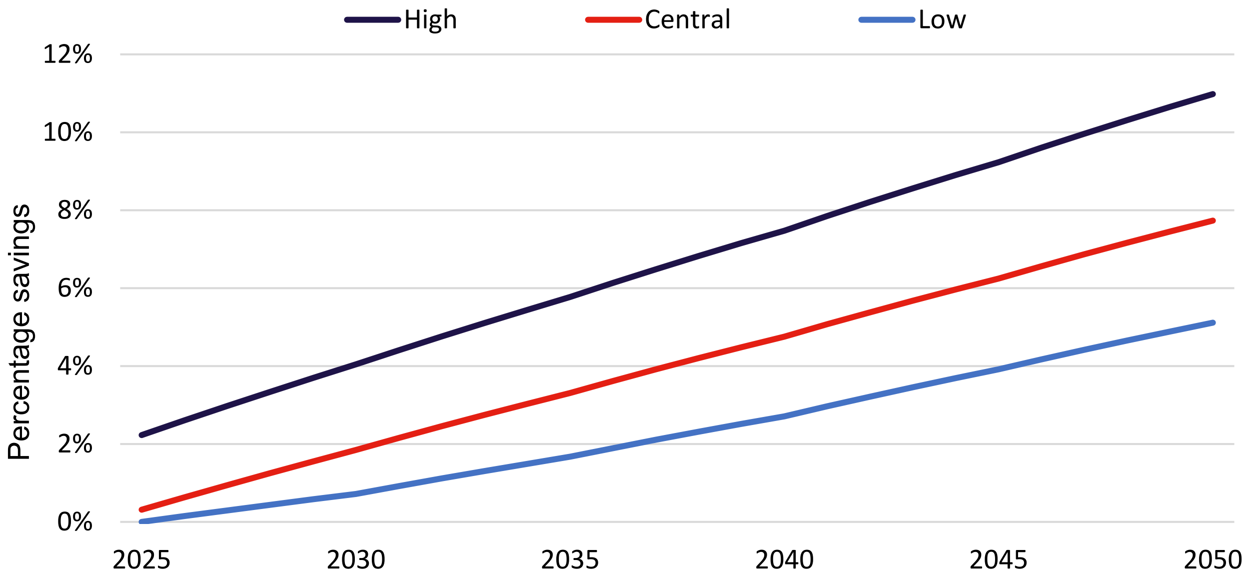
Figure 13: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.2.10.2 BAU Electricity

The range of BAU electricity savings by 2050 is 5.1 – 11.0%.

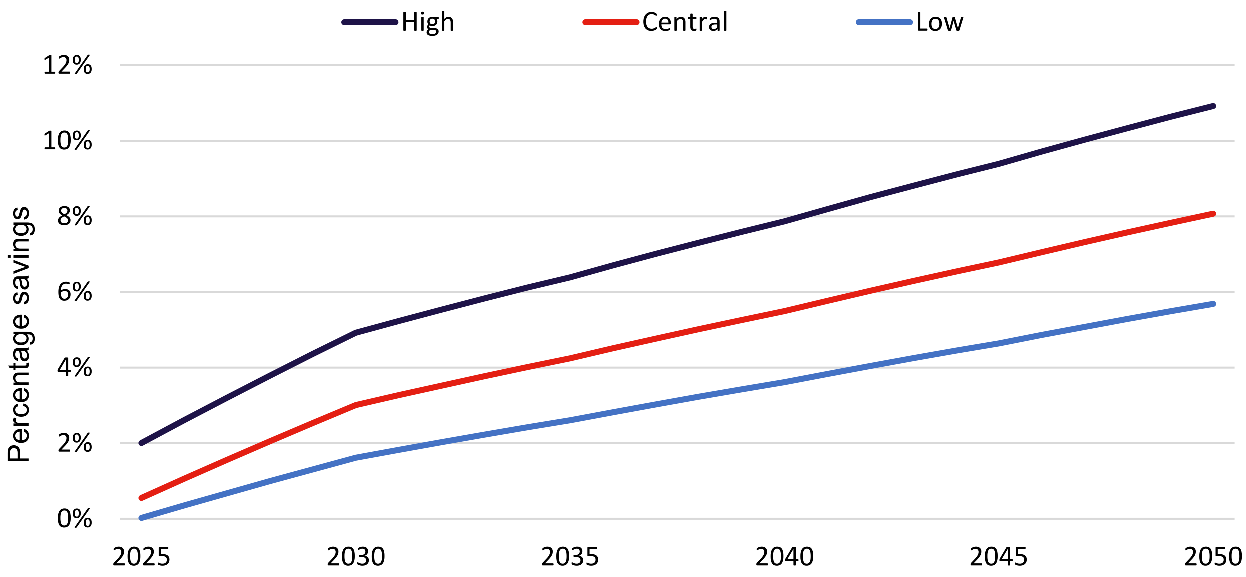
Figure 14: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.2.10.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 5.7%-110%.

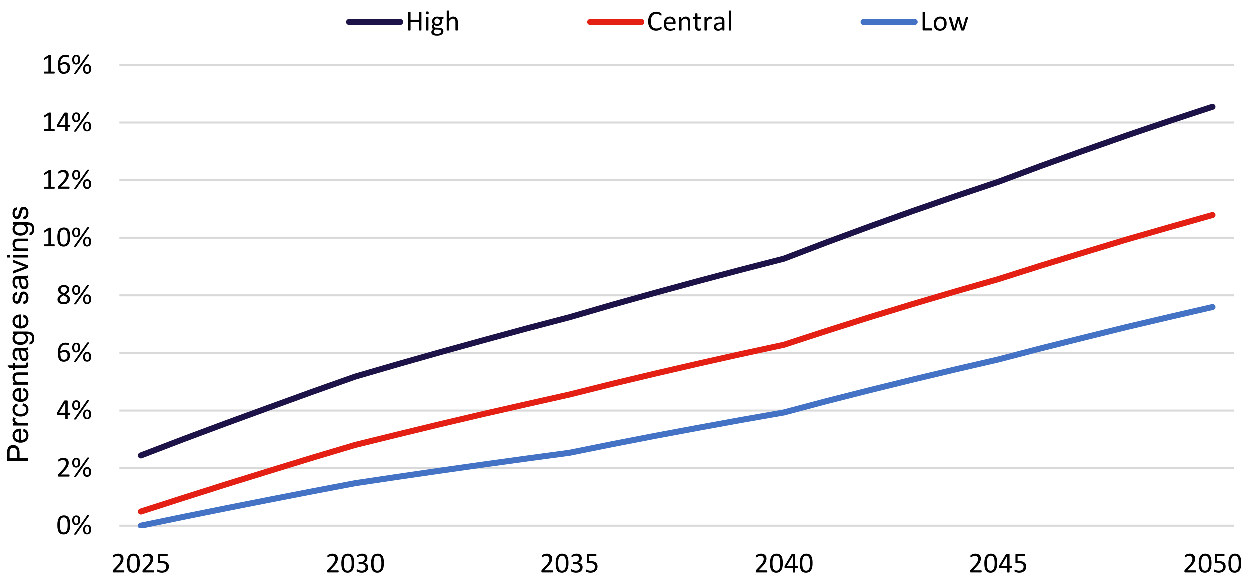
Figure 15: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.2.10.4 Max Tech Electricity

The range of BAU electricity savings by 2050 is 7.6 – 14.6%.

Figure 16: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.2.11 Limitations

The following limitations are applicable to the analysis carried out for the F&D sector and should, therefore, be kept in mind when considering the results presented here:

Due to diversity of sector, workshop attendance was not representative of the Food & Drink industry across different sub-sectors and sizes. Many of the stakeholders were only able to provide reliable views relating to their own operations or sub sectors. For example, there was better representation from larger energy users, and these organisations tend to have greater capability of implementing EE measures and consequently there is a risk their views are not representative of smaller energy users.

The literature review lacked quantifiable evidence on the energy savings, adoption, applicability, adoption and costs of EE measures. Therefore, evidence on these variables used in the analysis is primarily informed by workshop attendees.

To manage modelling burden several of the efficiency measure classifications include multiple sub measures some of which are quite varied. For example, Process Design includes incremental measures and large-scale upgrades. There was limited granular data to inform the variation in sub measures and so all the modelling remains at a high level.

Decarbonisation is becoming a priority for the sector, and it is unclear how this could align with adoption of EE measures. Electrification of heat in the Food & Drink sector will pay a very significant role in decarbonisation of the sector, owing the relatively lower grade of heat needed. This will have an impact upon sector attitudes to the development of heat recovery projects from combustion generated heat.

It is not entirely clear why the Max Tech savings in 2024 are reduced compared to 2015. One possible explanation is that the stakeholders in RM2024 tended to be overrepresented by large organisations and these organisations are more likely to have already implemented measures than small organisations. There is a long tail of smaller energy consumers in the Food & Drink sector, which in aggregate consume an appreciable proportion of the sector’s energy.

When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category’s energy use for a ‘representative site’ within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of “percentage energy savings”.

5.3 Sector 3 (Paper & Pulp)

5.3.1 Definition and context

- The Paper & Pulp sector analysed in this work covers activities included in the following SIC codes:
- 17.1 Manufacture of Pulp, Paper & Paperboard

The “Paper” sector as considered in this work involves the process of producing pulp – the raw material used in papermaking – and the papermaking process itself. At the time of writing there are thought to be approximately 40 pulp and paper mills operating in the UK, only one of which is a standalone pulp mill. Of the remaining sites about half are integrated mills, which means they produce their own pulp for production of paper. The other half are papermaking only sites which purchase pulp from a third party, often from overseas. The majority of integrated mills produce pulp from recovered paper and only two sites do so from virgin wood, both via mechanical pulping. Consequently, only EE measures associated with recovered paper pulping and mechanical pulping are relevant in the UK context, in addition to the EE measures directly associated with the process of turning pulp into paper/board product. The measures presented in this report reflect this.

Disregarding the different approaches to pulping, the papermaking process is very similar across the main product types (packaging, newsprint, tissue and speciality papers). However, one significant difference is in the drying of tissue products. As with the drying process for other paper products, tissue drying uses steam-heated roller dryers, known as ‘Yankee dryers’, however it also involves the use of hot air generated directly from natural gas combustion through a process called ‘Through Air Drying’. Therefore, the range of EE measures that are applicable to paper mills depends on the types of paper products that the mills specialise in.

The paper sector is a significant user of Combined Heat & Power (CHP), and the application of additional CHP is an EE measure in so far as it would lead to a primary energy saving (i.e. less primary energy input to make available the power and heat required in papermaking).

5.3.2Literature Review

5.3.2.1 Sources Identified and their Relevance

For the Paper & Pulp sector, 28 literature sources were reviewed and sorted into high, medium and low relevance. Sources were rated based on a combination of factors. Two out of the 27 sources were rated high, 12 were rated medium and 14 were rated low. The single country from which the highest proportion of the literature was assessed was China, which is unsurprising given its leading position in the global paper production. The 4 UK sources assessed presented general roadmaps for the sector, with limited information on specific EE measures. The literature was mostly taken from meta data and peer-reviewed sources, usually from academic institutions, equating to 15 sources. The “Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board” produced by the EU’s Joint Research Centre provides a detailed overview of what is technically and economically available in the pulp and paper industry to improve environmental performance (in 2015).

The meta-review “Assessment of emerging energy-efficiency technologies for the pulp and paper industry: a technical review”, published in the Journal of Cleaner Production in 2016, provides a useful overview of emerging EE measures while another meta-study “Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options” gives a more up-to-date and comprehensive overview of EE technologies. This study, published in Renewable and Sustainable Energy Reviews, reviewed 466 studies and aimed to assess the main determinants of energy and carbon emissions emerging from the pulp and paper, the benefits of this industry adopting low-carbon manufacturing processes, and barriers that need to be tackled to enable such adoption. A sociotechnical perspective was used to understand the full range of industrial and economic activities within a decarbonised pulp and paper industry and present promising avenues for future research.

The sources collectively present an understanding of the challenges and opportunities in achieving EE and carbon emissions reduction within the pulp & paper industry.

5.3.2.2 Conclusions from Literature Review – Gaps and Limitations

Limited information on the costs associated with EE measures was evident in the literature studied. Furthermore, the interactions of EE measures with other measures and deep decarbonisation technologies are often not addressed in the literature studied. Consideration is also not often given to whether the measure precludes fuel switching to electricity, hydrogen or biofuel or the adoption of CCUS.

5.3.3 Engagement

Engagement with the sector took the following forms:

- 1 interview with the Sector Association – Confederation of Paper Industries (CPI)
- Interviews with 5 operators (Northwood Tissue, WEPA, Smurfit Kappa, Palm Paper, DS Smith) and 1 associated company (Suez)
- Questionnaires, with responses received from 4 stakeholders
- One 3-hour workshop attended by the CPI, and the 5 operators

5.3.4 Main categories of Energy Use

For the purposes of modelling energy savings, the Paper & Pulp sector has been resolved into the following categories against which EE measures have been applied (including baseline energy consumption):

Table 19: Share of each fuel type in the baseline attributed to each category in the Paper & Pulp sector

Category	Percentage of Total Sector Energy Use (%)				
	Electricity	Gas	Coal	Oil	Biomass
Paper Machine	30%	73%	73%	73%	73%
Tissue	18%	18%	18%	18%	18%
Dryer	13%	58%	58%	58%	58%
Non-CHP	0%	33%	100%	100%	20%
Total Sector Energy	**100%**	**100%**	**100%**	**100%**	**100%**

Note percentages do not add up to 100% because of overlaps in energy categorisation. Also, and not all categories are presented here as they were not in scope of the EE measures referenced e.g. CHP.

5.3.5 Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and future adoption. Applicability and adoption were discussed during the workshop in the context of whether the EE measures were dependent or independent (Deep Decarbonisation Dependency).

Table 20 lists the prioritised measures and their dependency on Deep Decarbonisation scenarios.

Table 20: EE Measures Prioritised for the Paper & Pulp Sector and Dependency on Deep Decarbonisation Scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Energy Management (Total sector)	Covers energy management systems (such as ISO 50001), installation of sub-metering for gas, electricity and steam, collection of energy data and data integration into process control and IT systems. **RM2015 measure.**	Independent
Improved Process Control (Total sector)	Covers improvements and additions to site process control systems to increase the proportion of time that on-specification product is being produced. RM**2015 measure.**	Independent
Heat Integration and Heat Recovery including Waste Heat (Total sector)	Covers improvements to mill processes to make heat use more efficient by cascading available heat flows from highest to lowest quality. Includes trying to find uses for the residual "waste" heat left at the end of the process (typically warm water and warm, moist air). **RM2015 measure.**	Independent
State-of-the-art Steam Systems (Total sector)	Relates to the steam drying cylinders and covers dryer condensate systems utilising stationary siphons and spoiler bars with optimised differential pressures and blow-through steam for condensate evacuation from each drying cylinder. **RM2015 measure.**	Independent
Upgrade Motors, Install VSDs, Match	Covers (a) replacing motors with ones having higher efficiency, not over-sizing motors,	Independent

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Pumping Capacity to Duty (Total sector)	installing variable speed drives where applicable (as opposed to fixed speed); (b) matching pumping capacity to required duty, avoiding over-sizing pumps, avoiding throttling etc. **RM2015 measure.**	
Heat Pumps, ORC Heat Recovery Technology (Total sector)	Covers the introduction of developing technologies to supply heat (e.g. using heat pumps to efficiently provide heat using electricity or using an organic Rankine cycle installation to recover waste heat). **RM2015 measure.**	Independent

5.3.6 Non-Prioritised Measures

The non prioritised measures are listed in Table 21.

Table 21: EE Measures Non-Prioritised for the Paper & Pulp Sector and Dependency on Deep Decarbonisation Scenarios

Measure Name	**Measure Description**	**Deep Decarbonisation Dependency**
Use flash steam from condensate (Total sector)	Flash steam is released from hot condensate when its pressure is reduced e.g. when exiting a "steam trap"/. Heat can be recovered from flash steam which can lead to energy savings.	Independent
Steam box to increase sheet temperature and dryness (Paper machine)	Steam boxes increase the temperature of the mesh conveyor in sheet formation (see diagram), reducing viscosity of water contained in the fibres, to make drainage easier and increase production - so less energy needed to produce the same amount	Independent
Extended Nip Press: Tissue (Tissue)	Long nip presses in the press section achieve higher dryness, reducing the energy costs in the drying section.	Independent
Improved dewatering in press section beyond extended Nip Press (Dryer)	Making water removal more efficient in the press section after extended nip press.	Independent

Measure Name	Measure Description	Deep Decarbonisation Dependency
Hot pressing (Dryer)	Increases sheet temperatures directly in the nip press, decreasing the viscosity of the water and enhancing its removal. This is done by heating a large diameter roll which contacts the sheet of paper directly, so the paper is heated and pressed at the same time.	Independent
High consistency forming (Paper machine)	Energy savings through forming more consistent paper at the beginning of the paper machine.	Independent
Impulse drying (Paper machine)	A technology used for extracting water from the paper web on the machine, using steam.	Independent
Infrared profiling (Dryer)	Allows for easy and quick inspection of a wide range of equipment such as motors, mechanical equipment, liquid levels in boilers and other vessels, heat loss and leakage throughout the plant. Enables repairs / changes to be made in targeted areas, reducing unnecessary energy consumption.	Independent
Increase dew point in hood from 55°C to 70°C (Dryer)	Dew point = temp to which air must be cooled to become saturated with water vapour. Increasing this creates better drying conditions so a more efficient machine.	Independent
Heat recovery on hoods present (Paper machine)	Recover waste heat from hoods currently used in industry	Independent
Heat recovery on hoods future (Paper machine)	Recover waste heat from hoods which will be used in the future	Independent
Oxygen trim control to adjust burner inlet air (Non-CHP)	O2 trim control continuously monitors the flue gases and adjusts the burner air supply accordingly.	Dependent
Economisers on steam boilers (Non-CHP)	Recovers heat from boiler exhaust gases and transfers it to the incoming boiler feed water increasing thermal efficiency.	Dependent
High consistency pulping (Total sector)	This technology has a large production capacity, low power consumption, and easy maintenance. Less chemicals are required than in other forms of pulping, and it requires less maintenance.	Independent

Measure Name	Measure Description	Deep Decarbonisation Dependency
Efficient screening (Total sector)	Paper for recycling is de-inked through screening, chemical addition and flotation	Independent
Sludge dryer (Total sector)	Evaporating the water in waste sludge, to then be made into pulp.	Independent
Match pumping capacity to duty, avoid oversizing pumps & motors, avoid throttling, use VSD and efficient motors where possible (Total sector)	Make vacuum pumps as energy efficient as possible, in de-watering wet paper	Independent
Use fans or blowers for low vacuum applications (Total sector)	Vacuums used to de-water wet paper to a greater degree before the energy-intensive step of drying paper. Low-vacuum is needed for forming and web de-watering, while high-vacuum is needed in the pressing section of the paper machine.	Independent
Optimize steam turbine control (Total sector)	Make steam turbines more efficient using control processes.	Dependent
Review of system pressure, leak detection etc. (Total sector)		Independent
Only use necessary agitation (turn off agitators, slow down agitators, zone agitation where appropriate) (Total sector)	The Agitator Machine helps to maintain the pressure of the flow of the slurry within the paper machine. Most of the paper mill agitators incorporate process control to maintain better control over the mixing process. Reducing use makes paper machines more efficient as less energy is used.	Independent

5.3.7 Key assumptions

The current arrangements for paper makers to source their pulp will remain unchanged into the future. This means that pulp will either be imported or, where produced in the UK, will be via paper recycling or mechanical pulping.

The current make-up of the sector in terms of products made (e.g. board, newsprint, sanitary and speciality) will remain unchanged.

5.3.8 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.4 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the paper sector came to light and these are listed below.

The following barriers were identified during the literature review:

- The complexity of the pulp & paper industry poses a significant obstacle to investments in EE. The variety of processes used, scale of operations and raw materials used represents a key barrier as mills may have different capacities in terms of the scale of operation, levels of capital and skills, and mitigation opportunities. This makes it difficult to evaluate a measure applied elsewhere to a specific mill under consideration, with the result that the measure is not pursued.
- Additionally, Paper & Pulp is a capital-intensive industry, and this can lead to a cautious approach to business. Equipment in pulp and paper mills are often kept in continuous service for multiple decades, and this means that the opportunities of significant EE savings associated with wholesale changes to the paper making machine arise infrequently.
- There has been a tendency towards piecewise analysis of EE opportunities which misses the opportunity to leverage complementary EE measures, the result of which is that the costs of savings are higher than would have been the case if a more systems approach had been taken.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

Paper production process is complex and integrated, and EE measures applied to existing paper making machines often have to involve the paper making machine manufacturer. This, adds to the complexity and cost of such EE measures.

5.3.9 Results

The tables and graphs below show the inputs and results of the modelling for the Paper & Pulp sector. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an ‘average’ site within a sector.

5.3.9.1 Key parameters derived

Table 22: Energy savings and CapEx

Measures (Sector energy use category)	**Elec Savings (%) (range)** *RAG*	**Fuel for heat savings (%) (range)** *RAG*	**CapEx for an 'average' site (2024 prices) (range)** *RAG*
Energy management including installing meters for steam, electricity, air, and gas to allow for online energy balances (Total sector)	5% (not provided) *Amber*	10% (not provided) *Amber*	£480,000 (not provided) *Red*
Improved process control across the entire mill (process & utilities) (Total sector)	10% (not provided) *Red*	10% (not provided) *Red*	£3,600,000 (£1,200,000 - £5,900,000) *Red*
(Waste) heat recovery and heat integration (Total sector)	-1% (-3 - 3%) *Red*	9% (6-12%) *Red*	£2,000,000 (£1,500,000 - £2,500,000) *Amber*
State-of-the-art steam system. Includes condensate system with stationary siphons and spoiler bars, with optimized differential pressures for condensate evacuation (Total sector)	1% (not provided) *Amber*	13% (not provided) *Amber*	£490,000 (£400,000 - £750,000) *Red*
Match pumping capacity to duty, avoid oversizing pumps & motors, avoid throttling, use VSD and efficient motors where possible (Total sector)	15% (15-25%) *Amber*	0% (0%) *Amber*	£960,000 (not provided) *Red*
Organic Rankine cycles, heat pumps and similar heat recovery technology (Total sector)	-1% (not provided) *Red*	3% (not provided) *Red*	£1,000,000 (not provided) *Red*

Table 23: Applicability and adoption rates for BAU and Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Energy management including installing meters for steam, electricity, air, and gas to allow for online energy balances	97%	55%	68%	83%	94%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			85%	96%	98%
Improved process control across the entire mill (process & utilities)	97%	63%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			70%	77%	94%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			87%	93%	97%
(Waste) heat recovery and heat integration	96%	73%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			75%	78%	94%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			90%	94%	96%
State-of-the-art steam system. Includes condensate system with stationary siphons and spoiler bars, with optimized differential pressures for condensate evacuation	99%	71%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			75%	85%	95%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			77%	88%	99%
	100%	78%	**BAU 2030**	**BAU 2040**	**BAU 2050**

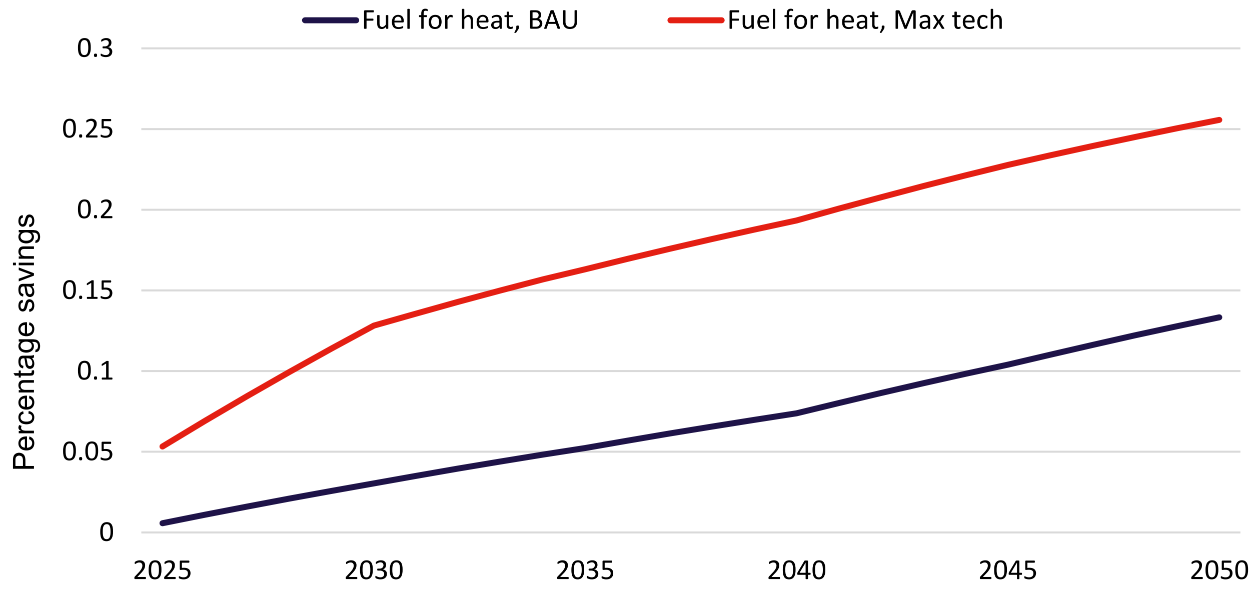
Match pumping capacity to duty, avoid oversizing pumps & motors, avoid throttling, use VSD and efficient motors where possible			80%	85%	90%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			83%	91%	99%
Organic Rankine cycles, heat pumps and similar heat recovery technology	79%	5%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			15%	40%	72%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			15%	40%	72%

These measures were entered into the DESNZ model and this yielded the detailed results set out in the sections below.

5.3.9.2 RM2024 Fuel for heat Results

Figure 17 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 17: Paper & Pulp sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios

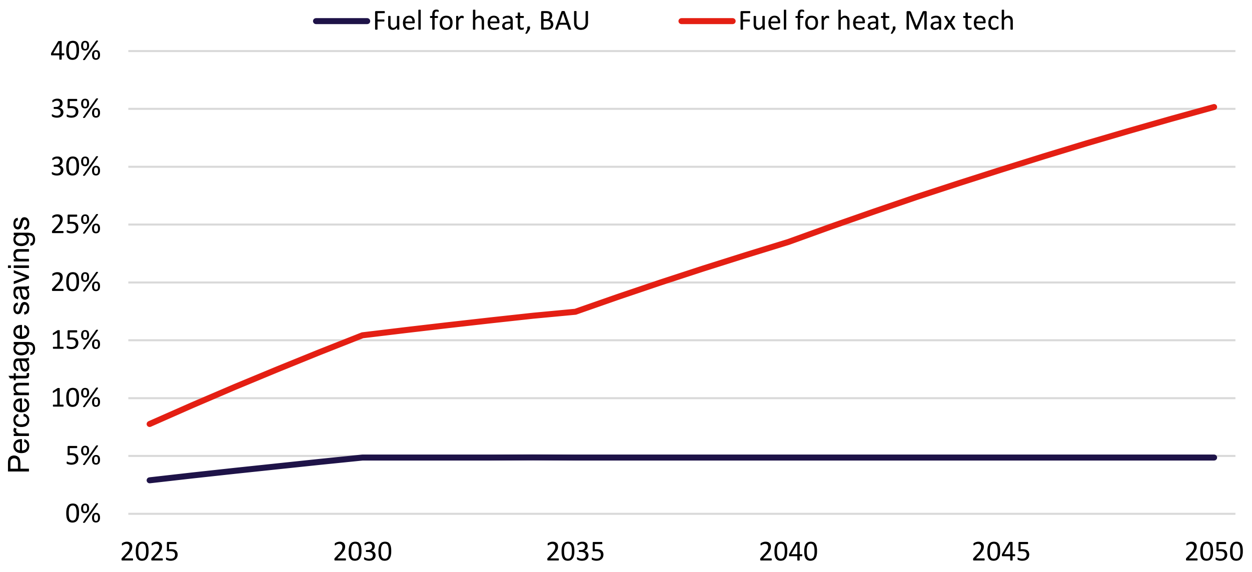


The Max Tech scenario shows a significantly more rapid increase in savings up to 2030, reaching around13% compared to 3% for BAU. After this point, the gap in savings remains relatively consistent, such that the difference by 2050 is around12%; Max Tech peaks in 2050 at 26% compared to 13% for BAU. The difference in the savings profile between BAU and Max Tech is mainly due to earlier adoption of these mature EE techniques in the Max Tech scenario. RM2024 Max Tech foresees a higher adoption in 2025 than in BAU for all prioritised measures, thereafter the rate of increase in adoption over time is similar to BAU. Adoption levels for some of the non-prioritised measures (for example, hot pressing, impulse drying, improved dewatering and high consistency forming) also increased across the time period in the Max Tech scenario. The effect is to deliver fuel-for-heat savings earlier.

5.3.9.3 RM2015 Fuel for heat Savings

Figure 18 shows the Fuel for heat savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat.

Figure 18: Paper & Pulp sector (2015 Roadmaps) – Fuel for heat Savings, expressed as a percentage of the baseline electricity, for the BAU and Max Tech scenarios



The trends between scenarios differ considerably here, with BAU savings remaining flat post 2030, whilst Max Tech starts from a higher saving (8%) and shows an almost steady increase out to 2050.

The RM2024 BAU Fuel for heat savings profile reaches about 13% in 2050 compared to the 5% reached in RM2015 BAU (relative to their respective baseline years, which are different). RM2015 BAU assumed adoption of many measures that impact on Fuel for heat at 100% by 2030 hence the flat savings profiles after 2030. RM2024 BAU envisages adoption over a longer timeframe until about 2040.

The RM2015 scenarios included 28 measures whereas RM2024 concentrates on 6 prioritised measures and also includes the effects of several non-prioritised measures. RM2015 Max Tech envisaged significant adoption (e.g. 100% by 2050) of such non-prioritised measures as Improved Dewatering, Hot Pressing, High Consistency Forming, Impulse Drying & Future Hood Heat Recovery technology. RM2024 did not contemplate such high adoption rates in 2050 for these measures because the view of adoption of such measures has been revised during the RM2024 work. Therefore, the Max Tech estimate of fuel-for-heat savings are lower in RM2024 than in RM2015.

The RM2015 BAU scenario assumed 0% adoption of ORC/Heat Pump technologies in 2050 (and 100% in Max Tech) which allowed Max Tech to deliver larger heat savings than BAU. RM2024 assumes 72% adoption by 2050 for both BAU & Max Tech and so there is no benefit in the Max Tech scenario compared with BAU in RM2024.

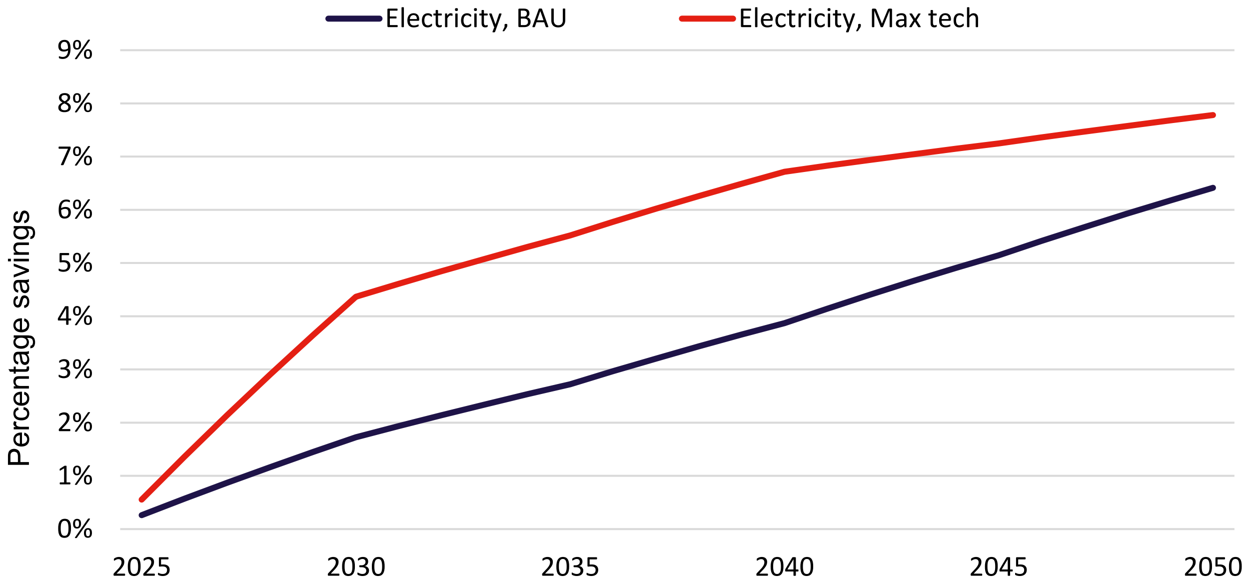
The RM2015 Max Tech scenario assumed 100% adoption by 2050 for almost all identified current EE measures and 100% is in some instances higher than assumed in the RM2024 modelling.

The RM2015 Max Tech model envisaged some adoption of 100% electrification - at a level of 0% in 2040 increasing to 25% of the sector in 2045 & 2050. Replacing direct fuel boilers with electric boilers saves significant quantities of Fuel for heat. RM2024 does not consider electrification and so the savings of Fuel for heat from the swapping of gas steam boilers with electric boilers or steam generating heat pumps are present in RM2015 but not present in RM2024. This partly explains why the Fuel for heat savings are higher in RM2015 then in RM2024.

5.3.9.4 RM2024 Electricity Savings

Figure 19 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 19: Paper & Pulp sector (2024 Roadmaps) – Electricity savings, expressed as a percentage of the baseline electricity, for the BAU and Max Tech scenarios

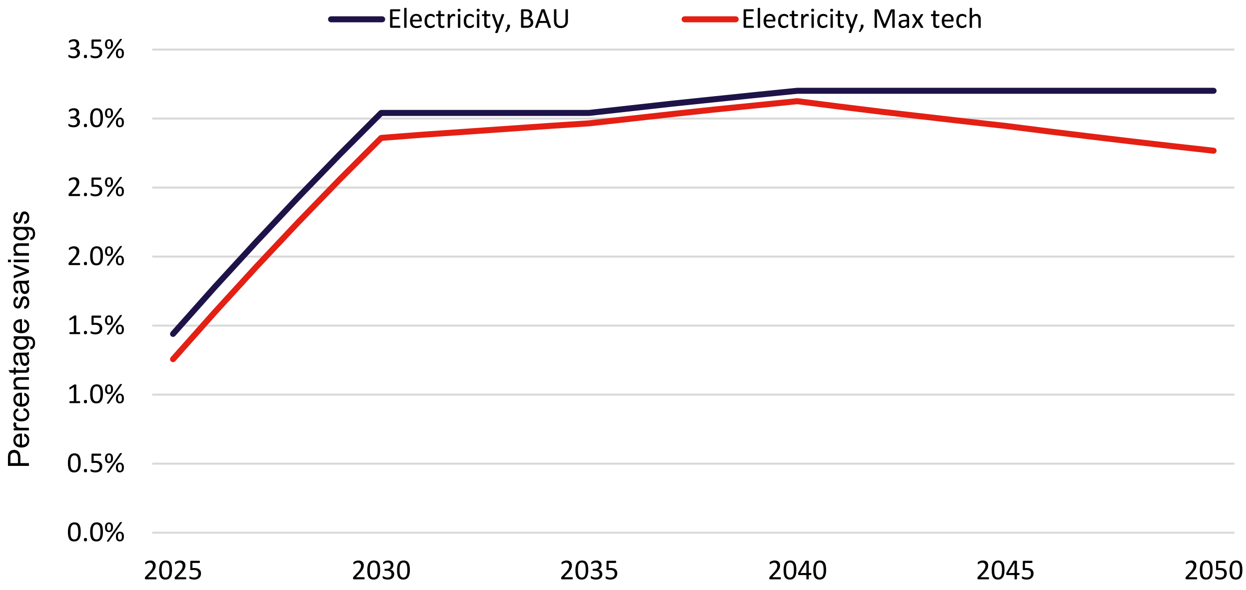


Under Max Tech and BAU scenarios, electricity savings peak in 2050 at around 8% and 6.5% respectively. The savings are achieved significantly more rapidly under the Max Tech scenario, with around 6% savings reached in 2038, 12 years earlier than under BAU. However, the gap between Max Tech and BAU does narrow by 2050, relative to the period 2030 to 2040. The difference in the electricity savings profile between BAU and Max Tech in RM2024 is mainly due to earlier adoption of these mature EE techniques in the Max Tech scenario. RM2024 Max Tech foresees a higher adoption in 2025 than in BAU for all prioritised measures; thereafter the rate of increase in adoption over time is similar to BAU. However, the earlier electricity savings delivered by this change tail off after 2040 as some measures approach maximum possible adoption in 2040 and the increment in their adoption thereafter slows down. The adoption rates for non-prioritised measures affecting electricity consumption remained constant in both the Max Tech & BAU scenarios and so do not influence the Max Tech result as much as those in the fuel-for-heat category.

5.3.9.5 RM2015 Electricity Savings

Figure 20 shows the electricity savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity.

Figure 20: Paper & Pulp sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The earlier delivery of savings under RM2024 Max Tech (compared with BAU) is not seen in RM2015, with the two profiles following very similar trajectories. Both deliver savings starting from 2025 rising to about a peak of around 3% in 2040. RM2015 BAU assumed 100% adoption by 2030 of many measures that impact electricity, hence Max Tech delivers little difference in the post-2030 period to BAU.

The overall savings across the board are significantly lower in the RM2015 study compared with RM2024. The 3% peak is significantly lower than the savings determined under RM2024, with peaks in 2050 of around 8% and 6% for Max Tech and BAU scenarios respectively.

5.3.10 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 24: High and Low scenario definitions

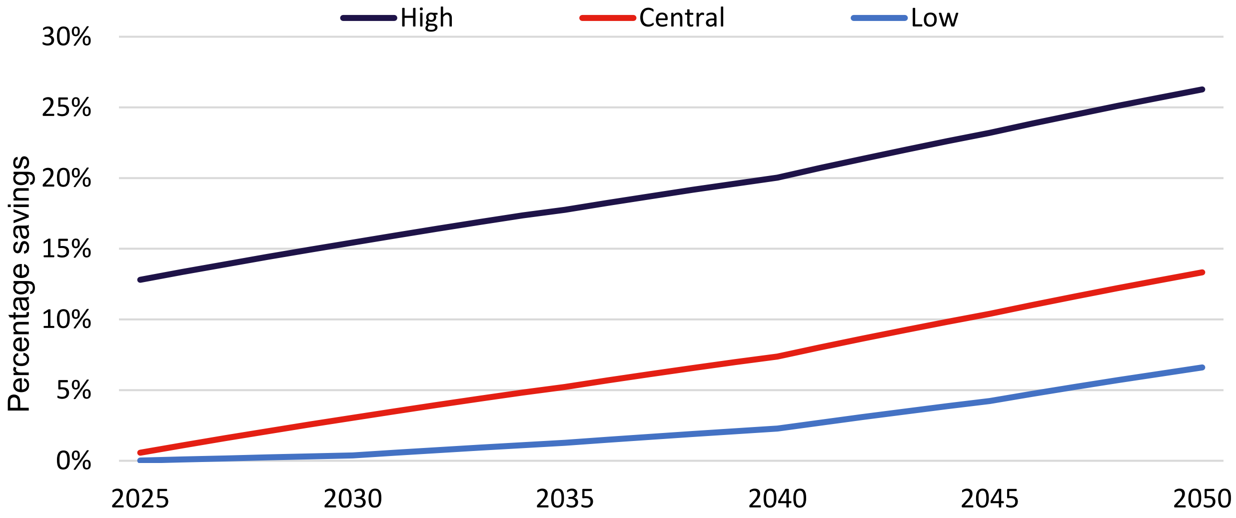
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.3.10.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 6.6%-26.3%.

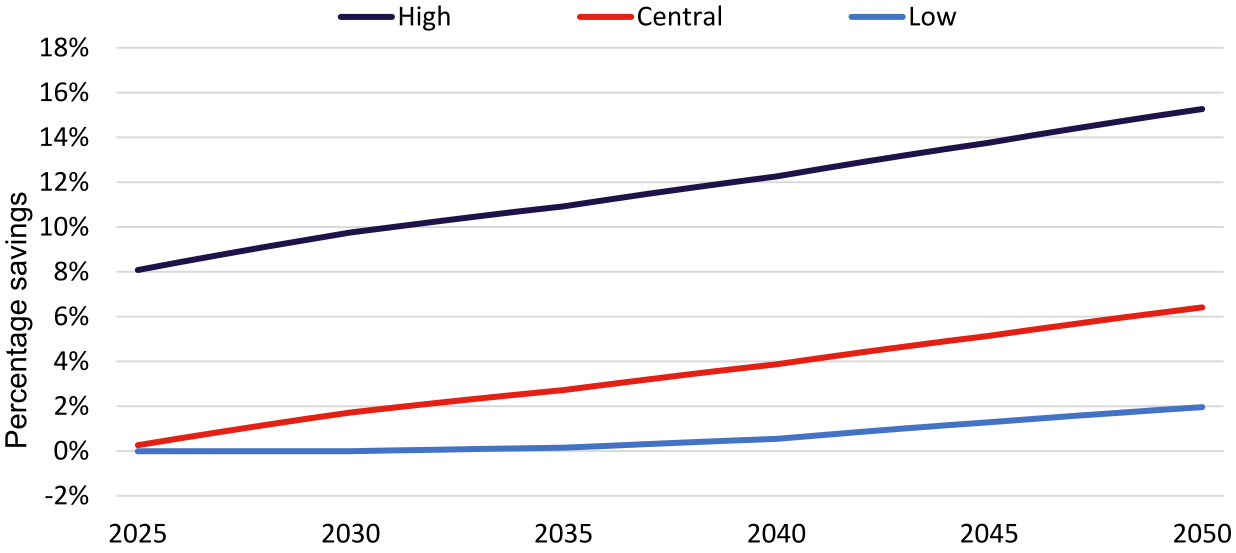
Figure 21: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.3.10.2 BAU Electricity

The range of BAU electricity savings by 2050 is 2.0 – 15.3%.

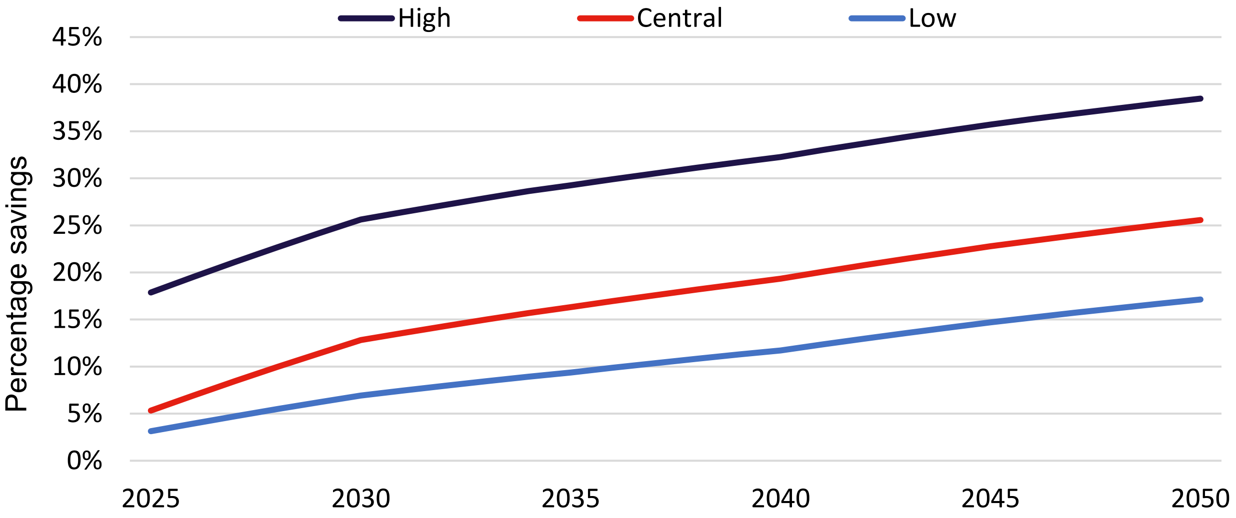
Figure 22: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.3.10.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 17.1%-38.5%.

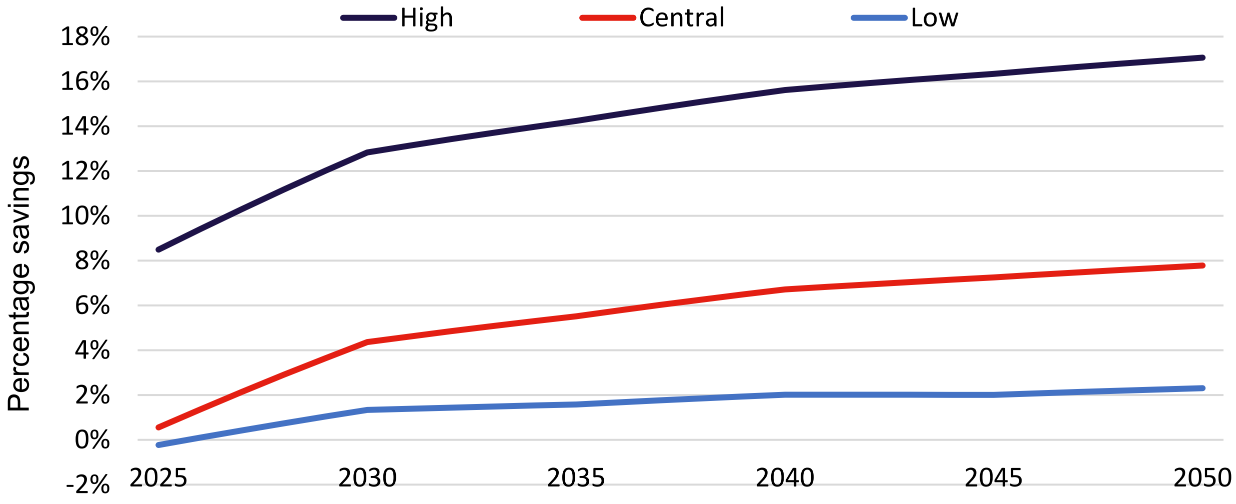
Figure 23: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.3.10.4 Max Tech Electricity

The range of BAU Fuel for heat savings by 2050 is 2.3 – 17.1%.

Figure 24: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.3.11 Limitations

The following limitations are applicable to the analysis carried out for the Paper & Pulp sector and should, therefore, be kept in mind when considering the results presented here:

The sector is heterogeneous in nature. There are 40 mills are of very different sizes (annual production capacities range from a few hundred tonnes up to 800,000 tonnes and annual direct fuel consumptions range from a handful of GWh to over 1,000 GWh). Applying absolute values to a particular EE measure with any certainty is difficult, especially concerning CapEx, since the CapEx of a project tends to scale with the size of a site.

Mills make different products and require different equipment to do so - not all EE measures are applicable to all mills.

EE strategies and investment decisions at paper mills can be complex as many sites have CHP and generate their own electricity. Opportunities to save heat or electricity on the paper machine can compromise the efficiency of CHP operation if not considered carefully.

There was limited operator engagement throughout the project partly due to commercial sensitivity and the risk of disclosing information to competitors. This limited the ability to corroborate findings from the literature and sector experts.

Workshop participation was limited to a few operators who represented a small number of mills. Views on payback, adoption and CapEx were generally only provided by one or two attendees.

When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category's energy use for a 'representative site' within the sector. Representative site is difficult to conceptualise, in particular in the paper & pulp sector where there is inherently a large distribution of size of site. This introduces a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of "percentage energy savings".

5.4 Sector 4 (Chemicals)

5.4.1Definition and context

The Chemicals sector analysed in this work covers activities included in the following SIC codes:

20 Manufacture of chemicals and chemical products

21 Manufacture of basic pharmaceutical products and pharmaceutical preparations

The chemicals sector is a very significant sector in terms of energy use. It is also very diverse and so represents a particular challenge for estimating unfulfilled EE potential in a way that is appropriate for the resources available to this project.

The UK chemicals sectors is commonly considered to be made up of the following sub-sectors:

- Bulk Inorganic Chemicals –
- Chlor-alkali
- Ammonia, Acids, Alkalines
- Fertilisers (LVIC-AAF)
- Bulk Inorganic Chemicals - Other (LVIC-O)
- Bulk Organic Chemicals (LVOC)
- Polymers
- Fine organic chemicals
- Speciality Inorganic Chemicals

The chemicals sector is in a state of flux with company acquisitions and rationalisations leading to the discontinuation of production of products (and therefore certain processes) over time. An example of this is the recent cessation of the production of ammonia in the UK because of high feedstock (natural gas) prices and other factors affecting competitiveness. The outlook for petrochemical crackers in UK is also very uncertain.

5.4.2 Literature Review

5.4.2.1 Sources Identified and their relevance

The literature review for the chemicals sector yielded thirty-two sources of various usefulness to this work, sorted into high, medium and low relevance. Sources were rated based on a combination of factors, geographical relevance, author credibility, recency of the publication and availability of statistics on cost and energy savings potential. Five out of the thirty-two sources were rated high, twenty-six were rated medium and one were rated low. The majority of the sources were from the European and British context (twenty-eight and three sources, respectively), whilst the rest were from other OECD countries. The literature was mostly taken from peer-reviewed sources, including those published by projects under the EU-CORDIS programme, equating to seven sources. The rest of the literature was taken from expert authors, including industry associations, EU-constituted industry technical expert working groups and product manufacturers.

Sources reviewed included both existing authoritative sources such as the European Union BREF documents for the chemicals industry giving the Best Available Techniques (BAT) for improved energy efficiency, as well other peer reviewed and expert author sources such as EU-Cordis reports giving the outputs from the Horizon 2020 programme for new technologies going beyond the current state of art in the sector, with TRLs between 4 to 8.

The EU-Cordis reports (for completed projects) comprise project reports as deliverables, as well as articles in academic journals giving additional details on work completed on the energy efficiency innovation by the project. Other literature reviewed included articles in Science Direct in particular, articles in other academic journals and expert author reports by other private and public organisations.

The sources collectively present an understanding of the challenges and opportunities in achieving energy efficiency and carbon emissions reduction within the chemicals industry.

5.4.2.2 Conclusions from Literature Review – Gaps and limitations

The main gaps identified during data collection are discussed below.

Despite the fact that energy savings and optimisation measures in the industry can be broadly described in different categories, the numerous processes and their variations means that it is difficult to gather data and list all the options available.

Information on CapEx, OpEx and installation costs for different processes and technologies both current best practice and in new process technologies beyond current state of the art was very sparse.

Information on the interaction of EE measures with other EE measures was rarely covered in the literature

5.4.3 Engagement

Engagement with the sector took the following form:

- 1 interview with the Sector Association – Chemical Industries Association (CIA)
- Interviews with 8 operators (Solenis, Ineos Acetyls, Victrex, Dow Silicones, Syngenta, CF Fertilisers, GEO Specialty Chemicals, Tronox), 2 academics and 2 consultancies (Green Alliance, Centre for Process Innovation)
- Questionnaires, with responses received from 4 stakeholders
- One 3-hour workshop attended by the CIA, 3 operators, 1 academic and 1 consultancy

5.4.4 Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and adoption out to 2050. Applicability and adoption were discussed during the workshop in the context of whether the EE measures were dependent or independent (Deep Decarbonisation Dependency).

Table 25 lists the prioritised measures and their dependency on deep decarbonisation scenarios.

Table 25: EE measures prioritised for the Chemicals sector and dependency on deep decarbonisation scenarios

Measure Name	Measure Description	Deep Decarbonisation Dependency
Improved Process Control	Hardware and Software upgrades to the centralised control systems of chemicals manufacturing sites. This measure include, as example, adoption of smart metering systems or AI powered software for the management and optimisation of the operations. **2015 measure.**	Independent
Improved Waste Heat Recovery	High grade heat recovery is a fundamental activity in the chemical sector. This measure includes, as example, pinch analysis, heat network and heat pumps. **2015 measure.**	Dependent
More Efficient Equipment	Improved process equipment includes the replacement of aged, or less-performing equipment with newer elements. This category includes major equipment substitution (i.e. Distillation columns, reactors) and the replacement of ancillary units as well (i.e. CHP). **2015 measure.**	Independent

Measure Name	Measure Description	Deep Decarbonisation Dependency
Improved Insulation	Improved insulation is focused on limiting or avoiding loss of heat in the site operations. **2015 measure.**	Independent
Improved Steam System Efficiency	Steam constitutes one of the main energy vectors in the chemical field, given its reliability and high thermal capacity. Steam system solutions include, as example, improved natural gas combustors in steam boilers, recovery of high temperature condensate, and the use of economisers in the system. **2015 measure.**	Dependent
High Temperature Operations - Microwaves	The use of microwaves is applied to high temperature operations (400 C plus) to minimise heat losses and avoid emissions due to natural gas, or other fuels, combustion. The main advantage of this solution, compared to conventional processes, is related to the fact that microwave can target the material processed rather than heating up the whole vessel. **RM2024. This measure has been excluded from the modelling given the low degree of engagement and know-how of the stakeholders.**	Independent

5.4.5 Key assumptions

The potential for heat pumps as an EE measure has been omitted from this analysis. While the use of heat pumps to displace fuel combustion in a boiler to generate hot water or even steam can produce significant energy savings, in the context of this study it is deemed a fuel switching measure and is therefore, strictly speaking, out of scope.

5.4.6 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.4 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the chemicals sector came to light and these are listed below.

The following barriers were identified during the literature review:

- Technical barriers that limit already demonstrated technology to improve EE include compatibility between the technology and current production process being operated, i.e., limited potential for the technical integration of EE measures into existing chemical plants (retrofit) and the financial and technical risk of unsuccessful development. There may also be plant specific factors on chemicals installations, given the complex multi-product nature of chemicals production, meaning that individual chemicals sites are often very different from each other. This limits the perceived replicability of measures.
- The ownership structure of plants in the UK context may also present a barriers. The – fragmented ownership of plants within chemicals industry clusters can lead to sub-optimal long-term strategies.
- Availability of external and internal capital for investment. This is primarily a barrier for smaller companies rather than large multinational businesses, although sites owned by multinational businesses have their own challenges with winning investment when competing with projects in other countries (see below).

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- Loss of competitiveness with the Eastern Asian countries, due to lower labour and energy costs, makes it difficult to secure funds to invest in EE measures in the chemicals sector in the UK.
- Most of the businesses in the chemical sector are part of multinational groups, with a common investment fund. To be able to access these funds, each company must compete with their foreign counterparts.
- Shortage of staff and, in particular, time is a general barrier to improving existing processes, which was cited by all of our interviewees. Typically, in large firms no more than 10 people are experienced in EE improvement related co-ordination and
- management and there are also shortages in the supply chain in the UK.

5.4.7 Results

The tables and graphs below show the inputs and results of the modelling for the Chemicals sector. EE measures for the Chemicals sector have broad definitions due to the heterogeneity of sector activities, hence the percentage energy savings for all measures are framed in proportion to total sector energy. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing CapEx requirements for the Chemicals sectors as a whole.

5.4.7.1 Key parameters derived

Table 26: Energy savings and CapEx

Measures	Elec Savings (%) (range) *RAG*	Fuel for heat savings (%) (range) *RAG*	Total sector CapEx (£, 2024 prices) (range) *RAG*
More efficient equipment	4% (not provided) *Red*	4% (not provided) *Red*	£600,000,000 (£500,000,000 - £1,500,000,000) *Amber*
Improved waste heat recovery	0% (not provided) *Red*	2% (0.3-2%) *Red*	£200,000,000 (£150,000,000 - £400,000,000) *Amber*
Improved steam system efficiency	0% (0%) *Red*	4% (not provided) *Red*	£100,000,000 (£80,000,000 - £200,000,000) *Amber*
Improved process control	4% (0.5-10%) *Amber*	3% (2-5%) *Green*	£50,000,000 (£40,000,000 - £100,000,000) *Green*
Improved insulation	0% (0%) *Red*	0.5% (not provided) *Red*	£50,000,000 (£40,000,000 - £100,000,000) *Green*

Table 27: Applicability and adoption rates for BAU and Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
More efficient equipment	90%	60%	65%	75%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			65%	80%	90%
Improved waste heat recovery	85%	75%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			75%	78%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			80%	85%	85%
Improved steam system efficiency	70%	60%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			62%	65%	70%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			70%	70%	70%
Improved process control	90%	65%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			70%	80%	85%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			80%	85%	90%

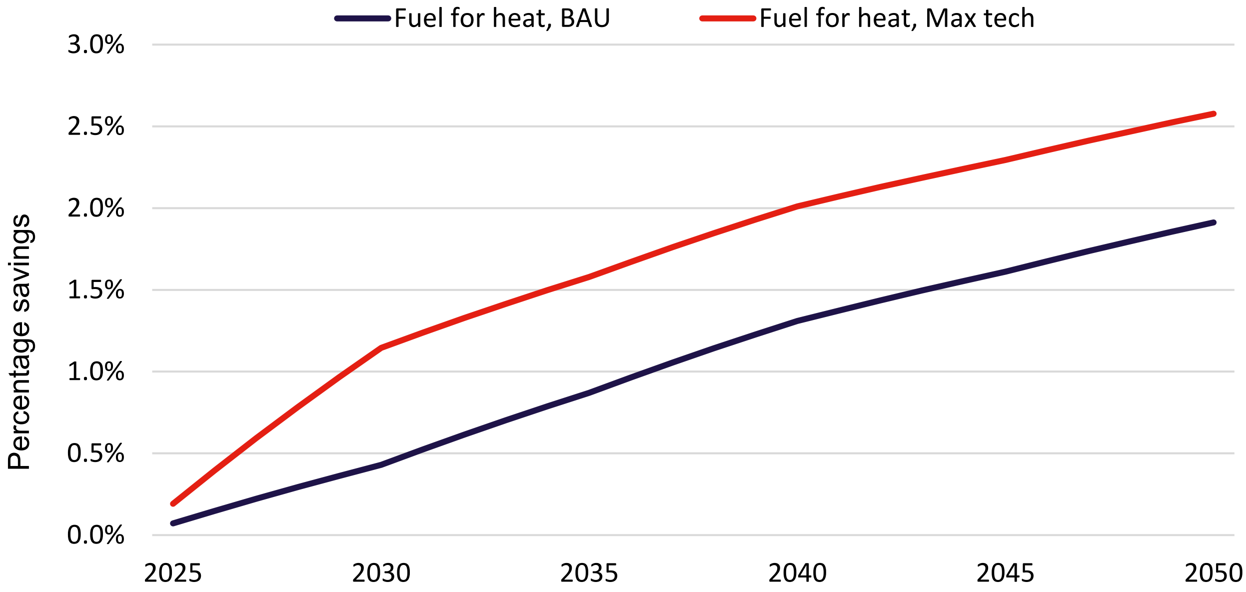
<table>
<tr><td rowspan="4">Improved insulation</td><td rowspan="4">95%</td><td rowspan="4">85%</td><th>BAU 2030</th><th>BAU 2040</th><th>BAU 2050</th></tr>
<tr><td>85%</td><td>88%</td><td>90%</td></tr>
<tr><th>Max Tech 2030</th><th>Max Tech 2040</th><th>Max Tech 2050</th></tr>
<tr><td>85%</td><td>90%</td><td>95%</td></tr>
</table>

These measures were entered into the DESNZ model, yielding the results set out in the sections below.

5.4.7.2 RM2024 Fuel for heat Savings

Figure 25 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 25: Chemicals sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios

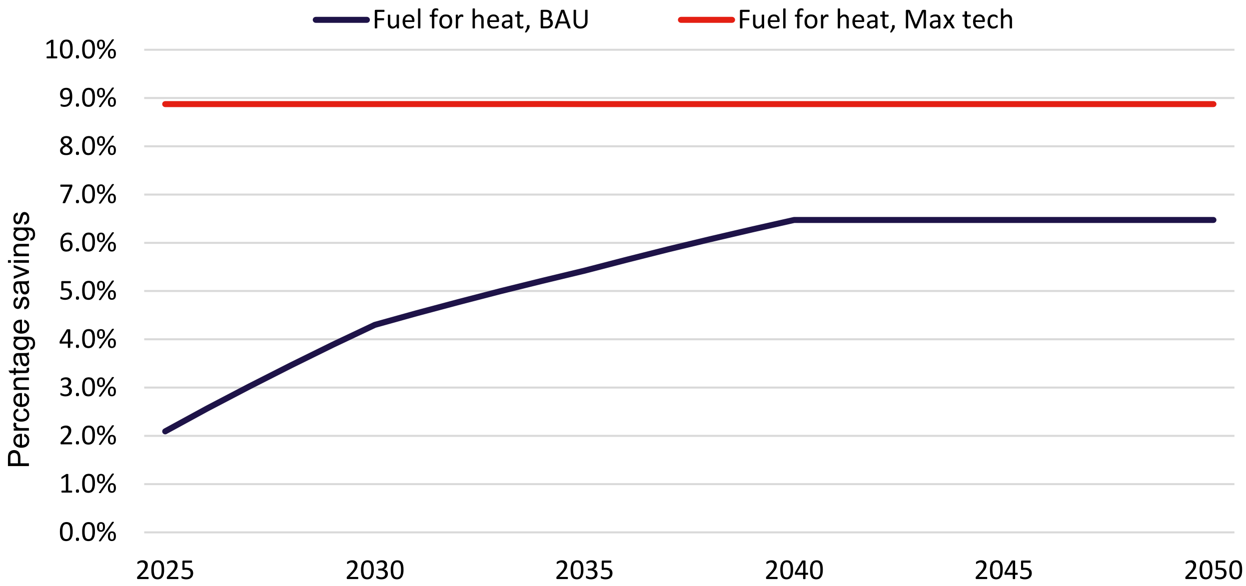


The two scenarios follow similar trajectories, though where Max Tech slows after 2030, the rate of increase of savings slightly increases for BAU. Max Tech shows higher savings consistently out to 2050, reaching a peak of around 2.5%, compared to 2% for BAU.

5.4.7.3 RM2015 Fuel for heat Savings

Figure 26 shows the Fuel for heat savings, determined under the previous project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat.

Figure 26: Chemicals (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



The Max Tech scenario shows an almost flat trajectory, with no increase in savings by 2050, compared to the starting point in 2025 of ~9%. Conversely, BAU shows a steady increase in savings out to 2040, at which point the savings flatten out. The rate of increase in savings is highest between 2025 and 2030 and slows between 2030 and 2040.

Here, the gap between Max Tech and BAU is around 2.5% by 2050, compared to 1% in the RM2024 study. Further, the overall potential savings shown are also higher with RM2015, with a Max Tech peak of 9% compared to 2.5%.

Comparing the 2015 and 2024 scenarios, there are two likely explanations for why the savings potential is lower for RM2024 than RH2015. These are:

- The sector has already implemented, directly or indirectly, EE measures to limit their running costs, especially in the last 24 months, after the start of the Ukrainian conflict.
- The sector has a long history of energy optimisation, accelerated by the several rounds of ESOS performed in the last 10 years.

Therefore, the potential energy savings, still achievable by the industry, are considerably lower than indicated in RM2015. However, there is still a considerable amount of energy savings that can be achieved (2.5%), especially in high temperature operations (i.e. Furnaces and other high temperature processes).

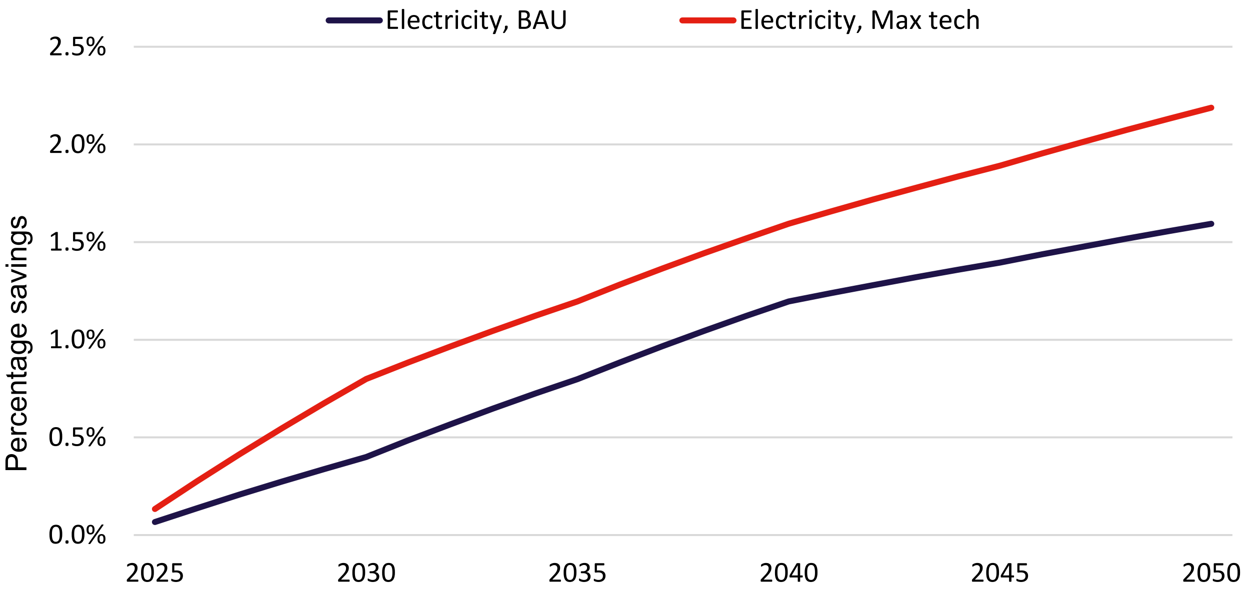
Those processes currently present the greatest potential to reduce energy consumption. However, this would require a considerable CapEx investment to partly or fully replace those units with more efficient ones. Given the barriers discussed, the remaining saving percentage will be achieved at a slow rate which will, in turn, depend other market forces. Nevertheless, the chemical industry, according to most stakeholders, already largely implemented most of the energy savings measures available to it.

The main differences between Max Tech and BAU scenarios is due to the constraints and challenges which the sector is facing (i.e. limited competitive edge in the worldwide market and high OpEx).

5.4.7.4 RM2024 Electricity Savings

Figure 27 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 27: Chemicals sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The two scenarios show a similar trajectory out to 2040, after which the rate of increase under BAU slows somewhat. Max Tech shows a relatively consistent increase out to 2050, reaching a peak of around 2.2%. BAU also peaks in 2050, reaching savings of 1.6%.

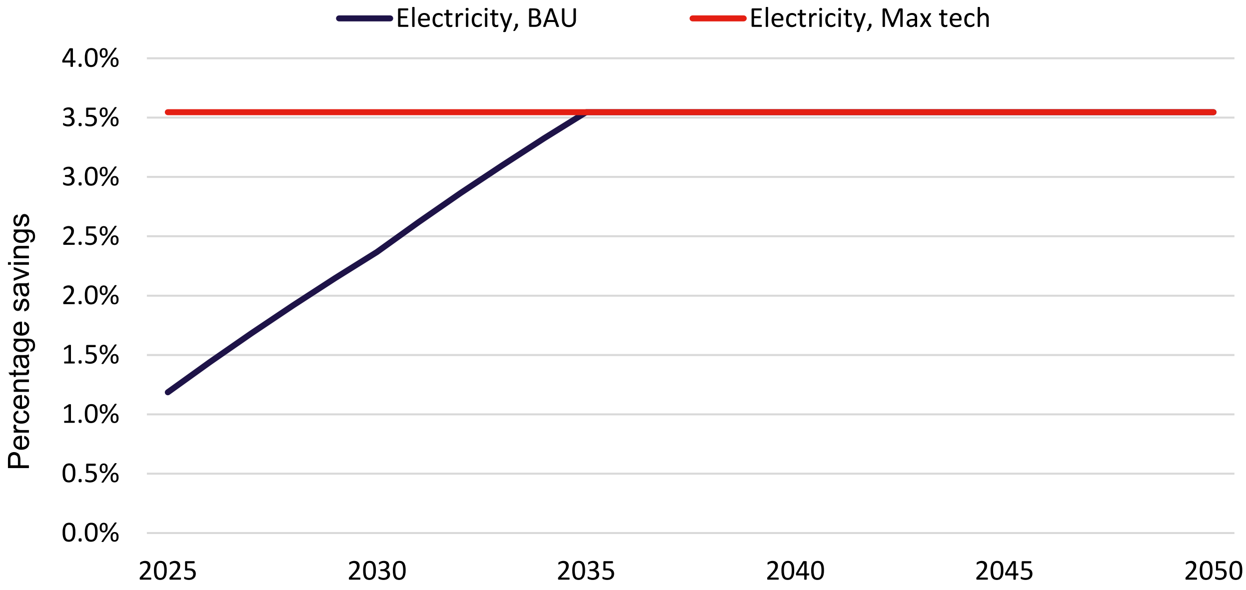
The sector’s EE measures are well-established and widely adopted, leaving limited room for further improvements. Despite this, many measures offer good payback periods, making investments viable when funds are available. The RM2024 BAU scenario projects a steady adoption of these EE measures through 2050.

The difference in electricity savings between the BAU and Max Tech scenarios in RM2024, starting in 2025, is primarily due to the earlier implementation of mature EE techniques in the Max Tech scenario. RM2024 Max Tech anticipates a significantly higher adoption in 2025 compared to BAU for all measures. After 2025, the adoption rates increase similarly in both scenarios. However, the early electricity savings from this change diminish after 2040 as some measures near their maximum adoption, slowing their incremental increase. The adoption rates for non-prioritised measures affecting electricity consumption remain constant in both scenarios, thus having less impact on the Max Tech results compared to those in the fuel-for-heat category.

5.4.7.5 RM2015 Electricity Savings

Figure 28 shows the electricity savings, determined under the previous project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity.

Figure 28: Chemicals sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The Max Tech scenario shows higher savings in 2025, at around 3.5% versus 1.2% for BAU, and remains flat out to 2050. However, by 2035, the scenarios converge, with BAU showing a steady increase up to 2035, and then remaining flat out to 2050.

Compared with RM2024, BAU and Max Tech savings for RM2015 are consistently higher than those identified in RM2024, with both scenarios reaching savings of 3.5% compared to around 2.2% and 1.6% for Max Tech and BAU for RM2024 respectively. Further, there is no gap between the scenarios shown with RM2015, compared to a gap of ~0.6% under RM2024.

This is due to the different metrics adopted; adoption and applicability rates differ from those of RM2015 given the different nature of the metrics. RM2015 adoption rates for the sector (0%) were based on a relative approach, not including the actual adoption rate of some of these measures in the sector. The RM2024 approach consider the adoption and applicability rates on an absolute basis. The methodology change, despite providing a more robust view of the sector, also generates a substantial difference with the RM2015 results.

5.4.8Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 28: High and Low scenario definitions

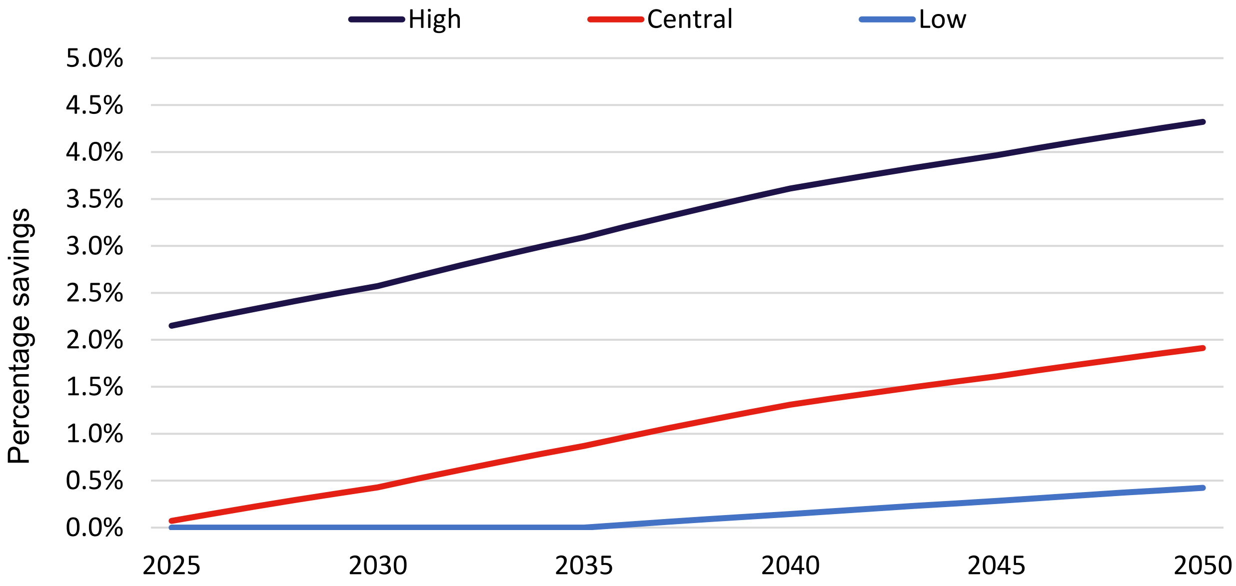
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.4.8.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is around 0.5– 4.3%.

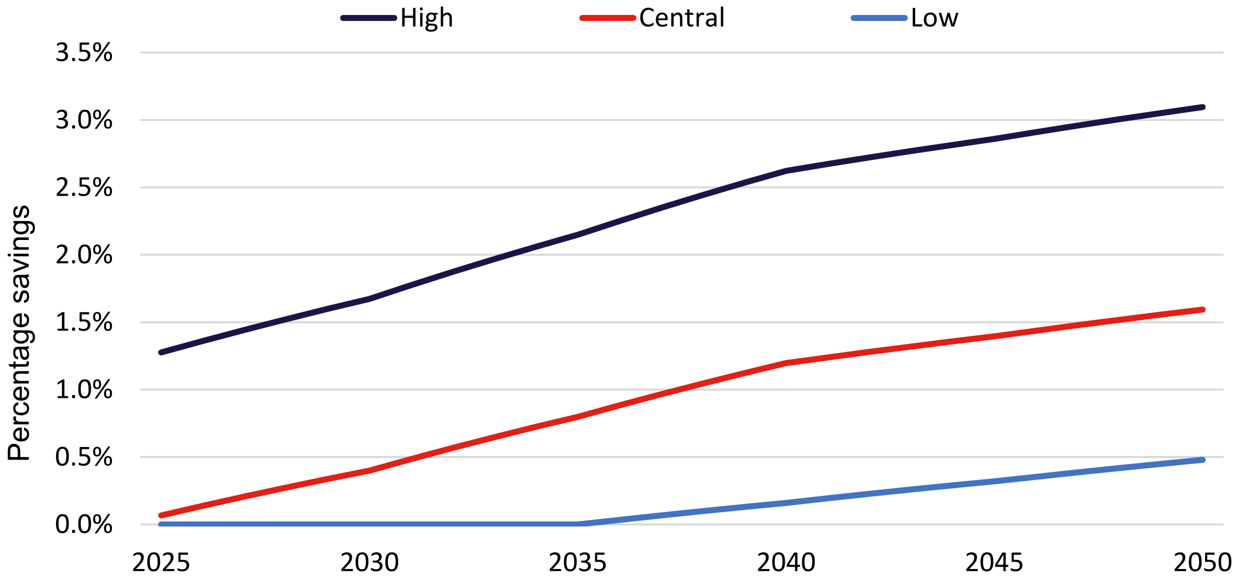
Figure 29: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.4.8.2 BAU Electricity

The range of BAU Fuel for heat savings by 2050 is around 1.0% – 3.1%.

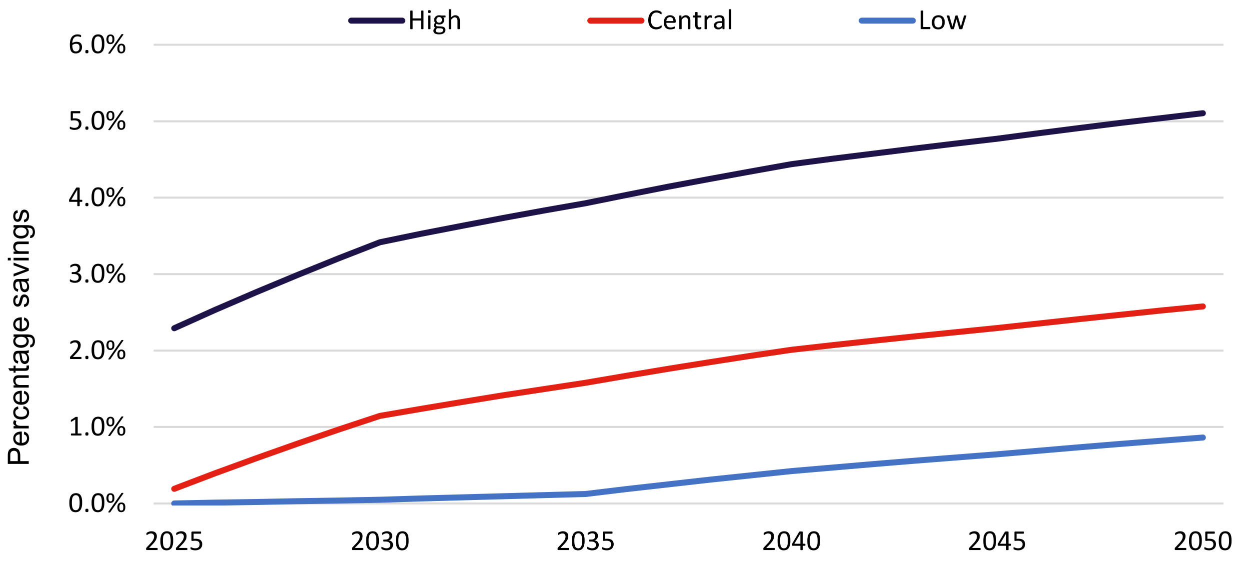
Figure 30: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.4.8.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is around 1.0%-5.1%.

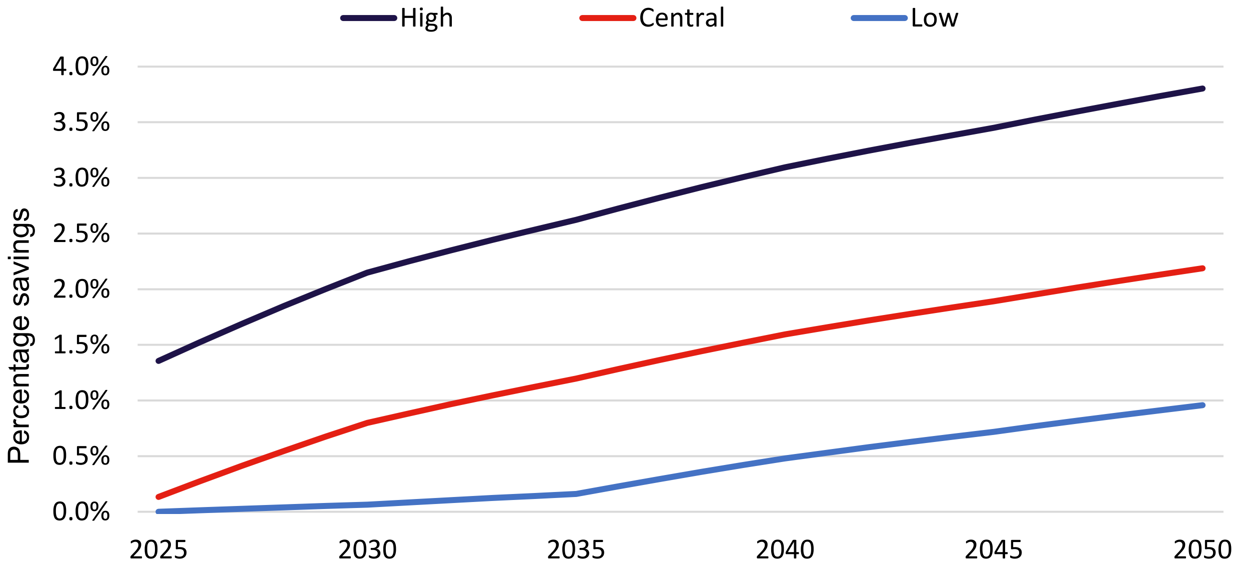
Figure 31: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.4.8.4 Max Tech Electricity

The range of BAU Fuel for heat savings by 2050 is 1.0% – 3.8%.

Figure 32: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.4.9 Limitations

The following limitations are applicable to the analysis carried out for the Chemicals sector and should, therefore, be kept in mind when considering the results presented here:

The Chemicals sector, especially in the UK, presents a wide variety of operations, processes and products. Given the heterogeneity of the sector, the EE measures adopted have been identified only at a high level. This has often led to confusion of engaged stakeholders, as they often specialise only in their specific sub-sector (i.e. Bulk Chemicals).

Limited responses have been gathered regarding the applicability and adoption rates for most of the EE measures, given the factors mentioned above.

The CapEx associated with the more efficient equipment measures is particularly high, compared to those proposed in 2015, as stakeholders are now considering this type of measure to include the replacement of pivotal process equipment, such as distillation columns and reactors, which are often major investments.

The lack of competitiveness of the UK Chemicals sector, due to high energy costs and direct competition with eastern Asian countries, strongly limits sites’ capital availability. Several stakeholders have stressed this factor and highlighted that some sites have already reduced or limited their processing capacity. However, the extent of this phenomenon is not entirely clear in the sector. For example, recent information shared by the Chemical Industries Association (CIA) with DESNZ show that the activity index of chemicals production in the UK is about 20-30% lower now than before the Covid-19 pandemic.

When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category’s energy use for a ‘representative site’ within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of “percentage energy savings”.

5.5 Sector 5 (Iron & Steel)

5.5.1 Definition and context

The Iron & Steel sector analysed in this work covers activities included in the following SIC codes:

- 24.1 Manufacture of basic metals
- 24.2 Manufacture of tubes, pipes and profiles of steel
- 24.3 Manufacture of other products of first processing of steel

Owing to the radical changes being undertaken at the UK’s remaining integrated steel works (i.e. their conversion from blast furnace to electric arc furnace-based steel making) this study has not considered processes upstream of hot metal casting at integrated steelworks.)

The steel sector in the UK can be crudely analysed as being comprised of two main subsectors: primary or secondary (recycled) steel production and steel processing. Steel production occurs at the two remaining integrated steelworks (Port Talbot and Scunthorpe) and a few Electric Arc Furnace (EAF) sites. These steel producers produce semi-finished products (e.g., blooms, billets and plates) which are typically sent downstream to other sites for further processing.

The steel sector in the UK is at a crossroads. During the course of this study, both integrated sites announced plans to shut down the Blast Furnace (BF)/Basic Oxygen Steelmaking (BOS) route and replace these with the EAF route. EE measures identified in this study applying to certain processes will not be pursued by the industry. These processes are: coke production, sinter plant, blast furnaces and BOS furnaces. The casting process at the integrated steel works (and associated EE measures) remains relevant.

5.5.2 Literature Review

5.5.2.1 Sources Identified and their relevance

The literature review for the Iron & Steel sector yielded 60 sources of various usefulness to this study, sorted into high, medium and low relevance. Sources were rated based on a combination of factors, geographical relevance, author credibility, recency of the publication and availability of statistics on cost and energy savings potential. 20 out of the 60 sources were rated high, 28 were rated medium and 12 were rated low. The majority of the sources were from the European and British context, 31 and 7 sources respectively, whilst the rest were from other OECD countries. The literature was mostly taken from peer-reviewed sources, including those published by projects under the EU-CORDIS programme, equating to 33 sources. The rest of the literature was taken from expert authors, including industry associations, EU-constituted industry technical expert working groups and product manufacturers. Key sources for the sector reviewed included both existing authoritative sources such as the European Union Best Available Techniques (BAT) reference documents (BREF) for iron and steel giving the BAT for improved EE in the iron and steel, and ferrous metals processing industries, as well other peer reviewed and expert author sources such as EU-CORDIS[14] reports. The latter give the outputs from the Horizon 2020 programme for new technologies going beyond the current state of art in the sector, with TRLs between 4 to 8.

The Other literature reviewed included articles in Science Direct in particular, articles in other academic journals and expert author reports by other private and public organisations.

The sources collectively present an understanding of the challenges and opportunities in achieving EE and carbon emissions reduction within the iron and steel industry.

It should be noted that while the literature review addressed all processes associated with the primary, secondary and downstream processing of iron and steel, the subsequent analysis of EE potential was confined to secondary steelmaking and downstream processing, Specifically, processes upstream of casting hot metal at integrated steelworks were omitted. The rationale for this is that both integrated steelworks in the UK have plans to convert from the blast furnace/basic oxygen steelmaking (BF/BOS) route to the Electric Arc Furnace (EAF) route.

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[14] EU-CORDIS reports comprise project reports as deliverables, as well as articles in academic journals giving additional details on work completed on the EE innovation by the project.

5.5.2.2 Conclusions from Literature Review – Gaps and Limitations

The main gaps identified during data collection are discussed below.

- Information on CapEx and OpEx for different technologies, both current best practice and, in particular, new technologies currently being developed was very scarce.
- The interaction of EE measures with other EE measures was not discussed as a topic in its own right.

5.5.3 Engagement

Engagement with the sector took the following forms:

- 1 interview with the Sector Association – UK Steel
- Interviews with 4 operators (Liberty, Celsa UK, British Steel, Tata Steel), 1 academic (Zushu Li, University of Warwick) and 1 researcher (Jon Bolton, Materials Processing Institute)
- Questionnaires with responses received from 3 stakeholders
- One 3-hour workshop attended by the UK Steel, 4 operators, 1 consultant and 1 academic

5.5.4 Main categories of Energy Use

For the purposes of modelling energy savings, the Iron & Steel sector activities have been aggregated into the following categories against which EE measures have been applied (including baseline energy consumption):

Table 29: Share of each fuel type in the baseline attributed to each category in the Iron & Steel sector

Category	**Percentage of Total Sector Energy Use (%)**				
	Electricity	**Gas**	**Coal**	**Oil**	**Biomass**
Total Integrated	*46%*	*6%*	*99.7%*	*0%*	*0%*
BOF	11%	5%	0%	0%	0%
Sintering	14%	1%	0%	0%	0%
Other Integrated	21%	0%	99.7%	0%	0%
EAF	35%	27%	0.3%	0%	0%
Secondary Processes	19%	67%	0%	0%	0%
Total Sector Energy	**100%**	**100%**	**100%**	**0%**	**0%**

The sector is analysed as consisting of three main sections:

(1) Primary steelmaking which includes the processes up to and including the casting of hot metal produced via the Blast Furnace/Basic Oxygen Steelmaking (BF/BOS) route. This corresponds to the category above known as Total Integrated.

(2) Secondary steelmaking which includes the processes up to and including the casting of hot metal produced via the EAF steelmaking route. This corresponds to category EAF.

(3) Downstream activities for the processing of cast steel, which may be carried out downstream of casting at BF/BOS site and EFA sites or at other sites which do not make steel but receive it and process it. This corresponds to category Secondary Processes.

Owing to the complexity of integrated steel sites, further process breakdowns are undertaken within the Integrated category to observe the blast and basic oxygen furnace activities (BOF), the sintering activity for producing sinter burden for the blast furnace (sintering) and other activities at integrated steelworks (Other Integrated).

Note: Owing to the radical changes being undertaken at the UK's integrated steelworks, only the parts of the sector represented by (2) and (3) are analysed in this work.

5.5.5 Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and adoption out to 2050. Applicability and adoption rates were discussed during the workshop in the context of whether the EE measures were dependent or independent (Deep Decarbonisation Dependency).

Table 30 and Table 31 list the prioritised and non-prioritised measures, the categories of energy consumption to which they apply, and their dependency on deep decarbonisation scenarios.

Table 30: EE measures prioritised for the Iron & Steel sector and dependency on deep decarbonisation scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Improved Automation & Process Control (Total sector)	Automatic management of production conditions to maintain quality, throughput, and efficiency in the plant. Achieves small energy savings. **2015 measure.**	Independent
Improved Planning & Throughput Optimisation (Secondary processes)	Reduces the need to 'keep warm' and thereby reduces heat loss and ensures better utilisation of rolling mill capacity. Similarly, avoiding furnace overloading will lead to reduced energy consumption per unit. **2015 measure.**	Independent

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Re-heating Furnace Optimisation (Secondary processes)	Improvements include optimising control of heating time using computer modelling, burner upgrades (use of recuperative, regenerative, or pulsed burners, oxy-fuel or flameless combustion), reduction in excess air / air leakage, and furnace wall insulation. **2015 measure.**	Independent
Use of Premium Efficiency Electrical Motors and VSDs (Total sector)	Replacement of motors across the site to new, more efficient motors. **2015 measure.**	Independent
Endless Strip Production (ESP) (Secondary processes)	Casting and rolling processes performed in a single step; hot strand of metal directly rolled in an endless process, without having to cut slab ingots beforehand and potentially reheat, which saves time and energy. **2015 measure.**	Independent

5.5.6Non prioritised measures

Table 31: EE measures non-prioritised for the Iron & Steel sector and dependency on deep decarbonisation scenarios

Measure Name	**Measure Description**	**Deep Decarbonisation Dependency**
Heat Recovery & Re-use - Conventional Options (Total sector)	Recovering waste heat so that it can be re-used	Dependent
Scrap Densification / Shredding (Electric arc furnace)	Densifying scrap materials from the EAF so that they take up less volume, thus decreasing space taken up in landfills, and storage and transformation costs.	Independent
Heat Recovery & Re-use - Innovative Options (Total sector)	Recovering waste heat so that it can be re-used	Dependent
Improved Process Control (Electric arc furnace)	Process control automatically manages production conditions to maintain quality, throughput, and efficiency in the EAF.	Independent

5.5.7 Key assumptions

The replacement of blast furnaces and associated integrated steelmaking activities with EAF can be expected to result in net energy savings per tonne of steel produced, with reduced fuel demand and an increase in electricity demand. However, there are also additional factors which affect the total energy use, such as a change in the production level which may also come from this transition. It is assumed that the new EAFs which are installed as part of this transition are best available technology and that there is no opportunity for adoption of EAF related EE measures identified in this study in these new facilities. Therefore, RM2024 modelling does not include the energy use in the blast furnace route nor the replacement EAFs.

5.5.8 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.3 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the iron & steel sector came to light and these are listed below:

- Limited potential for the technical integration of EE measures into existing iron and steel plants (retrofit) and the financial and technical risk of unsuccessful development. For example, the recovery of all grades of waste heat is a significant opportunity for the iron and steel industry to improve their EE, but matching recovered heat to industrial demand is more complex, not least because production and demand may not be aligned, either temporally or spatially.
- In the UK context uncertainty over the future of primary steelmaking at the two integrated steelworks remaining in the UK is itself a barrier to investment in EE measures.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- Significant plans to change from primary steel making (BF/BOS route) to secondary making (EAF route) are claiming much of the capital budgets available to steel producers. While this will achieve a large step reduction in carbon emissions it diverts away from EE project that could be applied to downstream processing.
- High electricity prices reduce margins and reduce availability of capital to fund EE projects.

5.5.9 Results

The tables and graphs below show the inputs and results of the modelling for the Iron & Steel sector. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range.

There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an 'average' site within a sector.

5.5.9.1 Key parameters derived

Table 32: Energy savings and CapEx

Measures	**Elec Savings (%)** **(range)** ***RAG***	**Fuel for heat savings (%)** **(range)** ***RAG***	**CapEx for an 'average' site (2024 prices)** **(range)** ***RAG***
Improved automation & Process control (Total sector)	0% (0-1%) *Red*	1% (0-2%) *Red*	£1,200,000 (£600,000 - £18,000,000) *Red*
Re-heating furnace optimization (Secondary processes)	0% *(0%)* *Green*	5% (3-7%) *Red*	£10,000,000 (£5,000,000 to £15,000,000 per furnace) *Red*
Improved planning & Throughput optimisation (Secondary processes)	0% (0-1%) *Red*	5% (3-7%) *Amber*	£450,000 (£225,000 - £675,000) *Amber*
Use of premium efficiency electrical motors (Total sector)	10% (5-15%) *Red*	0% (0%) *Green*	£1,250,000 (£1,200,000 - £1,300,000) *Amber*
Endless strip production (ESP) (Secondary processes)	0% (0%) *Green*	40% (30-50%) *Green*	£78,000,000 (£39,000,000 - £117,000,000) *Amber*

Table 33 Applicability and adoption rates for BAU and Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Improved automation & Process control	100%	30%	40%	60%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			90%	100%	100%
Re-heating furnace optimization	100%	20%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			40%	60%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			80%	100%	100%
Improved planning & Throughput optimisation – Secondary processes	100%	50%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			60%	70%	80%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			80%	100%	100%
Use of premium efficiency electrical motors	95%	20%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			30%	40%	50%
			Max Tech 2030	**Max Tech 2040**	**Max Tech 2050**
			75%	95%	95%

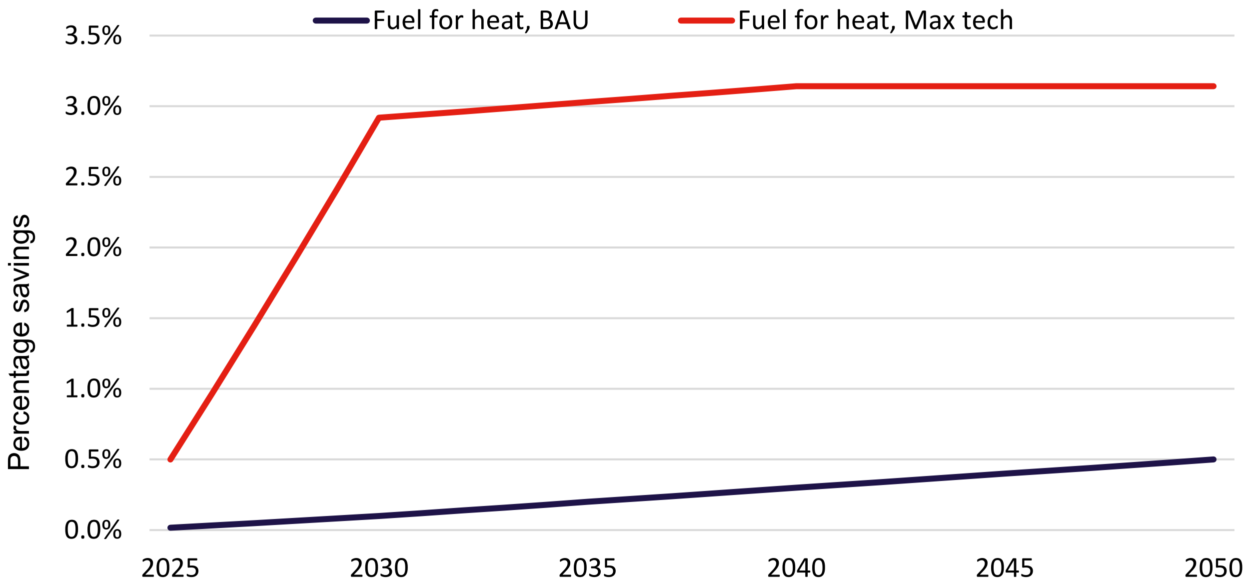
<table>
<tr><td rowspan="4">Endless strip production (ESP)</td><td rowspan="4">50%</td><td rowspan="4">0%</td><td>BAU 2030</td><td>BAU 2040</td><td>BAU 2050</td></tr>
<tr><td>0%</td><td>0%</td><td>25%</td></tr>
<tr><td>Max Tech 2030</td><td>Max Tech 2040</td><td>Max Tech 2050</td></tr>
<tr><td>50%</td><td>50%</td><td>50%</td></tr>
<tr><td>Batch annealing with 100 % hydrogen (Reheating/Annealing)</td><td>measure removed</td><td>measure removed</td><td>measure removed</td><td>measure removed</td><td>measure removed</td></tr>
<tr><td>Optimisation of ladle stirring</td><td>measure removed</td><td>measure removed</td><td>measure removed</td><td>measure removed</td><td>measure removed</td></tr>
</table>

These measures were entered into the DESNZ model and this yielded the detailed results set out in the sections below.

5.5.9.2 RM2024 Fuel for heat Savings

Figure 33 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 33: Iron & Steel sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



Fuel for heat savings under the Max Tech scenario increase by around 2.5 percentage points between 2025 and 2030, however savings remain relatively flat at around 3% after this point. The significant increase between the present and 2030 is due to an increase in the uptake of endless strip production over that period.

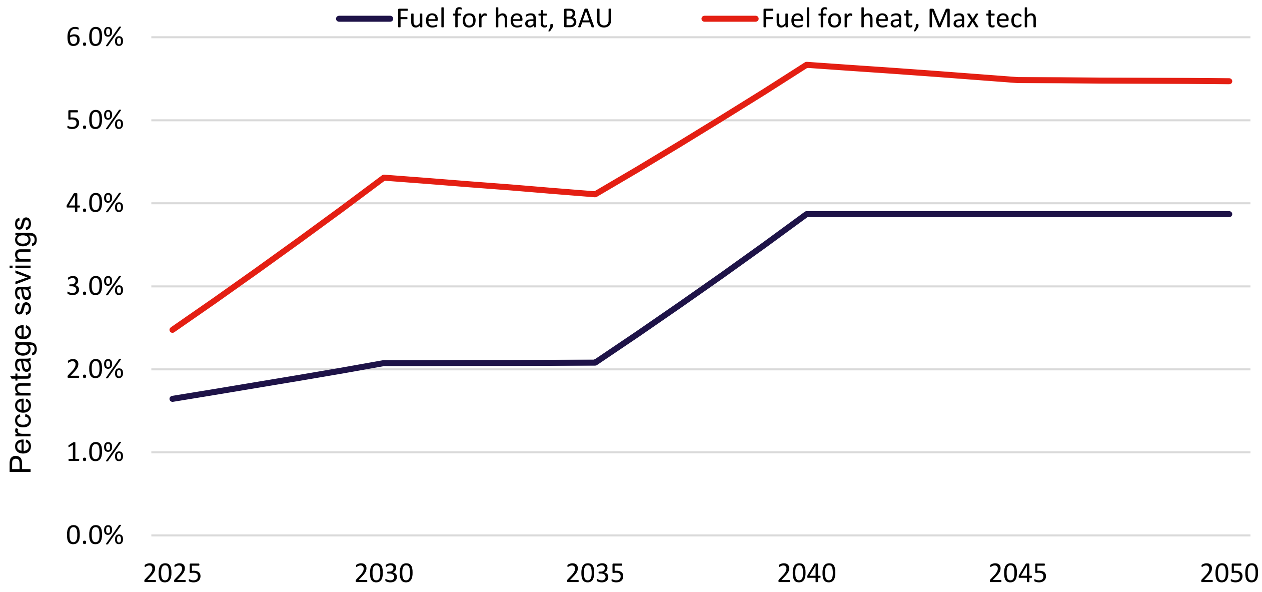
Max Tech reaches its peak savings by 2040, earlier than BAU, which shows a steady increase between 2025 and 2050, although the Max Tech peak is significantly higher at just over 3% compared to 0.5%.

The main reason for the difference between BAU and Max Tech scenarios is due primarily to investment constraints in the sector, including feedback that investment usually only takes place when the payback is short (6-12 months). This presents a significant barrier to take up of heat efficiency measures to the extent that only <1% reduction is anticipated under BAU as part of incremental improvement to controls and optimisation.

5.5.9.3 RM2015 Fuel for heat Savings

Figure 34 shows the Fuel for heat savings, determined under the previous project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline Fuel for heat.

Figure 34: Iron & Steel (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



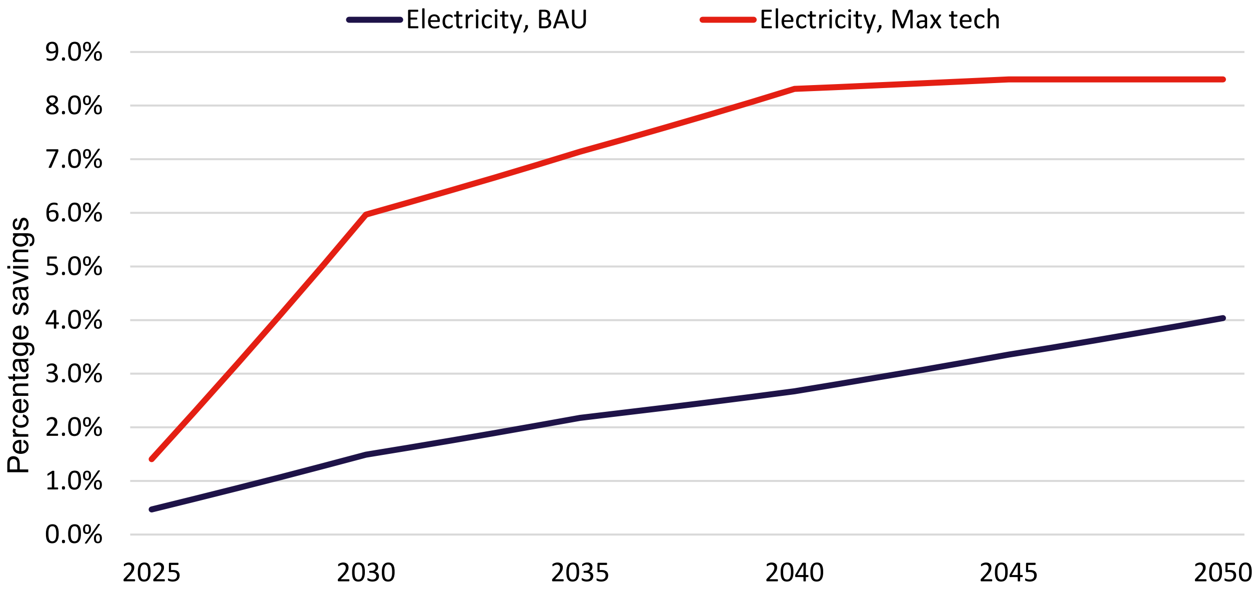
The 2015 results are not comparable on a like for like basis to the 2024 results. The 2015 results represent energy savings as a percentage of total sector energy use including blast furnace (integrated) route production. For RM2024, the energy use in blast furnaces and their replacement EAFs is excluded from the analysis. This production route accounts for the majority of fuel use in the sector.

Compared with RM2024, the RM2015 results show higher savings across the board, and a more staggered profile, with increases in savings followed by flat periods showing no savings increases, indicating the lumpy nature of EE implementations across a relatively small number of high capacity production units. The RM2015 Max Tech and BAU scenarios are similar in terms of profile with both showing a significant jump between 2035 and 2040, and no further savings increases after this point. Savings under Max Tech and BAU both peak in 2040, at just under 6% and 4% respectively.

5.5.9.4 RM2024 Electricity Savings

Figure 35 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 35: Iron & Steel sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The Max Tech scenario shows a much more rapid increase of savings, and peaks at a considerably higher ~8.5% compared to 4% under BAU. Where the BAU steadily increases over time, the Max Tech trend shows a rapid increase between 2025 and 2030, slowing down between 2030 and 2040, and remaining flat out to 2050.

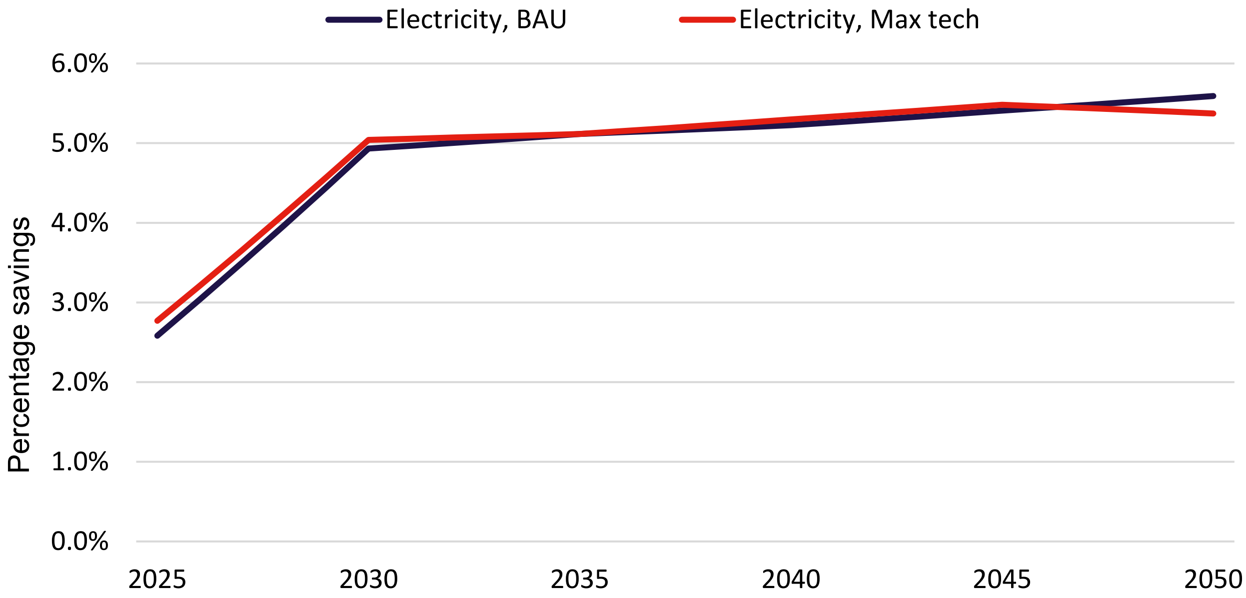
The Max Tech savings could be realised with rapid adoption of improved automation and process control, improved planning and throughput optimisation in downstream processes and replacement with premium efficiency motors, achieving up to ~5.5% energy savings by 2030, followed by additional uptake of these measures.

The main difference between BAU and Max Tech is due to BAU assuming that measures are taken up to a lesser extent and more gradually than in Max Tech, due primarily to investment constraints in the sector, including feedback that investment usually only takes place when the payback is short (6-12 months). For 2024 electricity savings results, the main contributor is primary efficient or variable speed drive motors.

5.5.9.5 RM2015 Electricity Savings

Figure 36 the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of the baseline electricity.

Figure 36: Iron & Steel sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenario



Here, both trends are very similar with a rapid increase between 2025 and 2030, and a slowing down out to 2050, where both scenarios peak at ~5.5% savings.

For electricity, the RM2024 results for the Max Tech scenario achieve a slightly higher percentage saving over a similar temporal pathway up to 2050, reaching 8.5%.

5.5.10 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 34: High and Low scenario definitions

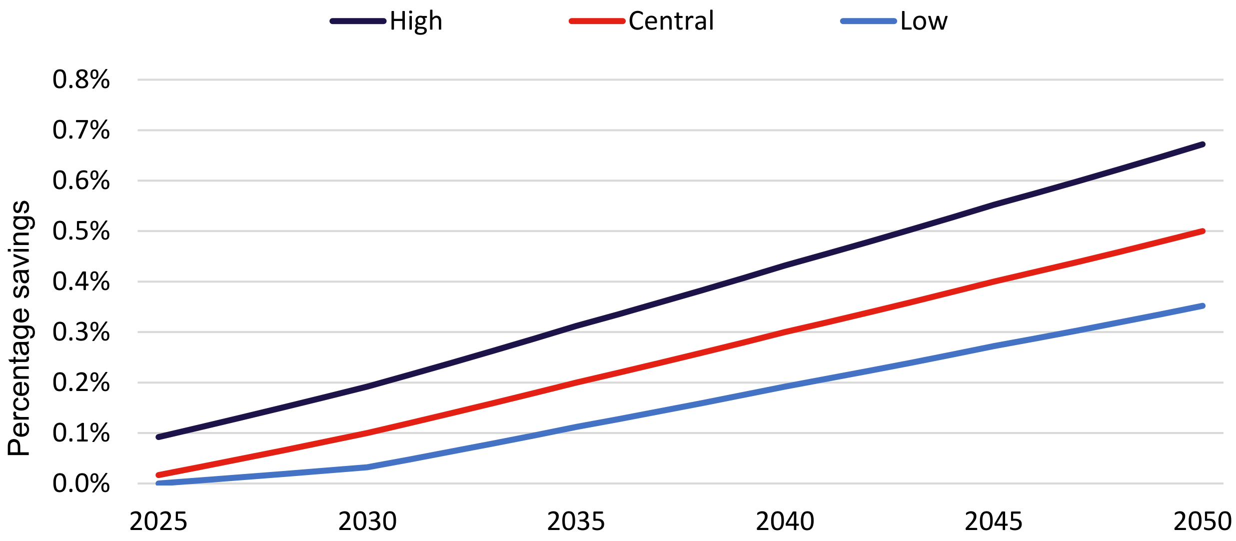
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.5.10.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 0.4% – 0.7%.

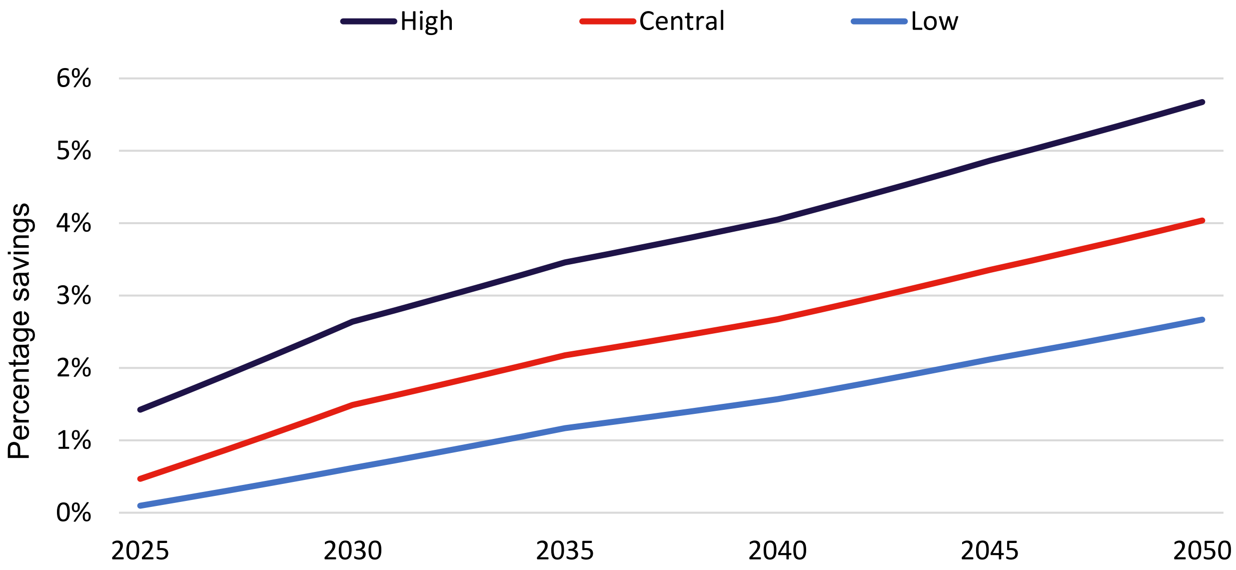
Figure 37: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.5.10.2 BAU Electricity

The range of BAU Fuel for heat savings by 2050 is 2.7% – 5.7%.

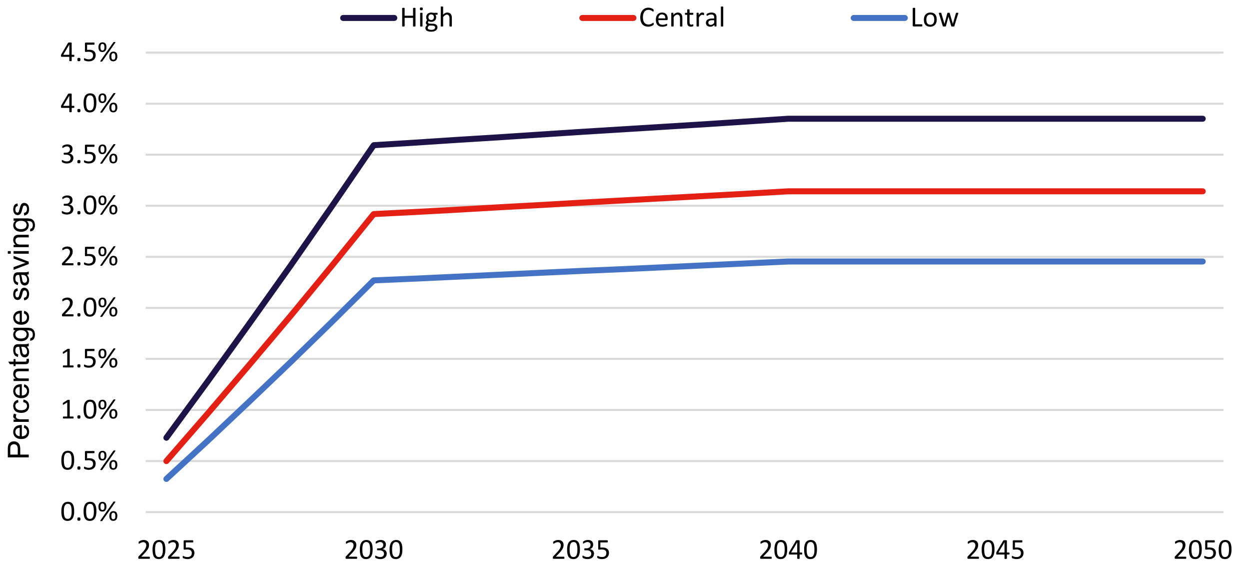
Figure 38: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.5.10.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 2.5%-3.9%.

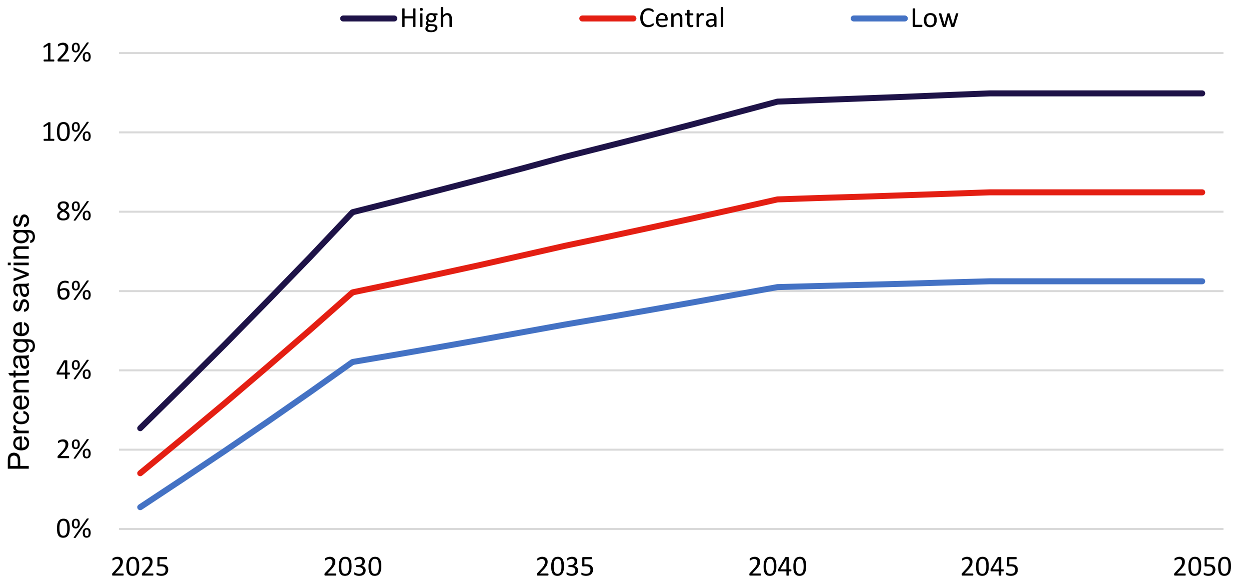
Figure 39: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.5.10.4 Max Tech Electricity

The range of BAU Fuel for heat savings by 2050 is 6.3% – 11.0%.

Figure 40: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.5.11 Limitations

The following limitations are applicable to the analysis carried out for the Iron & Steel sector and should, therefore, be kept in mind when considering the results presented here:

- The analysis excludes the significant energy reduction impact of the replacement of the blast furnace production route to EAF production.
- Not all producers were able to attend the workshop which reduced the opportunity for discussion and reaching agreement across stakeholders. However, significant producers who could not attend the workshop were taken through the workshop material separately and their input recorded.
- To manage scope within workshops, the top seven EE measures were prioritised and so the potential shown here is not a complete view of the potential within the sector. However, the prioritisation of measures pre-workshop has, by default, identified the measures with the greatest potential.
- There is uncertainty over what the adoption of EE measures might be in the future given uncertainty about whether the replacement of blast furnaces with EAFs will also result in upgrading of downstream assets, which could bring BAU closer to Max Tech, or affect the compatibility of measures (e.g. endless strip production).
- Data has not been identified within this study with sufficient granularity to model premium efficiency motors and VSDs separately, so these are covered in a combined measure for upgrading of motors.
- When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category’s energy use for a ‘representative site’ within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of “percentage energy savings”.

5.6 Sector 6 (Glass)

5.6.1 Definition

- The Glass sector analysed in this work covers activities included in the following NACE codes:

  23.1 Manufacture of glass and glass products

There are three main subsectors of glass production activity covered by this scope. These are: container glass (e.g. bottles and jars), flat glass (e.g. architectural, automotive) and glass fibre (e.g. fibres for glass reinforced composites, insulation).

Energy consumption is dominated by glass melting which is overwhelmingly via the combustion of natural gas, although some glass furnaces also use electricity as a source of heat in furnaces via electrodes. Downstream of glass melting, there is heat demand in forehearths and lehrs and electricity consumption to facilitate glass forming.

The use of waste glass (known as cullet) in the raw material feed to the glass furnace is a regularly used method for reducing the energy consumption associated with melting. In the context of this study this is regarded as a resource efficiency measure (rather than an EE measure) and so is not included in the analysis.

5.6.2 Literature Review

5.6.2.1 Salient Sector Specific Points

The majority of energy consumed by the UK glass sector is consumed within the flat and container glass subsectors. Smaller subsectors include glass fibre, domestic glass, speciality glass and glass wool. All these subsectors produce glass via a melting stage, either from scratch using the basic raw materials of silica, soda ash, limestone and other additive materials or via the melting of recovered glass (cullet). Consequently, glass manipulation, (such as glass toughening for the automotive or buildings glazing sectors) is excluded from this analysis.

From interviews with the sector association (British Glass) energy consumption for melting has by far the largest share of energy use, thought to constitute 62% and 78%, respectively, in the flat and container glass sectors. Consequently, data relating to melting EE measures will be especially important to collect. There is a range of large melting furnace types currently utilised in the glass sector, including recuperative, regenerative and oxy-fuel furnaces. The applicability of the identified EE measures is dependent on the incumbent furnace and so it is important to take this into consideration when considering the adoption of the different EE measures. For example, the literature review identified technical issues with conventional heat recovery from the furnace flue (e.g. for preheating combustion air) in oxy-fuel furnaces, where thermo-chemical heat recovery is instead used.

A number of EE measures relate to changing the composition of the batch fed to the furnace (e.g. use of fluxing agents). While these measures may in the first instance be associated with the batching process, because they relate to batch composition, the process where they deliver energy savings is in melting and so they are considered to map to the melting process. Another EE measure of this type is the increase of cullet in the batch fed to the furnace. While this can save significant quantities of Fuel for heat, on account of it lowering the temperature required for melting, this has been identified as a resource efficiency measure and therefore associated savings are not in the scope of this research.

The high temperatures involved with glass production mean that heat recovery can be expected to be a significant opportunity. Consequently, it is important to understand in detail the extent to which heat is already being recovered to minimise fuel use and the grades of remainder heat in order to understand the other uses to which this heat might be put (e.g. power generation using ORC.)

Glass melting furnaces have production campaigns which can last years, meaning it can take years for furnaces to cool to allow for maintenance like insulation repair/upgrade. The duration of these maintenance outages and their frequency will have an impact upon the implementation time of EE measures. This also has to be taken into consideration when projecting adoption of EE measures whose implementation involves shut-down of the furnace.

5.6.2.2 Sources Identified and their relevance

The literature review for the Glass sector yielded 17 sources of various usefulness to the roadmap, sorted into high, medium and low relevance. Sources were rated based on a combination of factors, geographical relevance, author credibility, currency of the publication and availability of statistics on cost and energy savings potential. Two out of the 17 sources were rated high, 3 were rated medium and 12 were rated low. The majority of the sources were from the European and British context, 2 and 11 sources respectively, whilst the rest were from other OECD countries. The literature was taken from a range of different source types, with 5 sources taken from peer-reviewed sources. The rest of the literature was taken from expert authors, including industry associations and product manufacturers.

A range of information was collected from each of the reviewed sources, however certain sources provided more detailed relevant information than others, while some gaps also existed within each of the reviewed papers. One of the sources identified which contained a large amount of valuable information was a paper titled ‘EE Improvement and Cost Saving Opportunities for the Glass Industry, An ENERGY STAR® Guide for Energy and Plant Managers’, produced by Berkeley Labs. Although this paper was published in 2008, it is a credible source and discusses EE measures that can be implemented in the glass industry, including case studies.

An additional source considered in this review was the meta-data paper titled ‘Decarbonising the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options’, published in 2022 by the Renewable and Sustainable Energy Reviews journal, covering a global context. The paper details the key applications for glass, as well as exploring a diverse range of solutions to improving EE in the glass industry.

The article ‘A review of decarbonization options for the glass industry’, published in 2021 in the Energy Conversion and Management Journal, provides key details on EE measures in the glass industry. Most notably, the TRL and barriers to implementation for these technologies is also outlined in detail and hence is of great relevance to this study.

The sources collectively present an understanding of the challenges and opportunities in achieving EE and carbon emissions reduction within the glass industry.

5.6.2.3 Conclusions from Literature Review – Gaps and Limitations

A number of gaps were identified when reviewing literature on EE measures in the glass industry. Firstly, there are a number of gaps regarding costs, particularly the installation costs. Information on capital and operating costs were sparse within the literature. Benchmark costs, such as those expressed in units like £/MWh or £/MW were not found in literature for capital or operating costs for most of the EE measures specific to the glass industry. Additionally, the interactions of EE measures with other measures and deep decarbonisation technologies have not been addressed in detail in the literature studied. Consideration is usually not given to whether deep decarbonisation approaches such as fuel switching to electricity or hydrogen, or the adoption of CCUS electrification, preclude the adoption of a particular EE measure. Consequently, it has been necessary to use a combination of Ricardo expert knowledge, and information derived from interviews and workshops, to understand this issue. A limited number of papers provided details on the TRL of the EE measures, however this was not for the complete suite of EE measures and hence some gaps also exist in respect of the EE measure characteristic.

5.6.3 Engagement

Engagement with the sector took the following form:

- 1 interview with the Sector Association – British Glass
- 2 interviews with glass sector technical support organisations (Glass Futures and Glass Technology Services)
- Interviews with 2 operators (Encirc Ltd Saint-Gobain Glass (UK) Ltd)
- Questionnaires, with responses received from 3 stakeholders
- One 3-hour workshop attended by British Glass, 4 operators, 1 consultant and 1 academic

5.6.4 Main categories of Energy Use

For the purposes of modelling energy savings, the Glass sector has been resolved into the following categories against which EE measures have been applied (including baseline energy consumption):

Table 35: Share of each fuel type in the baseline attributed to each category in the Glass sector

Category	Percentage of Total Sector Energy Use (%)				
	Electricity	Gas	Coal	Oil	Biomass
Furnace Fuel Heat	0%	92%	92%	92%	92%
Other	100%	8%	8%	8%	8%
Total Sector Energy	100%	100%	100%	100%	100%

The nature of the glass sector is that the overwhelming majority of the fuel used for heat is generated in the glass melting furnace. Such is the importance of this category of energy use and the EE measures associated with it, that it is recognised as a category in its own right. The remaining fuel combustion for heat is associated with processes such as forehearths and annealing.

5.6.5Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and adoption out to 2050.

Applicability and Adoption were discussed during the workshop in the context of whether the EE measures were dependent or independent (deep decarbonisation dependency).

Table 36 lists the prioritised measures and their dependency on deep decarbonisation scenarios.

Table 36 EE measures prioritised for the Glass sector and dependency on deep decarbonisation scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Improved Furnace Construction – conventional (from 2012 level) (Furnace fuel heat)	Steady improvements in the design of conventional furnaces that are ongoing and become available as a furnace is rebuilt. **2015 measure**	Independent
Improved Furnace Design – Innovative (Furnace fuel heat)	More radical changes in furnace design. **2015 measure**	Independent
Batch Pelletisation/Scrap Densification/Shredding (Furnace fuel heat)	Production of pellets comprised of the separate batch components with the correct proportions, which are quicker and easier to melt. **2015 measure.**	Independent
Waste Heat Recovery – Raw Materials Pre-heating (Total sector)	**Recovery of heat from the furnace to pre-heat raw materials2015 measure**	Dependent
Waste Heat Recovery – Electricity from Waste Heat (Total sector)	**Recovery of heat from the furnace to generate electricity 2015 measure**	Dependent
Motors and Drives (Total sector)	High Efficiency Motors, VSDs, High Efficiency Belts (Cog Belts). **New 2024 measure after interview feedback**	Independent
Compressed Air Measures (Total sector)	Reduction in leakage, better system layout, compressor VSDs, better controls, reduction in air inlet temperature. **New 2024 measure after interview feedback**	Independent

5.6.6 Non prioritised measures

Table 37 EE measures non-prioritised for the Glass sector and dependency on deep decarbonisation scenarios

Measure Name (Sector energy use category)	**Measure Description**	**Deep Decarbonisation Dependency**
Waste heat recovery – other (Total sector)	Recovery and reuse of heat from plant other than the furnace (e.g. air compressors)	Independent
Batch reformulation (Furnace fuel heat)	Inclusion of additives to the batch which bring about a reduction in the temperature at which glass melts	Independent

5.6.7 Key assumptions

The adoption of EE measures related to improvements to furnace design is determined by assumptions about the frequency with which furnaces need to be rebuilt. Rebuild intervals of once every 15 years are assumed.

The adoption of some of the measures (most notably heat recovery from the furnace) is influenced by wider deep decarbonisations scenarios. Presently, electrification of furnace heat is assumed to prevail over hydrogen, and this has influenced the adoption of dependent measures. A different outturn for fuel switching in the sector would change these adoption assumptions.

5.6.8 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.4 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the glass sector came to light and these are listed below.

The following barriers were identified during the literature review:

Batch (and cullet) pre-heating:

- Pre-heating of only the batch is considered problematic and not a proven technology. Therefore, pre-heating projects would tend to consider a batch and cullet mixture and, therefore, cullet would normally need to be available. A 50% cullet content in the batch is normally considered necessary for this EE measure to be viable. There also needs to be plenty of available space for this measure.

Selective batching:

- May not be suitable for large scale glass manufacturing.
- The efficiency improvements during melting may be outweighed by the additional energy requirements of the selective batching process.

Waste heat recovery:

- Glass melt leaving the melting furnace must follow a defined temperature profile, hence waste heat cannot be recovered from molten glass. Therefore, for all waste heat recovery options, only waste heat from exhaust gases can technically be used.
- There may be space constraints making the siting of heat recovery plant difficult. They may be appreciable distances between the waste heat source and the heat sink (application consuming the recovered heat) which make the implementation of heat recovery and reuse technically and economically challenging.

Use of fluxing agents:

- The economic case of for improving EE through use of fluxing agents is linked to the cost of the fluxing agents and the value of gas consumption avoided as a result of achieving a lower melting temperature. High fluxing agent prices may make the measure uneconomic.

Oxy-fuel fired furnaces:

- Auxiliary equipment is needed for supply of oxygen, or oxygen needs to be purchased separately. Operating costs are therefore likely higher due to the additional electricity costs associated with oxygen generation.
- There may be space constraints on some sites, resulting in limited space available for an oxygen generation plant.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- Conservatism within the sector means that there is a reluctance to be the first mover on an EE project.

5.6.9 Results

The tables and graphs below show the inputs and results of the modelling for the Glass sector. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an ‘average’ site within a sector.

5.6.9.1 Key parameters derived

Table 38 Energy savings and CapEx

Measures	**Elec Savings (%) (range)** ***RAG***	**Fuel for heat savings (%) (range)** ***RAG***	**CapEx for an 'average' site (2024 prices) (range)** ***RAG***
Improved furnace construction - conventional (from 2012 level) (Furnace fuel heat)	0% (0%) *Green*	5% (4-6%) *Amber*	£1,100,000 (+/- 30%) *Amber*
Improved furnace design - Innovative (Furnace fuel heat)	0% (0%) *Green*	20% (15-25%) *Amber*	£40,000,000 (+/- 30%) *Amber*
Batch pelletisation (independent)/ Scrap densification / shredding (Furnace fuel heat)	0% (0%) *Green*	5% (4-6%) *Amber*	Not given
Waste heat recovery - other (dependent) (Total sector)	Not given	Not given	Not given
Waste heat recovery- raw materials pre-heating (Total sector)	0% (0%) *Green*	12% (8-15%) *Green*	£3,400,000 (+/- 30%) *Red*
Waste heat recovery - electricity from waste heat (Total sector)	14% (+/- 3%) *Green*	0% (0%) *Green*	£5,500,000 (+/- 30%) *Green*

Measures	**Elec Savings (%)** **(range)** ***RAG***	**Fuel for heat savings (%)** **(range)** ***RAG***	**CapEx for an 'average' site (2024 prices)** **(range)** ***RAG***
Motor and drives (High efficiency motors, Variable speed drives, High efficiency belts (cog belts) (Total sector)	4% (3-5%) *Red*	0% (0%) *Green*	N/A – HEMs will only be implemented as and when existing motors need replaced, therefore no CapEx
Compressed air measures (reduction in leakage, better system layout, compressor VSDs, better controls, reduction in air inlet temperature) (Total sector)	6% (not given) *Red*	0% (0%) *Green*	£350,000 (not given) *Amber*

Table 39: Applicability and adoption rates for BAU and Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Improved furnace construction - conventional (from 2012 level)	100%	0%	23%	65%	95%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			23%	65%	95%
Improved furnace design - Innovative (independent)	100%	0%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			0%	0%	0%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			23%	65%	95%
Batch pelletisation (independent)/ Scrap densification / shredding	100%	0%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			4%	10%	20%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			40%	80%	80%
Waste heat recovery - other (dependent)	100%	0%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			0%	0%	0%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			0%	0%	0%
Waste heat recovery- raw materials pre-heating (dependent)	70%	0%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			0%	0%	0%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			0%	0%	0%

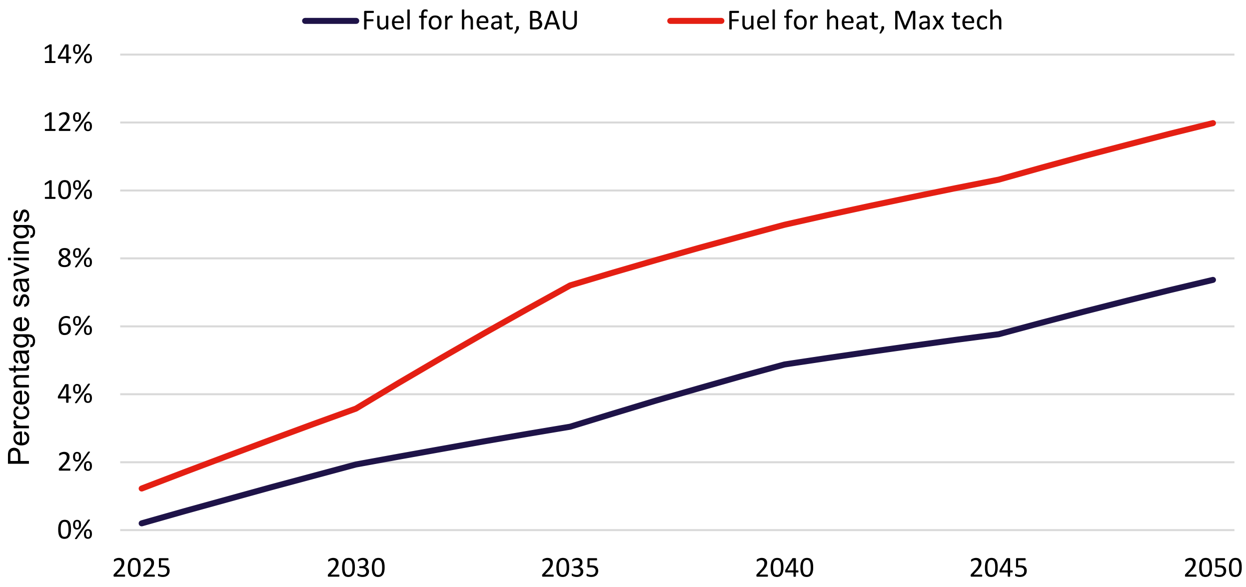
Waste heat recovery - electricity from waste heat (dependent)	40 %	0%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			0%	0%	0%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			0%	0%	0%
Motor and drives (High efficiency motors, Variable speed drives, High efficiency belts (cog belts)	100%	80%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			85%	90%	95%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			100%	100%	100%
Compressed air measures (reduction in leakage, better system layout, compressor VSDs, better controls, reduction in air inlet temperature)	100%	50%	**BAU 2030**	**BAU 2040**	**BAU 2050**
			55%	75%	100%
			MaxTech 2030	**MaxTech 2040**	**MaxTech 2050**
			100%	100%	100%

These measures were entered into the DESNZ model and this yielded the detailed results set out in the sections below.

5.6.9.2 RM2024 Fuel for heat Savings

Figure 41 shows the Fuel for heat Savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 41: Glass sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



Under BAU, the Fuel for heat savings show a steady increase with time, peaking at just over 7% by 2050. These savings are mainly driven by improvements in furnace design over time, which are implemented on the ground as furnaces come to the end of their lives and are rebuilt to higher levels of design efficiency. Improved process control is the other significant contributor to the increase in BAU savings seen over time.

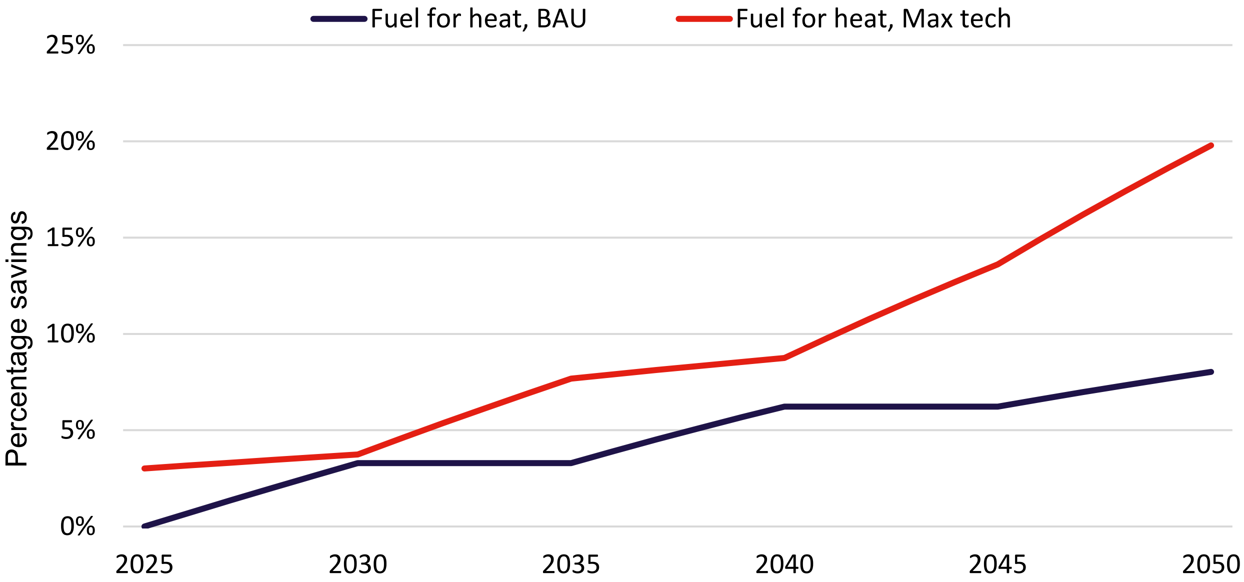
The main difference between the BAU and Max Tech Fuel for heat savings stems from the additional savings contributed by the batch pelletisation and batch reformulation measures. According to stakeholder engagement, these measures would see much higher levels of penetration under Max Tech, as the high investment costs associated with these measures are overcome (Max Tech assumes that all non-technical barriers to adoption are removed). Max Tech shows a 5% greater savings potential at both scenarios' respective peaks, with 12% Fuel for heat savings by 2050.

These is no appreciable difference in adoption of improved furnace design and process control under the BAU and Max Tech scenarios. This demonstrates that the EE improvements that come from improved furnace design are only realised when furnaces come to the end of their useful lives and that furnaces would not be retired earlier under Max Tech.

5.6.9.3 RM2015 Fuel for heat Savings

Figure 42 shows the Fuel for heat Savings, determined under the RM2015 study, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat.

Figure 42: Glass (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



In the RM2015 study, BAU savings reach around8% by 2050, whereas Max Tech savings achieve 20% by the same date. The two scenarios show a similar trend until 2040 at which point the Max Tech trajectory increases significantly, whereas the BAU trajectory remains relatively flat.

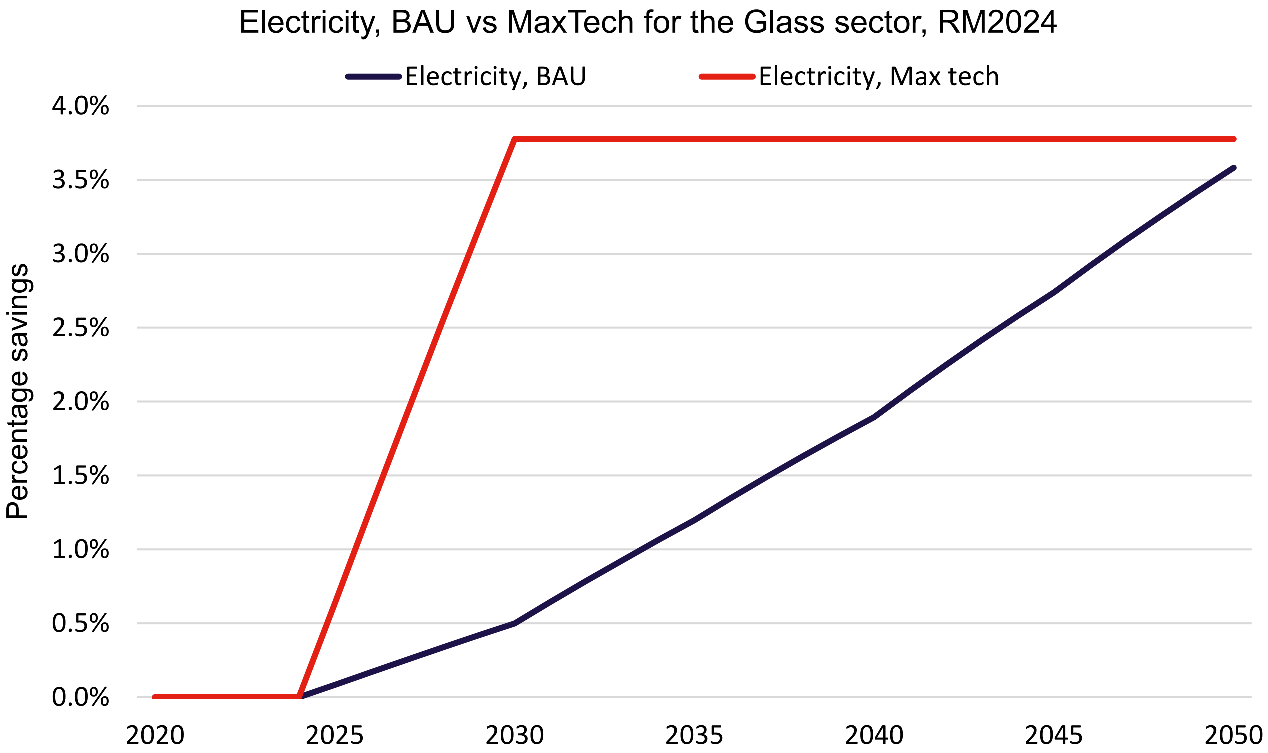
Considering the two Max Tech scenarios (RM2024 and RM2015), savings are higher in RM2015 than in RM2024, with savings 8% higher in the former then in the latter by 2050. This contrasts with where BAU savings which very similar in the two studies. This difference is explained by technical constraints on heat recovery measures, relating to space constraints and other on-site barriers, which we were told about during interviews and workshops and are reflected in the adoption figures agreed.

The gap between the two scenarios is also narrower in the RM2024 study, with Max Tech showing a 5% savings benefit over BAU compared with a 12% benefit from RM2015.

5.6.9.4 RM2024 Electricity Savings

Figure 43 shows the electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 43: Glass sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



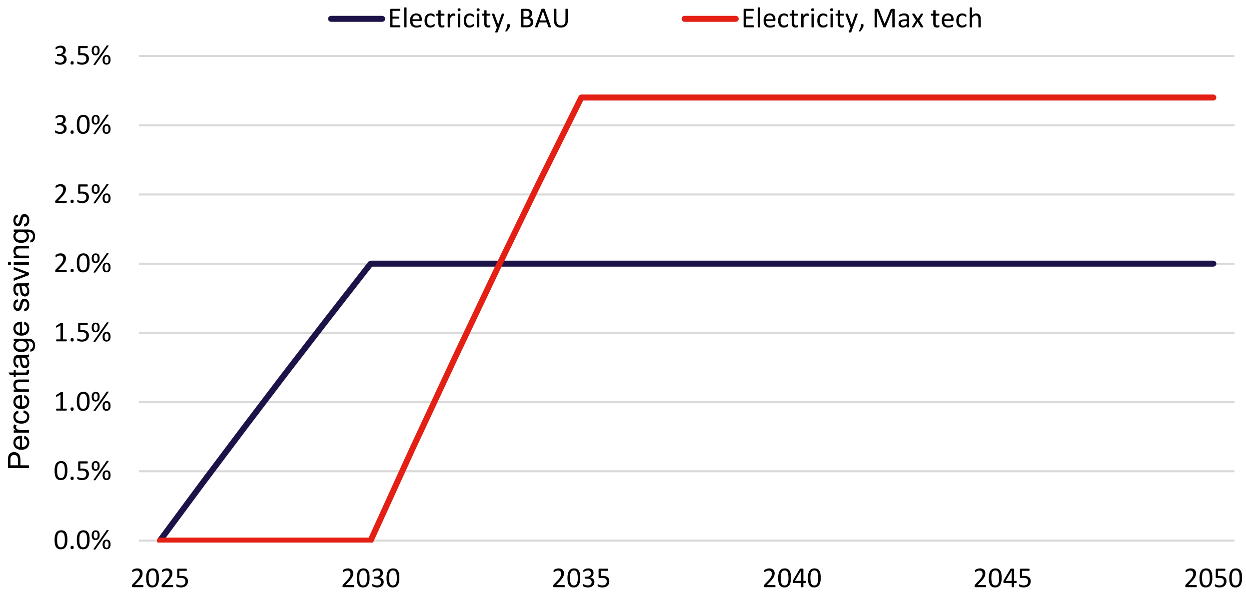
Where the BAU scenario shows a steady increase up to a 3.5% saving in 2050, the Max Tech scenario increases rapidly to its peak of 3.8% savings by 2030 and then remains flat out to 2050. The gap between the scenarios is small by 2050 at 0.2%; the largest gap between the scenarios is seen in 2030, with a gap in the savings of 3.3%.

All of the electricity savings seen are due to the adoption of high efficiency motors, VSDs and measures to improve the efficiency of compressed air generation. The difference between the BAU and Max Tech trajectories is explained by assumptions about when HEMs and VSDs are implemented. Under the BAU scenario, the assumption is that this only happens when the existing systems come to the end of their lives, while under the Max Tech scenario, these replacements can happen sooner, thereby bringing forward in time the savings.

5.6.9.5 RM2015 Electricity Savings

Figure 44 shows the the electricity savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline electricity.

Figure 44: Glass sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



The BAU and Max Tech scenarios both show similar trends in the RM2015 study, with BAU showing earlier savings than Max Tech, reaching a high of 2% by 2030 and then remaining flat out to 2050. Max Tech overtakes BAU in savings before 2035, reaching a high of 3.2% in 2035 and then also remaining flat out to 2050.

The BAU savings for electricity are slightly higher in RM2024 than in RM2015. This is likely due to the inclusion of savings from HEMs, VSD and compressed air, which were omitted from RM2015. This omission was identified from feedback during interviews, where the potential from these measures for the Glass were considered to be material.

5.6.10 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 40 High and Low scenario definitions

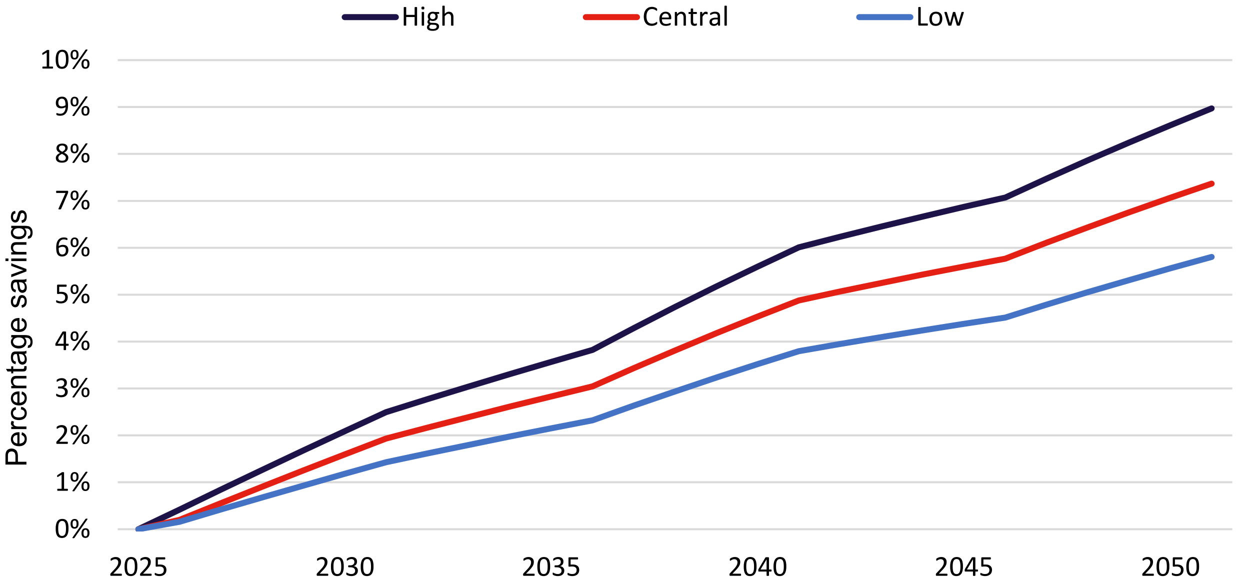
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.6.10.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 5.8% – 9.0%.

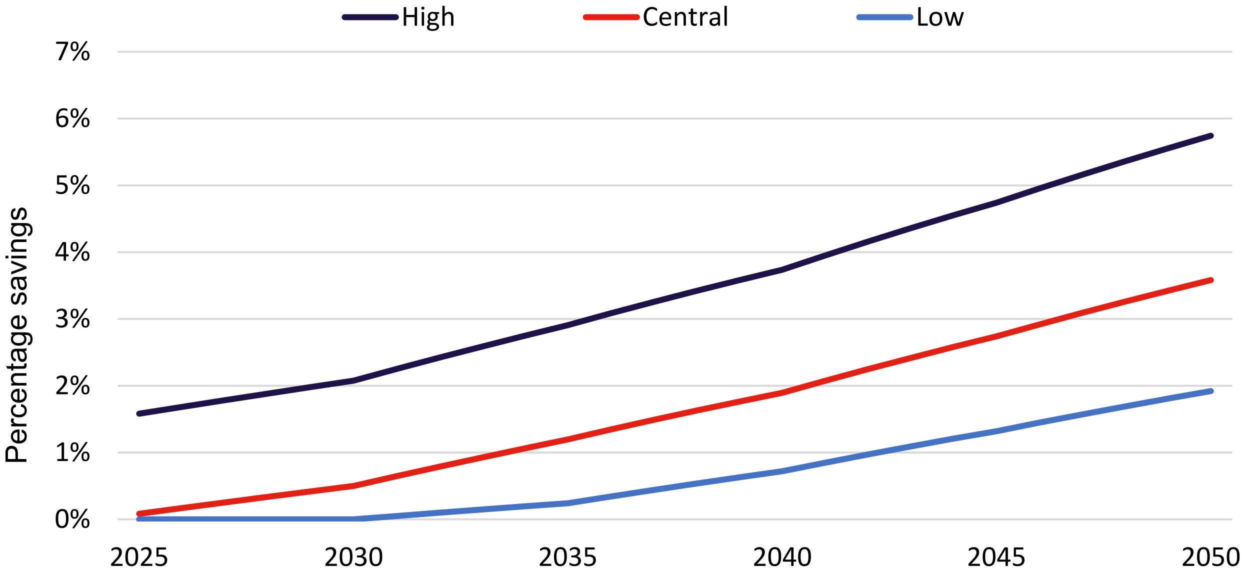
Figure 45: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.6.10.2 BAU Electricity

The range of BAU Fuel for heat savings by 2050 is 1.9% – 5.7%.

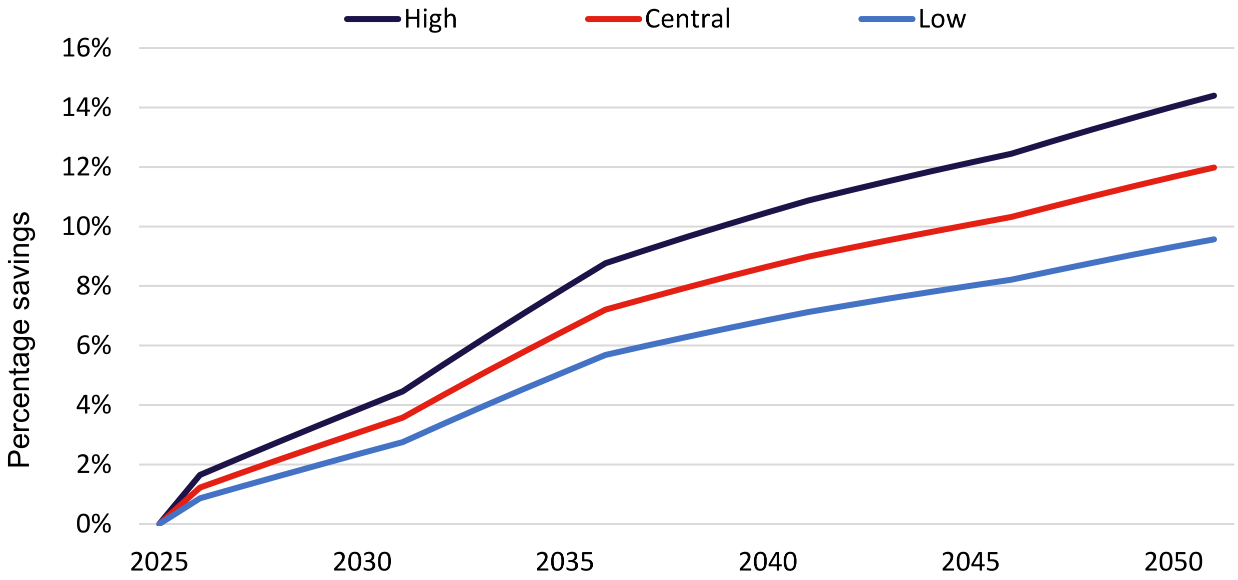
Figure 46: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.6.10.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 9.6%-14.4%.

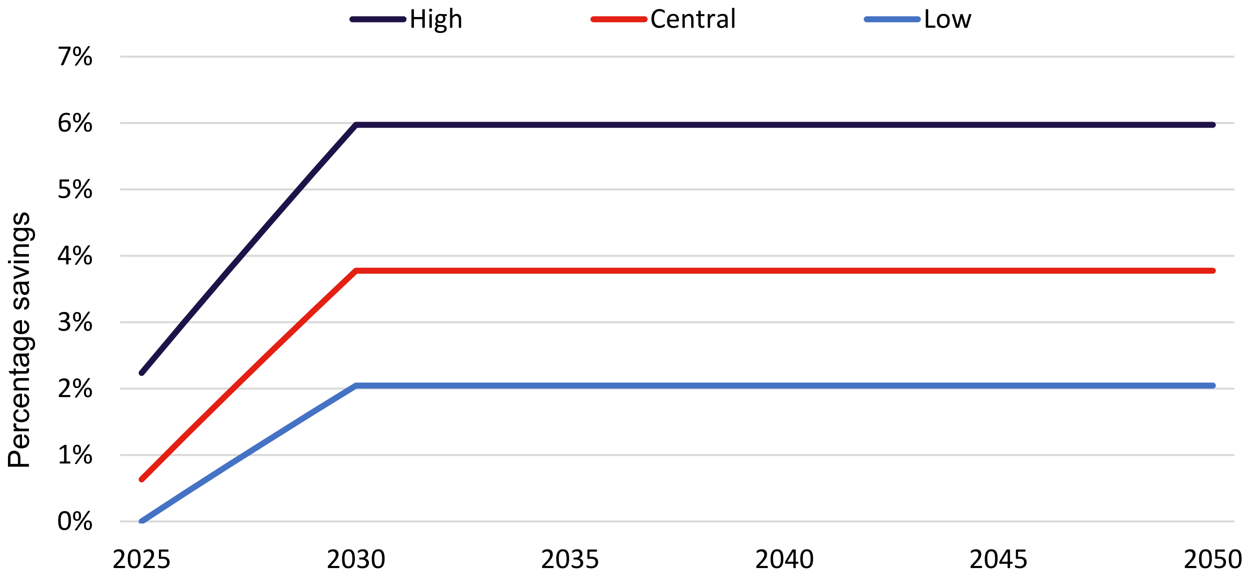
Figure 47: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.6.10.4 Max Tech Electricity

The range of BAU Fuel for heat savings by 2050 is 2.1% – 6.0%.

Figure 48: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.6.11 Limitations

The following limitations are applicable to the analysis carried out for the glass sector and should, therefore, be kept in mind when considering the results presented here.

While engagement from the sector association and similar whole sector organisations was good (interviews were held with, and workshop attendance was secured from, from British Glass, Glass Technology Services and Glass Futures) only two operators were interviewed and present at workshop [Encirc (container) and St Gobain (flat)]. Therefore, the actual operating perspectives derived during the workshop come from a relatively narrow section of the sector.

The literature yielded no evidence on adoption in 2024, applicability or future adoption of EE measures. All assumptions relating to these variables had to come from the workshops and, therefore, from a relatively narrow sub-set of the sector (see above).

To manage scope within workshops, the top eight EE measures were prioritised, but the modelling outputs include the savings from a larger number of EE measures. For these other, non-prioritised measures the existing information determining estimates of energy savings were not validated during workshops and so there is uncertainty attaching to them in this regard. The extent of this limitation is, however, thought to be limited because the prioritisation of measures pre-workshop did, by default, identify the measures with the greatest energy saving potential.

Establishing the rate of improvement from the specific EE measure “Improved furnace construction – conventional” ideally would have followed a detailed schedule of likely furnace replacement dates, but this was not available from the industry.

From interviews, the sector seems fairly settled that electrification is the fuel switching option that will be pursued outside of the industrial clusters (because of issues with availability of hydrogen). Increasing the use of electricity for supplying heat for melting reduces the quantities of waste heat available and, therefore, the applicability of heat recovery from the furnace. However, the feasibility of replacing the considerable natural gas demand for melting with electricity is likely to require significant upgrades to the incoming capacity of the electricity supply and, possibly, the capacity of the distribution system upstream of this consumption. The availability of these upgrades is uncertain and so there is a significant inherent uncertainty with the applicability and future adoption of furnace heat recovery EE measures.

It is difficult to conceptualise a "Representative Site", for which the CapEx per EE measure is declared and, as discussed earlier in this report, useable data on CapEx was rare in the literature. This meant that it was often necessary to rely on existing estimates of CapEx for the EE measures (adjusted for inflation) and ask stakeholders to comment on whether the inflated CapEx was reasonable. This approach is inherently difficult because there is a wide range of size of site within the sector (especially within the container glass sub-sector and between sub-sectors). Since CapEx is a function of the size of operations, there is, therefore, a high level of uncertainty associated with the CapEx values presented in this work.

When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category’s energy use for a ‘representative site’ within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of “% energy savings”.

5.7 Sector 7 (Cement)

5.7.1 Definition

The Cement sector analysed in this work covers activities included in the following SIC code:

- 23.51 Manufacture of cement

This sector covers the production of Portland cement clinker via pyroprocessing to produce cement clinker and the grinding of this clinker (and additive components) to produce cement. Pyroprocessing takes place in rotary kilns via the dry process in the UK. Clinker grinding takes place in different plant types (e.g. ball mills).

5.7.2 Literature Review

5.7.2.1 Sources Identified and their relevance

The literature review for the cement sector yielded 15 sources which were sorted into high, medium and low relevance. Sources were rated based on a combination of factors, including geographical relevance, author credibility, recency of the publication and availability of statistics on cost and energy savings potential. Seven out of the 15 sources were rated high, 8 were rated medium. No sources were found to have a low relevance. Several of the sources were from the European and British context, 3 and 4 sources respectively, whilst the rest were worldwide studies, or from other OECD countries. One source focused on China and another on Italy. This research was included as some relevant EE measures were mentioned. It's important to note that cement production processes are largely uniform worldwide. The UK exclusively employs dry processes (where the raw meal fed to the kiln is in a dry state as opposed to in the form of a slurry the form of a slurry), whereas a few other countries still utilize wet or semi-wet processes. Variations in raw materials and the number of cyclone preheaters used in kilns also exist. Consequently, EE measures applicable in other countries could be relevant to the UK, especially if they have not been implemented yet.

The literature was mostly taken from expert authors, including industry associations and product manufacturers, equating to 8 sources. The rest of the literature was taken from peer-reviewed sources, usually from academic institutions. The sources collectively present an understanding of the challenges and opportunities in achieving EE and carbon emissions reduction within the cement industry.

5.7.2.2 Conclusions from Literature Review – Gaps and Limitations

Information regarding installations costs was absent in the majority of the sources. Additionally, the literature often overlooks the interaction between EE measures when implemented together. Data on adoption rates of EE measures was also missing.

An important point taken away from the literature review is the long lifetimes of the main energy consuming assets in the cement sector and that production campaigns can last most of the year. These findings highlight limitations on the frequency with which plant can be replaced with newer, more efficient versions and when retrofits, improving overall efficiency of the system, can be carried out.

Levers that can be utilised to decarbonise the cement sector, include material substitution, fuel switching (high tolerance to increased use of a wide range of waste fuels without resulting issues such as fouling), CCUS and to a lesser extent, EE. Consequently, many literature sources cover decarbonisation measures that are not relevant to this study, and this means that a high degree of discipline is needed to concentrate on what is relevant.

The most important EE measures relate to those which affect the consumption of fuel for the generation of heat, and the main opportunities to reduce this are: the adoption of Best Available Technology (BAT) kiln systems (in terms of numbers of cyclone preheaters and the use of pre-calciners) and the recovery and reuse of heat. Regarding EE opportunities to improve the efficiency of electricity consumption, these include efficient grinding technologies (for the grinding of the clinker product and, potentially, solid fuels) and the use of efficient motors and drives, especially when applied to kiln fans to move the combustion products through the kiln.

5.7.3 Engagement

Engagement with the sector took the following forms:

- 1 interview with the Sector Association – Mineral Products Association (MPA)
- Interviews with 6 operators and other interested industry players (Breedon, Cemcor, CEMEX, Aggregate, Carbon Upcycling, Expedition Engineering) and 2 academics
- Questionnaires, with responses received from 3 stakeholders
- One 3-hour workshop attended by British Glass, 4 operators, 1 consultant and 1 academic

5.7.4 Prioritised measures

As mentioned above, to manage the scope of the work and the extent of stakeholder engagement necessary, some of the EE measures were prioritised for detailed analysis during the workshops. It is in respect of these prioritised measures that feedback was received and modelling variables updated for CapEx, adoption in 2024, applicability and adoption out to 2050. Applicability and adoption rates were discussed during the workshop in the context of whether the EE measures were dependent or independent (Deep Decarbonisation Dependency).

Table 41 lists the prioritised measures, the categories of energy consumption to which they apply, and their dependency on Deep Decarbonisation scenarios.

Table 41 EE measures prioritised for the Cement sector and dependency on deep decarbonisation scenarios

Measure Name	Measure Description	Deep Decarbonisation Dependency
Electricity Generation from Heat	Use of recovered low temperature heat to generate electricity (e.g. via organic Rankin cycle). Has been considered by most sites but currently not implemented due to payback period and other barriers. In future all recoverable heat will be used to support CCUS operation instead of electricity generation so potential for uptake decreases as CCUS is adopted. **2015 measure.**	Dependent
Kiln Process Technology (BAT Kiln)	Implementation of the most modern kiln technologies, considering size and related efficiency, with appropriate number of cyclone preheaters for raw material dryness and pre-calciner. Would only be implemented when an incumbent kiln comes up for replacement/rebuild. **2015 measure.**	Dependent
Electrical Efficiency Improvements	Includes voltage and power optimisation, motor management plans, properly sized motors, variable speed drives. Motors are used in mills, rotating the kiln and for moving materials (conveyors or fans). Already high level of adoption. **2015 measure.**	Independent
Efficient Clinker Cooler	Replacement of rotary (planetary) cooler at one site with a grate cooler. Grate coolers at other sites upgraded with more efficient plates and aeration. Increase in electricity consumption to reduce Fuel for heat consumption results in long payback (if at all). **RM2024 measure.**	Independent
Vertical Roller Mills for Clinker Grinding	Replacement of ball mills with roller mills which provide a more uniform grind with lower electricity use. Currently very low adoption. **RM2024 measure.**	Independent

5.7.5Non prioritised measures

Table 42 EE measures non-prioritised for the Cement sector and dependency on deep decarbonisation scenarios

Measure Name	Measure Description	Deep Decarbonisation Dependency
Oxygen enrichment technology	The use of oxygen enriched combustion air in the clinker burning process. This allows an increase of the fuel efficiency, production capacity or substitution of fossil fuels by low calorific value (or secondary fuels). This option includes oxygen enriched combustion and oxyfuel combustion.	Dependent
Vertical roller mills for clinker grinding	More energy efficient method of grinding clinker than the commonly used ball mills.	Independent

5.7.6 Key assumptions

Cement producer stakeholders expressed the expectation for CCUS to be adopted in most sites by 2040 and for the likelihood of dependent measures to therefore not be taken up.. since the emissions savings that would come from dependent measures would be secured via CCUS. However, for this analysis we have assumed that it could be feasible for Electricity Generation from Heat to be adopted in the interim period before the recovered heat is required for CCUS.

5.7.7 Specific barriers to sectors

From the literature review, questionnaire responses and discussions during the workshop, a number of barriers to the adoption of EE measures were identified. Many of these have broad applicability across the industrial sectors examined in this study and where this is the case they are discussed above in 4.4 Cross-cutting barriers to . However, some barriers specific to the circumstances faced by operators in the cement sector came to light and these are listed below.

The following barriers were identified during the literature review:

Prioritisation of Production and Downtime Minimisation:

- Plants prioritise continuous operation to cut costs and prevent equipment damage during shutdowns.
- Retrofits and replacements may create uncertainties, impacting production rates and specifications.

Waste Heat Recovery Challenges:

- Opportunities depend on physical installations and infrastructure feasibility.
- Depending on the conditions of raw materials, there may be no use of low-grade waste heat for drying or preheating and the conversion of this into power may be very inefficient and uneconomic.

Technological Maturity of Cement Manufacturing:

- Existing technologies show high efficiency, limiting gains from new equipment.
- Marginal benefits are seen in adopting Best Available Techniques (BAT) for countries with aging plants.

Improving Raw Mix Burnability:

- While this can generate thermal energy savings, it results in a deterioration in clinker grindability which can increase electricity consumption.

Preheater Modification through Cyclones with Lower Pressure Drop:

- Adaptation of preheater tower construction may be needed leading to far higher costs than may have been originally anticipated.

Additional Preheater Cyclone Stage(s):

- The technology competes with other options for waste heat recovery, and its impact on efficiency is limited if exhaust gas temperature is already low. The lack of standardised approaches may hinder widespread adoption.

Increase of Kiln Capacity:

- High investment costs are a significant barrier, and the lack of standardised practices for capacity increases may contribute to uncertainties in implementation.

Oxygen Enrichment Technology:

- Ruled by power price and investment costs. The integration of energy flows and the durability of refractory lining are crucial considerations. Lack of standardised procedures and regulations might impede the consistent implementation of oxygen enrichment technology. Additionally, the absence of extensive experience in the industry could pose challenges in optimising the technology for specific cement plant conditions.

Efficient Clinker Cooler Technology:

- The lack of experience in implementing new cooler technologies that facilitate heat recovery (e.g. grate coolers) and the absence of standardised practices might limit widespread adoption. High investment costs for cooler replacement could be a more significant barrier without clear guidelines or regulations.

- A final significant barrier to implementation is that EE measures often do not take precedence in the key recommendations from industry stakeholders for decarbonizing cement both in the UK and globally. Instead, the primary focus of relevant associations and sector experts is on developing a stable, visible Industrial carbon capture business model framework to facilitate investment planning. Other crucial recommendations include transitioning to alternative fuels and enhancing resource efficiency. EE measures, while mentioned, are less emphasized and, in some instances, are not included as decarbonization strategies in UK industry expert reports.

During the fieldwork (i.e. at interviews or during workshops) many of the above barriers were directly or indirectly cited. However, some barriers cited during the fieldwork stage that were not picked up during the literature review are listed below:

- Electricity in kiln consumption is increased with higher rates of fuel switching to biomass/waste because larger fans are needed due to increased air / waste gas flow volume.
- Complexity of contracts to engage third parties (e.g. ESCOs) makes it difficult for this route, which has the benefit of another party making the investment, to be pursued (most relevant to electricity generation from recovered heat).
- Uncertainty over the reliability of roller mills (the most impactful EE measure for electricity saving associated with clinker grinding).

5.7.8 Results

The tables and graphs below show the inputs and results of the modelling for the Cement sector. The percentage energy savings for EE measures in the Cement are framed in proportion to total sector energy. The red-amber-green (RAG) rating denotes the level of confidence associated with the data provided assessed by sector experts. Red signifies low confidence in results, amber, medium confidence, and green for high confidence. For some measure parameters, ranges were not provided as these did not receive input during the workshops, either due to a lack of time to discuss or limited evidence to propose a reasonable range. There were large ranges and uncertainties, in particular around CapEx estimates given limited data and complexities around framing an ‘average’ site within a sector.

5.7.8.1 Key parameters derived

Table 43 Savings and CapEx

Measures	**Elec Savings (%) (range)** *RAG*	**Fuel for heat savings (%) (range)** *RAG*	**CapEx for an ‘average’ site (2024 prices) (range)** *RAG*
Electricity Generation from Heat	6% (2-10%) *Amber*	0% (0%) *Green*	£19,000,000 (+/- 50%) *Red*
Kiln process technology (BAT kiln)	0% (0-2%) *Red*	3% (1-5%) *Red*	£325,000,000 (£246,000,000 - £325,000,000) *Amber*
Electrical efficiency improvements	6% (3-10%) *Amber*	0% (0%) *Green*	£39,000,000 (19,500,000 - £58,500,000) *Red*
Efficient clinker cooler	-4% (+/- 50%) *Red*	6% (+/- 50%) *Red*	£15,000,000 (£13,000,000 – £17,000,000) *Red*
Vertical roller mills for clinker grinding	10% (5-17%) *Amber*	0% (0%) *Green*	Not given

Table 44 Applicability and adoption rates for BAU and/Max Tech scenarios

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Electricity Generation from Heat	100%	0%	0%	0%	0%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			50%	25%	25%
Kiln process technology (BAT kiln)	100%	71%	BAU 2030	BAU 2040	BAU 2050
			71%	71%	71%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			71%	85%	100%
Electrical efficiency improvements	100%	93%	BAU 2030	BAU 2040	BAU 2050
			93%	95%	98%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			95%	97%	100%
Efficient clinker cooler	100%	95%	BAU 2030	BAU 2040	BAU 2050
			95%	95%	95%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			95%	100%	100%

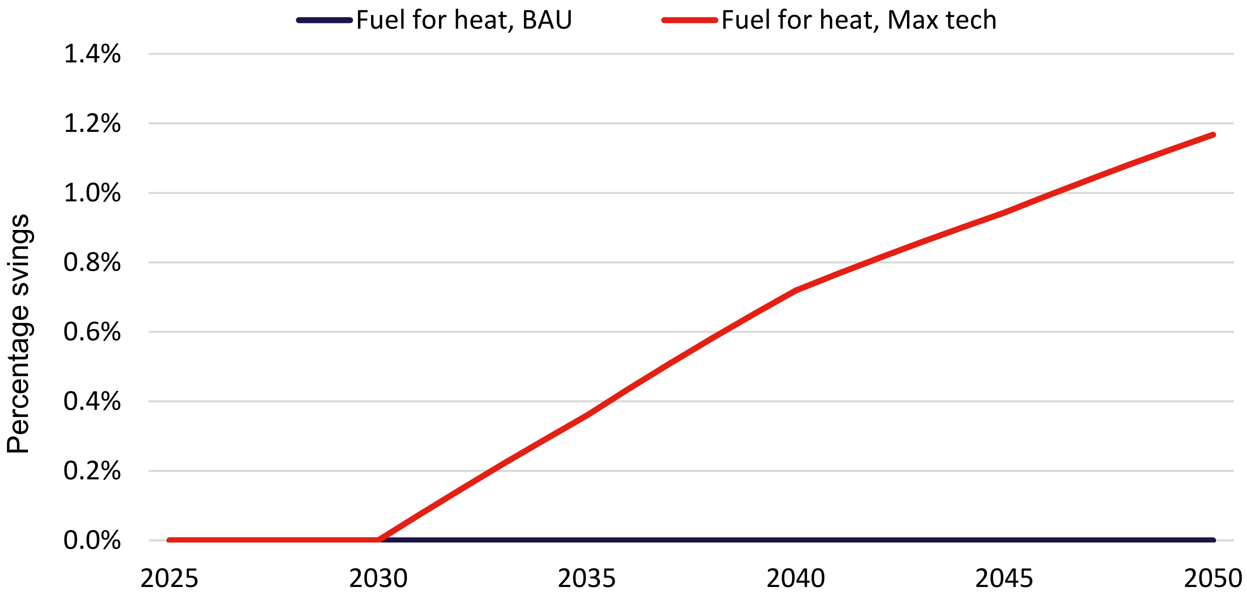
<table>
<tr><td rowspan="4">Vertical roller mills for clinker grinding</td><td rowspan="4">100%</td><td rowspan="4">10%</td><td>BAU 2030</td><td>BAU 2040</td><td>BAU 2050</td></tr>
<tr><td>20%</td><td>38%</td><td>45%</td></tr>
<tr><td>Max Tech 2030</td><td>Max Tech 2040</td><td>Max Tech 2050</td></tr>
<tr><td>100%</td><td>100%</td><td>100%</td></tr>
</table>

These measures were entered into the DESNZ model and this yielded the detailed results set out in the sections below.

5.7.8.2 RM2024 Fuel for heat Savings

Figure 49 shows the Fuel for heat Savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 49: Cement sector (2024 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios

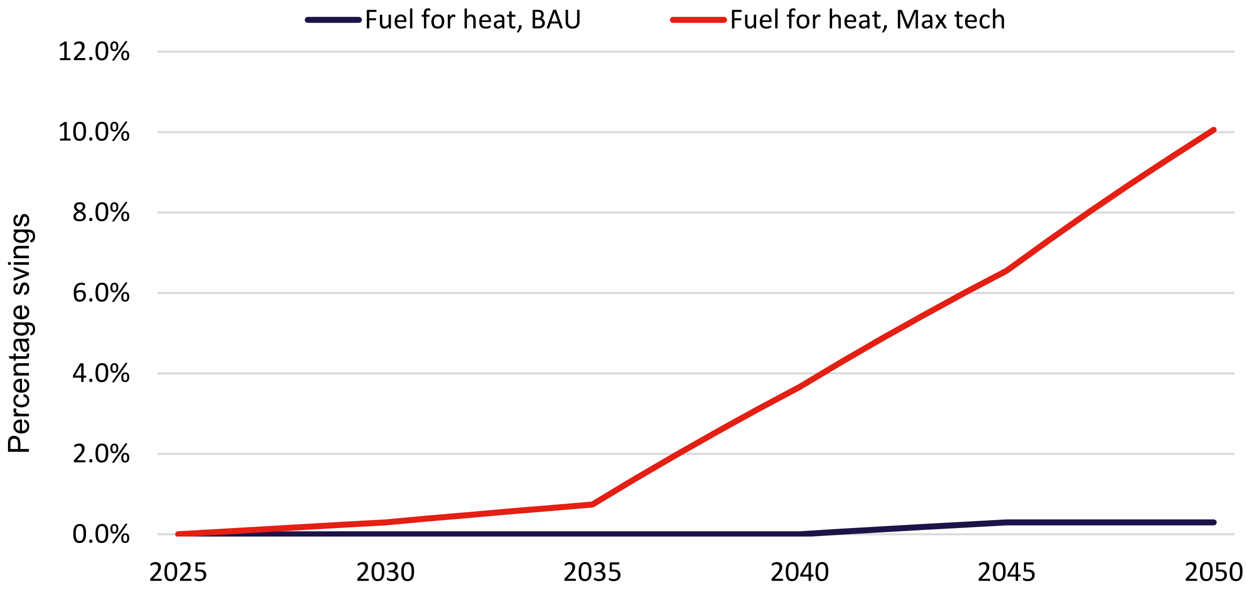


The BAU scenario shows zero savings out to 2050, while the Max Tech scenario shows a steady increase in savings, up to ~1.2% in 2050. This minor opportunity occurs due to only a gradual increase in take up of incremental improvement measures associated with saving Fuel for heat.

5.7.8.3 RM2015 Fuel for heat Savings

Figure 50 shows the Fuel for heat Savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat.

Figure 50: Cement (2015 Roadmaps) - Fuel for heat savings, expressed as a percentage of the baseline Fuel for heat, by year, for the BAU and Max Tech scenarios



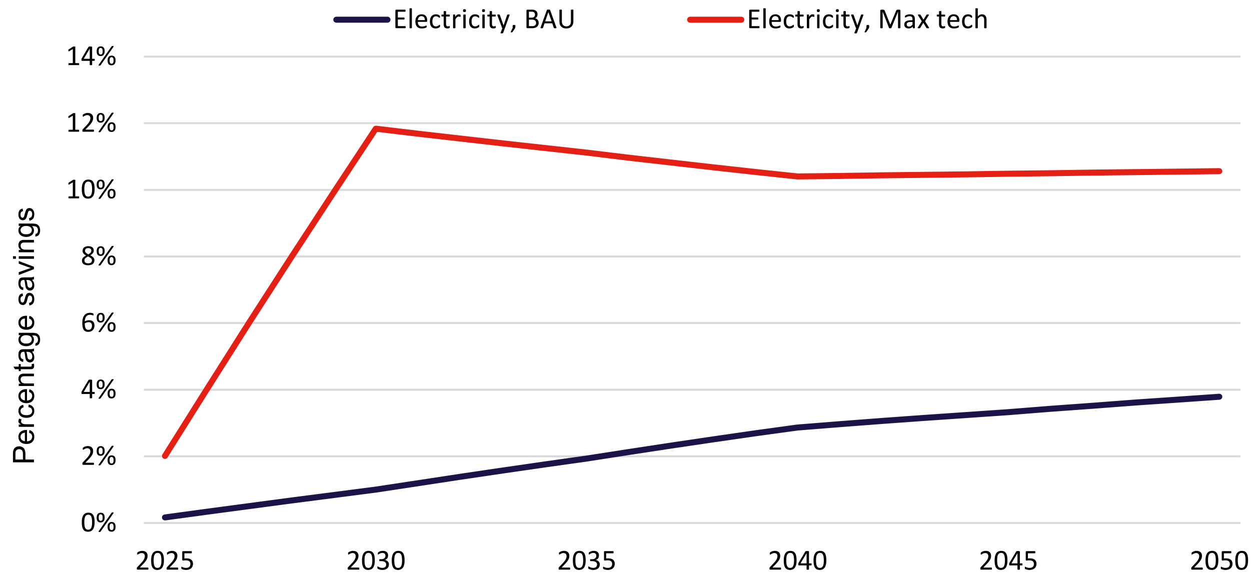
The BAU scenario only shows very slight savings from 2040, reaching a peak of <1% by 2045. Conversely, the Max Tech scenario shows a much higher saving by 2050; savings increase slowly between 2025 and 2035, reaching just 1%, however after this point, the trajectory increases considerably to reach savings of 10% by 2050.

The difference between RM2015 and RM2024 is minimal under the BAU scenario, however under Max Tech, the difference is considerable. Although the trends look similar, with both graphs showing an increase in trajectory from 2030/2035, the overall savings are significantly lower in the RM2024 study, with the peak savings 8.8% higher in the RM2015 study. The reason for this is due to stakeholder feedback indicating limited expectation of further adoption of measures as CCUS is increasingly seen as the means of decarbonising heat generation in the sector.

5.7.8.4 RM2024 Electricity Savings

Figure 51 shows the Electricity Savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Electricity. Shown are cumulative savings for prioritised and non-prioritised EE measures.

Figure 51: Cement sector (2024 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



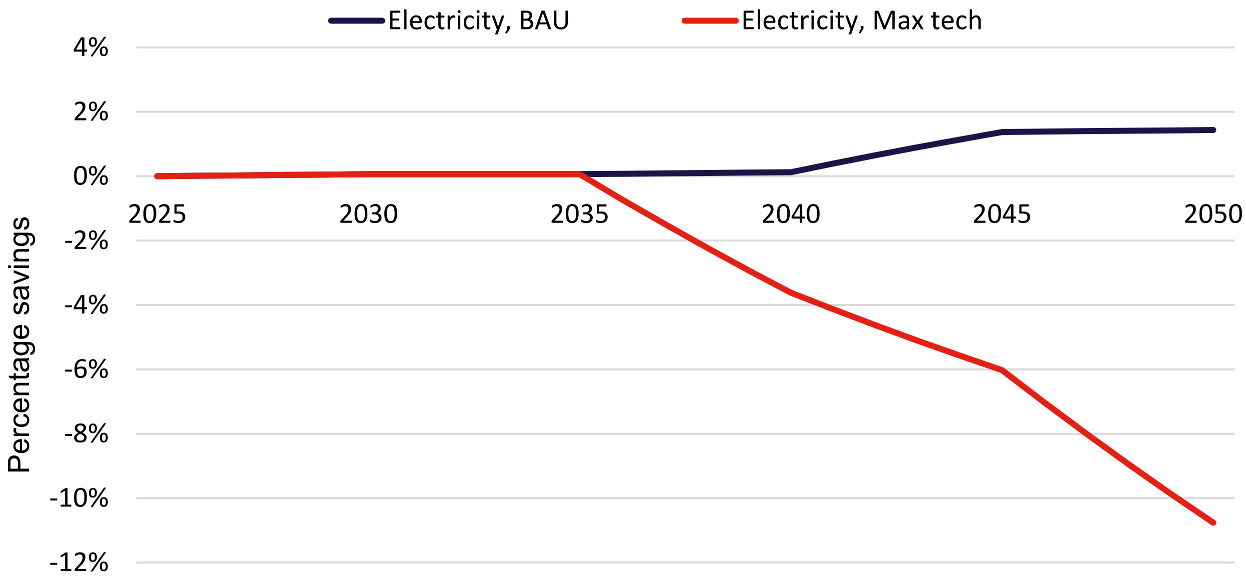
The Max Tech scenario rapidly reaches its highest savings of 12% by 2030, before reducing to 10.5% by 2040 and remaining flat out to 2050. This is due to the expected up take of CCUS meaning there is less available recovered heat to use for electricity generation since this heat would be needed for carbon capture solvent regeneration. Conversely, the BAU scenario shows a steady increase out to 2050, with the highest saving of 4%.

The main contributor to electricity savings here is the new measure for roller mills replacing ball mills. The main difference between BAU and Max Tech for electricity is due to BAU assuming that mills are upgraded as and when they come to the end of their lives, while Max Tech brings forward in time these replacements. Max Tech also includes additional take up of other measures (electrical efficiency improvements and electricity generation from recovered heat) resulting in a greater overall electricity saving.

5.7.8.5 RM2015 Electricity Savings

Figure 52 shows the Electricity Savings, determined under the RM2015 project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Electricity.

Figure 52: Cement sector (2015 Roadmaps) - Electricity savings, expressed as a percentage of the baseline electricity, by year, for the BAU and Max Tech scenarios



There are no savings under both scenarios out to 2035, at which point the trends diverge significantly, with Max Tech showing negative savings, up to minus 11% by 2050. BAU shows no savings until 2024, at which point savings start to increase up to 1.5%, out to 2050.

Both scenarios differ considerably between the RM2024 and RM2015 studies, though especially the Max Tech scenario which shows 10.5% savings versus minus 11% across both studies respectively. The reason for such a divergence is due to assumptions in the Max Tech scenario about the uptake of additional biomass as a fuel and the adoption of CCUS, both of which involve an increase in electricity consumption.

5.7.9 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 45 High and Low scenario definitions

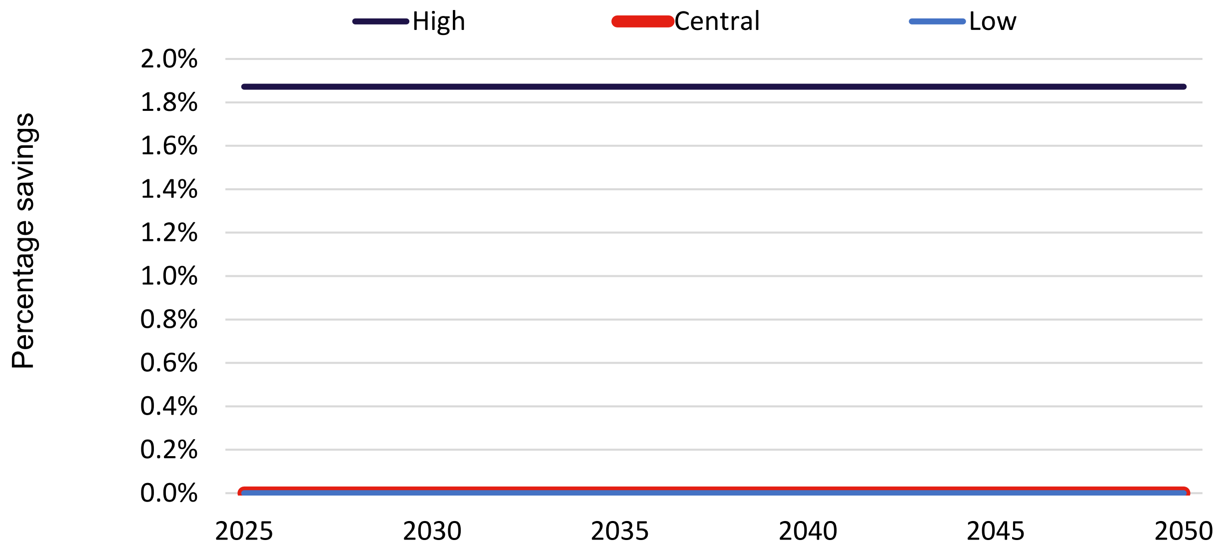
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of Adoption and % energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.7.9.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 0% – 1.9%.

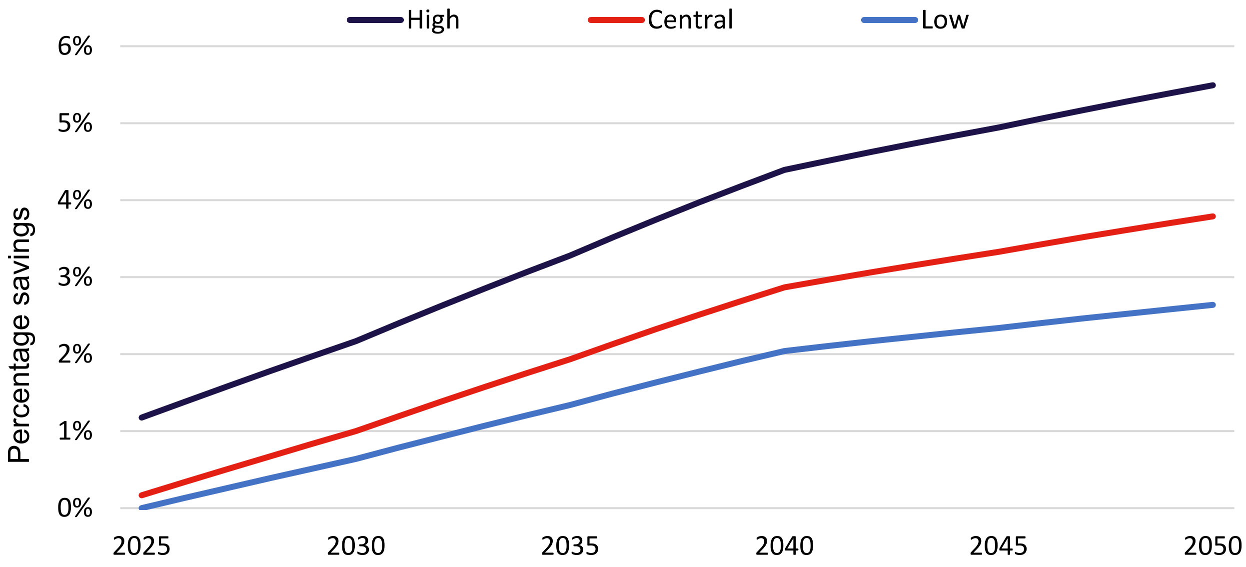
Figure 53: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.7.9.2 BAU Electricity

The range of BAU Fuel for heat savings by 2050 is 2.6% – 5.5%.

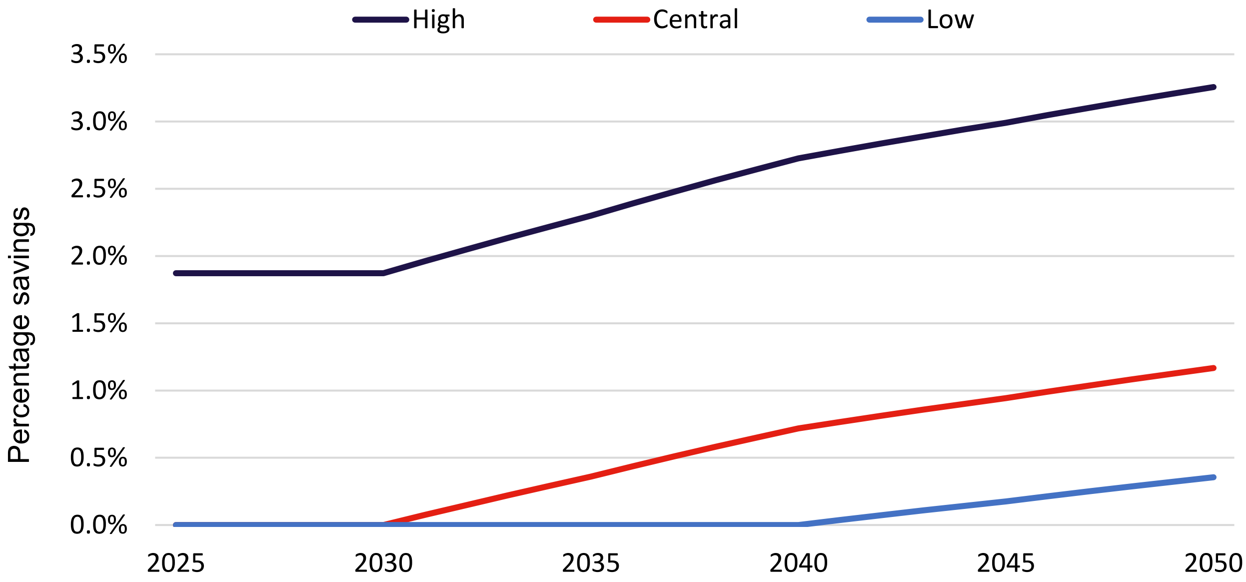
Figure 54: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.7.9.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 0.4%-3.6%.

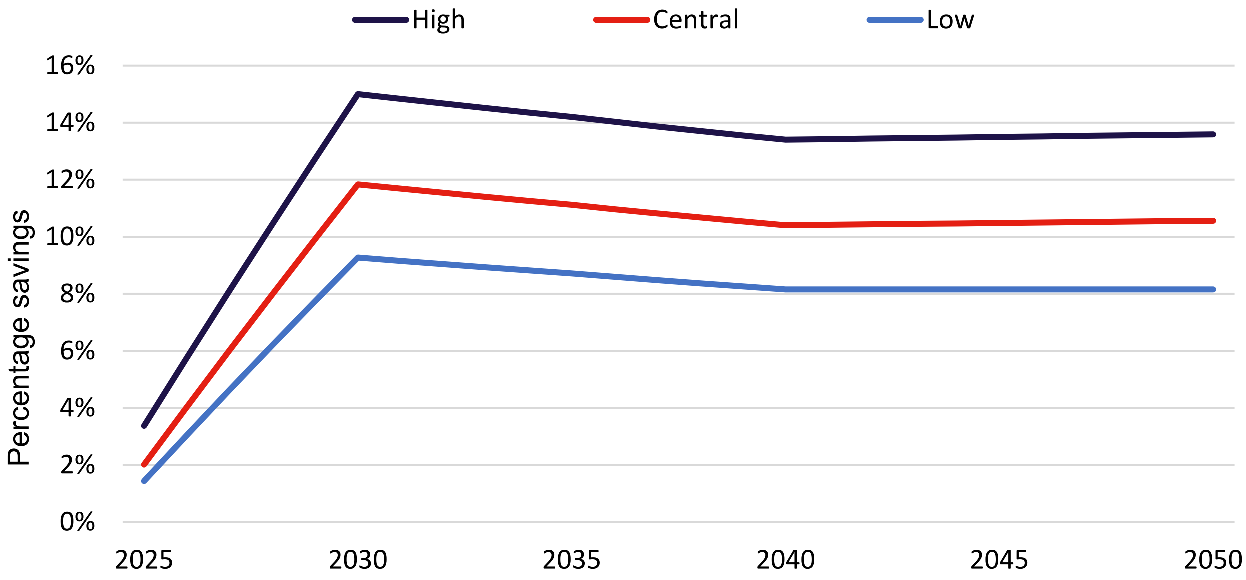
Figure 55: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.7.9.4 Max Tech Electricity

The range of BAU Fuel for heat savings by 2050 is 8.2% – 13.6%.

Figure 56: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.7.10 Limitations

The following limitations are applicable to the analysis carried out for the cement sector and should, therefore, be kept in mind when considering the results presented here:

- To manage scope within workshops, the top six EE measures were prioritised and so the research could not gain a complete view of EE potential within the sector. However, the prioritisation of measures pre-workshop has, by default, identified the measures with the greatest potential.

- It has been a challenge for stakeholders to conceptualise what the adoption of EE measures might be in the future against a background of action of deep decarbonisation measures, such as CCUS, fuel switching and material substitution (reduced clinker content in cement).
- Stakeholder feedback highlights the expectation that adoption of CCUS will use all recoverable waste heat, which removes the potential for electricity generation from this energy source.
- When interacting with stakeholders to update estimates of electricity and/or Fuel for heat savings, it was necessary to be very clear that the estimates were in respect of the EE measure under consideration as applied to the category's energy use for a 'representative site' within the sector. Representative site is difficult to conceptualise, in particular in sectors where there is inherently a large distribution of size of site and this does introduce a level of uncertainty about the percentage savings agreed upon by stakeholders. This is why the sensitivity analysis carried out includes the variable of "% energy savings".

5.8 Other Manufacturing

5.8.1 Definition

In the preceding sections of this report, the seven most energy-intensive industrial sectors (Refineries is dealt with in another dedicated report) have been examined in detail individually. However, this leaves a remainder of industrial energy consumption not covered. This is referred to as Other Manufacturing (OM) and this section of the report considers EE potential and barriers to implementation within OM.

Other Manufacturing constitutes activities represented by SIC (2007) 10-33 which are not covered by the eight priority sectors (Iron & Steel, Cement, Chemicals, Refineries, Food & Drink, Glass, Paper and Ceramics). In terms of SIC code classification this is: 13-16, 18, 22, 25-33 and parts of 23 (Non-metallic mineral products). Non-metallic mineral products include three of the priority sectors mentioned above (Cement, Glass and Ceramics), but Lime and Gypsum constitute subsectors within this larger sector of sizeable energy consumption and, as explained below, for the purposes of this study, it has been decided to include these two subsectors in OM.

Consequently, OM is defined as: SIC(2007) 13-16, 18, 22, 25-33 and Lime and Gypsum.

5.8.2 Literature Review

A literature review was carried out to understand further the distribution of energy consumption across the sub-sectors constituting OM, the processes carried out within OM and the EE measures most pertinent to improving OM's EE.

5.8.2.1 Distribution of Energy Consumption

In order to estimate the quantity of energy consumed by Other Manufacturing, Energy Consumption in the UK (ECUK) data were consulted. ECUK provides energy consumption for industrial sectors at the 2 SIC[15] code level. For five of the eight main sectors, it was possible to identify distinct 2 SIC code sector categories that covered their energy use. For the remaining three sectors (Cement, Glass and Ceramics) these are included in SIC(2007) 23 Manufacture of other non-metallic mineral products, which also includes a number of other sectors consuming meaningful quantities of energy (e.g. Lime, Gypsum, Mineral Wool, Kaolin). This means that only a proportion of SIC(2007) 23 is covered by the main sectors. An analysis of Climate Change Agreements (CCA) data allowed an estimate to be made of the proportion of SIC(2007) 23 not covered by Cement, Glass and Ceramics, which was 78%. Further, CCA data allowed an estimate to be made of the proportion of the remaining 22% accounted for by the other sectors included in this SIC(2007) 23. This found that about two-thirds of the remaining energy is accounted for by the Lime and Gypsum sectors. This means that about 92% of the energy covered by SIC(2007) 23 is accounted for by Cement, Glass, Ceramics, Lime and Gypsum. Consequently, it was decided that Lime and Gypsum were sufficiently important, distinct sectors to include in Other Manufacturing.

After removing estimates of the energy consumed by the eight main sectors from ECUK, (including all of the energy in SIC(2007) 23) about 23% of industrial energy consumption remains unaccounted for. Table 46 presents the proportion of this missing energy that ECUK indicates is taken up by non-core minor industrial sectors:

Table 46 Proportion of industrial energy consumption not covered by the eight main sectors which is claimed by individual non-core sectors

SIC (2007) Sector	Share of Energy Not Claimed by 8 Main Sectors
Manufacture of rubber and plastic products	29%
Manufacture of fabricated metal products (except machinery and equipment)	14%
Publishing, printing and reproduction of recorded media	12%
Manufacture of textiles	11%
Manufacture of machinery and equipment	9%
Manufacture of motor vehicles, trailers and semi-trailers	7%
Manufacture of furniture	7%
Manufacture of other transport equipment	4%
Manufacture of electrical machinery and apparatus	4%
Manufacture of wearing apparel; Dressing and dying of fur	2%
Manufacture of leather and leather products	<1%

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[15] Standard Industrial Classification

SIC (2007) Sector	Share of Energy Not Claimed by 8 Main Sectors
Manufacture of tobacco products	<1%

The top six of these non-core sectors account for 82% of the unaccounted-for energy and it was decided to attempt to evaluate the EE potential within these six subsectors. Consequently, we have attempted to individually analyse the EE potential within the following subsectors:

- Lime
- Gypsum
- Manufacture of rubber and plastics (as set out below, these were subjected to separate analysis)
- Manufacture of fabricated metal products
- Printing
- Textiles
- Machinery and equipment
- Motor vehicles

5.8.2.2 Processes Carried Out

In the analysis that follows, we consider the decided upon OM scope to fall into three main categories: OM less lime and Gypsum and, Lime (separately) and Gypsum (separately).

For OM less Lime and Gypsum, ECUK gives the following approximate distribution of energy consumption across high level processes

Table 47 Distribution of energy consumption across ECUK industrial sectors not covered by the eight main sectors (including all of SIC(2007) 23)

End Use Process	Share of Energy Not Claimed by 8 Main sectors
HT Process	2%
LT Process[16]	44%
Drying/Separation	11%
Motors and drives	23%
Compressed Air	9%
Refrigeration	4%
Other	6%
Total	100%

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[16] Predominantly the generation of hot water and steam.

This indicates that nearly 87% of the energy consumption is associated with the following four end use processes: LT processes (hot water and steam generation), drying and separation, motors and drives and compressed air. High Temperature process energy consumption is very small as is refrigeration. The overwhelming majority of energy consumption for refrigeration is, according to ECUK, consumed in the Chemicals, and Food and Drink sectors, which are covered in the main sectors. The overwhelming majority of HT process energy is also consumed in the main sectors. Consequently, for OM less Lime and Gypsum, it was decided to prioritise the identification and analysis of EE measures addressing the following processes: LT processes (hot water and steam generation), drying and separation, motors and drives and compressed air.

For Lime, the review of literature and engagement with the sector (see later) indicated the main energy consumption processes, and the spread of total subsector energy consumption across these processes, is as follows:

Table 48 Main energy consuming processes in the Lime subsector and the distribution of energy across them

Process	Electricity (%)	Fuel for heat (%)
Stone Crushing	30%	0%
Stone Preparation	20%	0%
Burning	25%	100%
Lime Milling	5%	0%
Hydration	5%	0%
Milk of Lime Production	5%	0%
Bagging/Packaging	10%	0%

Absolute numbers for energy consumption are not provided here, as the sector has a relatively small number of operators and to do so would risk disclosure. However, further context is provided by noting that electricity accounts for approximately 8% of total energy consumption and Fuel for heat 92%.

This means that the sector’s energy consumption is very heavily concentrated in the generation of heat for limestone burning in the lime kiln. Electricity consumption is more evenly distributed across the other processes, but about half of all electricity consumption in associated with feed preparation (including crushing).

For Gypsum the main energy consuming process and the approximate distribution of energy consumption across them is as shown in Table 49. Individual estimates of the share of energy consumption were possible for the two main heat consuming processes (calcination and board drying). This was not possible for the other processes of raw material drying and preparation, milling and board production) and so the estimated share of sector electricity and Fuel for heat is given as an aggregate figure for these processes.

Table 49 Main energy consuming processes in the Gypsum subsector and the distribution of energy across them

Process	Electricity (%)	Fuel for heat %
Calcining	20%	25%
Board Drying	15%	60%
Other, incl. raw material drying and preparation, milling and board production)	65%	15%

Calcining is the process whereby gypsum (CaSO4.2H2O) is converted into stucco (plaster of Paris) (CaSO4.1/2H2O) by the application of heat at temperatures between 120-180°C.

Stucco product is either supplied as powder, coving or plaster board. Plasterboard is a significant product output for the sector. Its production involves the creation of a stucco/water slurry which is sandwiched between sheets of paper before being dried. It is estimated that plasterboard drying consumes the majority of the heat in the sector.

5.8.2.3 Pertinent EE Measures

For OM (less Lime and Gypsum) the cross-cutting EE measures identified during the literature review for the main sectors were gathered-up and mapped to the priority ECUK processes. In addition to this, one very specific measure applying to the plastics sector (all electric injection moulding machines), was included – see 5.8.5 Prioritised measures below.

For Lime and Gypsum, the literature review confirmed that the overwhelming majority of the energy consumption is for heat consuming processes. Consequently, EE measures associated with saving heat were sought from the literature for these two sub-sectors - see below for specific details.

5.8.3 Engagement

Engagement with the subsectors making up OM consisted of:

- Gathering up the results of the literature review for each subsector relating to: main energy consuming processes, split of electricity and Fuel for heat across processes and the main EE measures applying across the processes
- Presenting this to subsector Sector Associations (SAs) to gain their validation and to fill gaps
- Discussing with stakeholders during interview the applicability of the individual measures across the sector and obtaining estimates of the current level of adoption of the EE measures

Not all of the OM subsectors were available within the project timeframe to go through this process. However, engagement was obtained from the SAs representing Plastics, Rubber, Lime, Gypsum and Motor Manufacturers.

5.8.4 Main categories of Energy Use

As stated above, the literature review allowed estimates of the distribution of energy consumption across process to be made. For OM (less Lime and Gypsum) this is presented in Table 47 and for Lime and Gypsum, this is presented in Table 48 and Table 49, respectively.

5.8.5 Prioritised measures

For the OM (less Lime and Gypsum), measures cross-cutting across the end use categories of LT process, motors and drives and compressed air were prioritised for the analysis. In order to manage the number of relevant cross-cutting measures, the full list was rationalised down to 10 distinct measures across the most important processes. For Plastics, an additional measure of All electric injection moulding machines was included.

To support the later use of these measures in the modelling, the literature review findings were used to attach typical electricity and Fuel for heat savings, where the savings are expressed relative to the ECUK process. The prioritised measures and their typical energy savings and payback are presented in Table 50.

Table 50 Prioritised measures for OM (less Lime and Gypsum), including literature-based estimates of energy savings and payback

ECUK End Use Process	EE measure	Electricity Savings	Fuel for heat Savings	Payback (years)
All	Energy Management System	6%	6%	1.5
Motors and Drives	Variable Speed Drives (VSDs) for variable driven loads (e.g. pumps and fans)	15%	0%	3
Compressed Air	Variable Speed Drive air compressors	15%	0%	7.5
Compressed Air	Compressed air maintenance and management (leak management, pressure minimisation, demand minimisation)	12%	0%	1
HT Process	Recuperative burners	0%	30%	3

ECUK End Use Process	EE measure	Electricity Savings	Fuel for heat Savings	Payback (years)
LT Process	Oxygen trim on combustion	0%	3%	3
LT Process	Pre-heating combustion air	0%	3%	5
LT Process	Use of economisers to preheat make-up water in steam generation	0%	7%	3
LT Process	Recover heat from boiler blowdown	0%	2%	5
LT Process	Maintenance programme for steam traps	0%	5%	1.25

The literature review for Lime and Gypsum revealed a number of key EE measures which, in the first instance, appear to be applicable. The actual applicability of these measures was discussed with the Lime and Gypsum SAs during interviews. A summary of these measures and the responses received from SAs during these discussions is summarised in Table 51 and Table 52.

Table 51 Main identified EE measures for Gypsum and response from sector on applicability and adoption

Sector	Process	EE Measure	SA Response
Gypsum	Calcination	Recovery and reuse of heat for combustion air preheating/raw materials preheating/electricity generation	No response
Gypsum	Gypsum board drying	Recovery and reuse of heat for combustion air preheating/raw materials preheating/electricity generation	No response
Gypsum	All	Energy management System (EMS)	No final response
Gypsum	Motors and Drives	VSDs on variable driven loads	No final response
Gypsum	Compressed air	Variable speed compressor	No final response
Gypsum	Compressed air	Compressed air maintenance	No final response

At the time of report writing, there was no response from the SA on the applicability and adoption of the prioritised EE measures. Follow engaged was not feasible due to the time constraints around the research project.

Table 52 Main identifies EE measures for Lime and response from sector on applicability and adoption

Sector	Process	EE Measure	SA Response
Lime	Lime kiln	Recovery of waste heat for material preheat	Already happening by default in types of kiln used (PRK, PFPK)
Lime	Lime kiln	Recovery of waste heat for preheating of combustion air	Already happening in both kiln types (PRK, PFRK)
Lime	Lime kiln	Recovery of waste heat for material or fuel drying	Only needed in PRK. Already happening.
Lime	Lime kiln	Recovery of waste heat for electricity generation	Waste heat from PRK and PFRK of too low grade after other recovery taken into account.
Lime	Lime kiln	Shortening LRK and adding a preheater	Already exhausted
Lime	Lime kiln	Conversion of simple shaft kiln to ASK or PFRK	Not considered practical.
Lime	Lime kiln	Adopt VSDs on combustion air and ID fans	Largely exhausted
Lime	Feed preparation	Adopt vertical roller mills for limestone preparation	No milling, just crushing
Lime	Lime milling	Adopt vertical roller mills for lime milling	Exhausted

From the responses received, the main EE measures are either already adopted to the maximum extent possible within the sector or not considered practical.

5.8.6Key assumptions

5.8.6.1 Adoption and applicability of cross-cutting EE measures (OM less lime and gypsum)

Separate interviews were carried out with the following SAs: plastics (BPF), rubber (BTMA), motor manufacturers (SMMT) and printing (an operator), in order to get their views on the current adoption and applicability of the cross-cutting measures across their sectors. At the time of writing the report, responses were received only from plastics from the point of view of the sector.

In order to improve coverage of Adoption, evidence submitted to DESNZ by SAs in support of Climate Change Agreement (CCA) target negotiations was examined and this allowed us to increase the number of OM sub-sectors for which an estimate of current Adoption of the cross-cutting measures was possible. For each cross-cutting measure a weighted current Adoption was calculated from the sub-sectors for which data were available, weighted according to energy consumption in the sub-sector.

Regarding applicability, an assumption has been made that the applicability of each measure is 100%, on the basis that the cross-cutting measures used in the analysis are very widely applicable against the ECUK energy end use category in question.

Table 53 Adoption and applicability rates for cross-cutting EE measures

Measure	Applicability	Adoption in 2024	BAU 2030	BAU 2040	BAU 2050
Energy Management System (EMS) implementation	100%	48%	68%	100%	100%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Variable Speed Drives (VSDs) for variable driven loads (e.g. pumps and fans)	100%	53%	BAU 2030	BAU 2040	BAU 2050
			69%	98%	100%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Variable Speed Drive air compressors	100%	41%	BAU 2030	BAU 2040	BAU 2050
			43%	46%	46%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Compressed air maintenance and management (leak management,	100%	55%	BAU 2030	BAU 2040	BAU 2050
			72%	100%	100%
			Max Tech 2030	Max Tech 2040	Max Tech 2050

pressure minimisation, demand minimisation)			95%	100%	100%
Recuperative burners	100%	50%	BAU 2030	BAU 2040	BAU 2050
			72%	100%	100%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Oxygen trim on combustion	100%	77%	BAU 2030	BAU 2040	BAU 2050
			81%	87%	87%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Pre-heating combustion air	100%	77%	BAU 2030	BAU 2040	BAU 2050
			79%	83%	83%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Use of economisers to preheat make-up water in steam generation	100%	74%	BAU 2030	BAU 2040	BAU 2050
			78%	85%	85%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%

Recover heat from boiler blowdown	100%	74%	BAU 2030	BAU 2040	BAU 2050
			79%	87%	87%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%
Maintenance programme for steam traps	100%	78%	BAU 2030	BAU 2040	BAU 2050
			86%	100%	100%
			Max Tech 2030	Max Tech 2040	Max Tech 2050
			100%	100%	100%

5.8.6.2 Adoption and applicability lime

The Sector Association (SA) responses to the Adoption and Applicability for the priority EE measures identified for Lime are as shown in Table 52. All EE measures agreed with the SA as Applicable were, according to the SA, adopted to their maximum extent within the sector. Consequently, it was deemed that there was no additional EE potential from the prioritised measures and the EE improvement rate for Lime is deemed to be flat.

5.8.6.3 Adoption and applicability gypsum

The adoption and applicability for the priority EE measures identified for gypsum are as shown in Table 51. Unfortunately, at the time of writing the report, there was no confirmation from the SA in adoption and applicability, and so it was not possible to estimate the outstanding EE potential associated with gypsum.

5.8.6.4 Adoption of cross-cutting EE measures OM (less lime and gypsum)

Consistent with the scenarios developed for the main sectors, two plausible adoption scenarios are observed for the cross-cutting measures applying to this part of the OM sector, i.e. BAU and Max Tech. The assumptions underlying the adoption under each of these are as follows:

BAU

- That the adoption rate between adoption in 2024 and applicability is determined by the paybacks of the cross-cutting measures, on the basis that the uptake of EE measures with shorter paybacks can be expected to be more rapid than those with longer paybacks.
- That EE measures with paybacks of less than 2 years are adopted to the maximum possible technical extent (defined by applicability) by 2040.
- That EE measures with payback greater than 8 years will not see increased adoption going forward
- For EE measures with payback between 2 and 8 years, the rate of adoption is inversely proportional to the payback and is achieved at a rate which is in between that established for measures with paybacks of 2 years and that established for measures greater than 8 years, according to the actual payback.

Max Tech

- That the applicability of all cross-cutting measures is 100% since these measures are considered to be widely applicable. Therefore, for the Max Tech scenario it is assumed that the OM sectors fully adopt the measures by 2030.

5.8.7 Specific barriers to sectors

As discussed above, interviews were held with the plastics, rubber, motor manufacturers, gypsum and lime sectors and during these interviews barriers to the implementation of EE measures was discussed.

By definition, the individual subsectors in OM are diverse in nature and so a range of barriers were quoted. However, the most commonly cited barriers were the downtime disruption associated with the implementation of measures and fears about the impact that any changes to process resulting from EE measure implementation might have on product quality. This barrier was found to be widely cited by all sectors examined in this study.

For sectors where companies have more options regarding where they can cite operations, the availability of capital for investments in the UK was mentioned. More generally, the crowding out of EE measure investment by other capital projects was a common issue, and this was particularly the case within the Motor Manufacturing subsector, where there is a greater imperative than in most subsectors to invest in product development to keep up with the competition, and this can squeeze out capital investment for EE measures.

Some of the sectors with large numbers of smaller operators stated that there were issues with a lack of knowledge and skills at the site level for identifying and developing EE projects. This finding particularly relates to the Plastics sector.

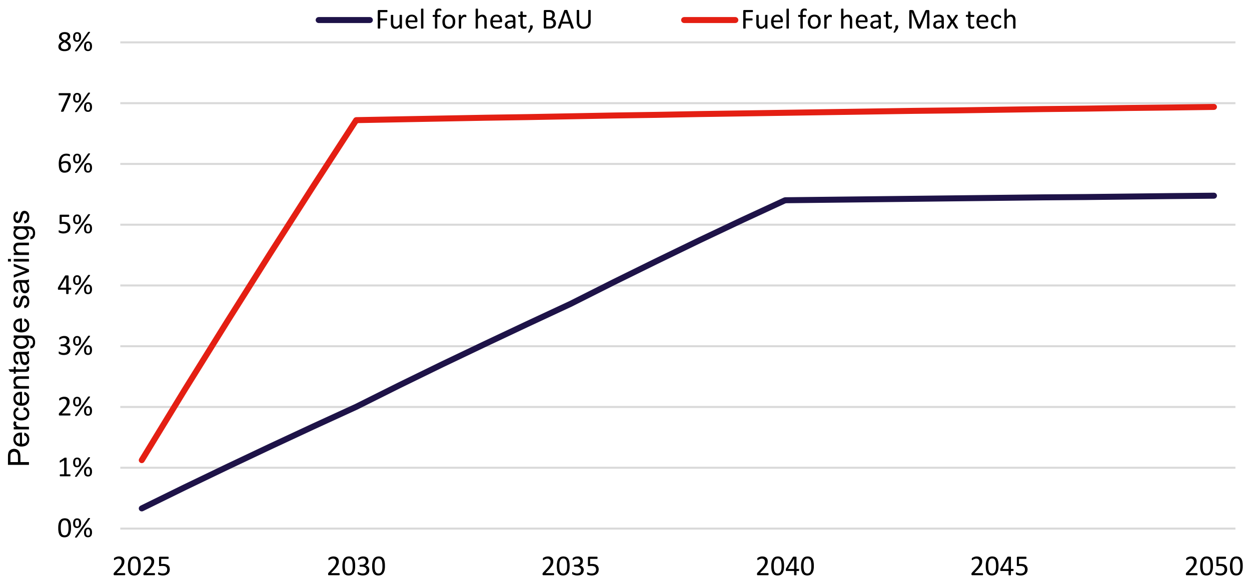
In terms of the support that government could provide to assist with further improvements in EE, full expensing or super deductions of the cost of EE projects was mentioned as was assistance with identifying and developing EE projects in cases where the skills/ experience to do this was absent.

5.8.8 Results

5.8.8.1 RM2024 Fuel for heat Savings

Figure 57 shows the Fuel for heat savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Fuel for heat. This is presented in aggregate for the OM (less lime and gypsum) and lime and gypsum sub-sectors of OM.

Figure 57: OM sector (2024 Roadmaps) expressed as percentage of the baseline Fuel for heat, by year, for BAU and Max Tech scenarios



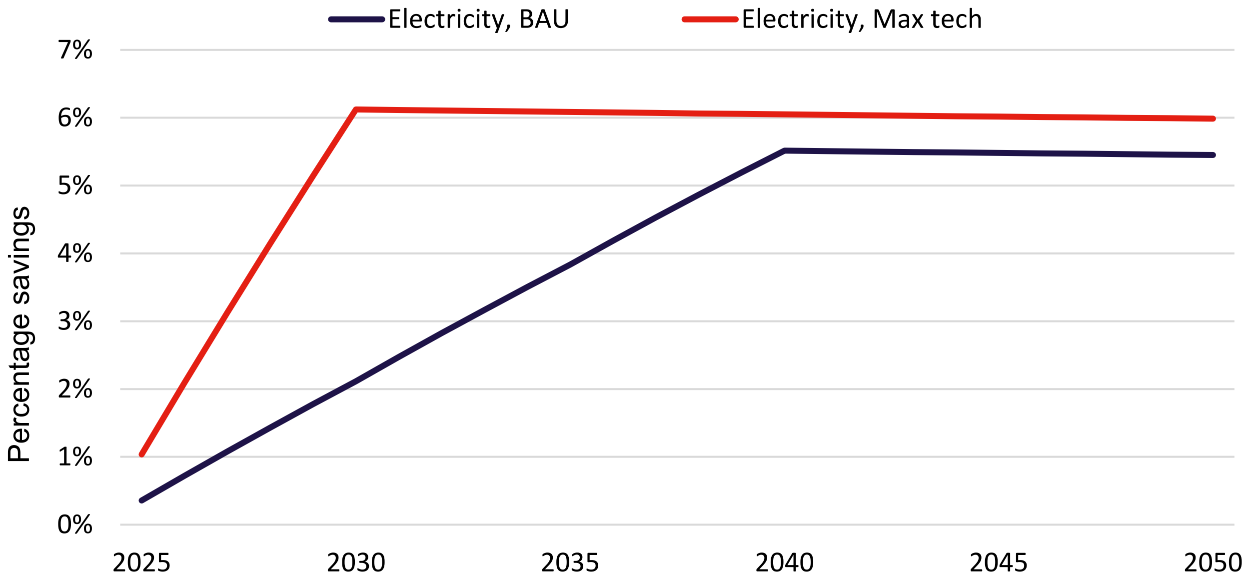
A similar trend can be seen under both scenarios, with a steady increase in savings before reaching a peak and plateauing out to 2050. However, Max Tech reaches this peak a decade earlier (by 2030, rather than 2040) and achieves higher max savings of 7% by 2050, compared with ~5.5% under BAU. The gap between Max Tech and BAU is therefore around1.5 percentage points by 2050.

The Max Tech Fuel for heat savings trend is explained by the assumption that adoption of all measures reaches full applicability by 2030. In contrast, the shape of the BAU Fuel for heat savings is the result of the assumption that adoption of all measures with a payback of less than 2 years reaches full applicability by 2040, but that measures with a payback of more than 8 years see no further adoption from their current levels of adoption. For measures with payback between 2 and 8 years, the rate of adoption is inversely proportional to the payback period.

5.8.8.2 RM2024 Electricity Savings

Figure 58 shows the Electricity savings, determined under this project, for the BAU and Max Tech scenarios, for years out to 2050, expressed as a proportion of baseline Electricity. This is presented in aggregate for the OM (less lime and gypsum) and lime and gypsum sub-sectors of OM.

Figure 58: OM sector (2024 Roadmaps) expressed as percentage of the baseline electricity, by year, for BAU and Max Tech scenarios



The trend shown is very similar to the Fuel for heat savings, in that the Max Tech and BAU scenarios again reach their peaks in 2030 and 2040 respectively, and both plateau after this point. The reason for this is the same as Fuel for heat – for Max Tech, adoption levels of all measures meet full applicability by 2030, whereas for BAU, adoption of all measures with a payback of less than 2 years achieves full applicability by 2040.

A key difference between electricity and Fuel for heat is the lower savings achieved under Max Tech for electricity. Electricity savings peak at around 6%, compared to 7% for Fuel for heat, while the BAU scenario remains consistent across both graphs. This results in a 0.5% difference between Max Tech and BAU for Electricity, compared with 1.5% for Fuel for heat savings.

5.8.9 Sensitivity of Results

The sensitivity of results is presented below for the BAU and Max Tech, exploring Central, High and Low scenarios when applied to the variables of Adoption and percentage Energy Savings. The definition of High and Low scenarios is as follows:

Table 54: High and Low scenario definitions

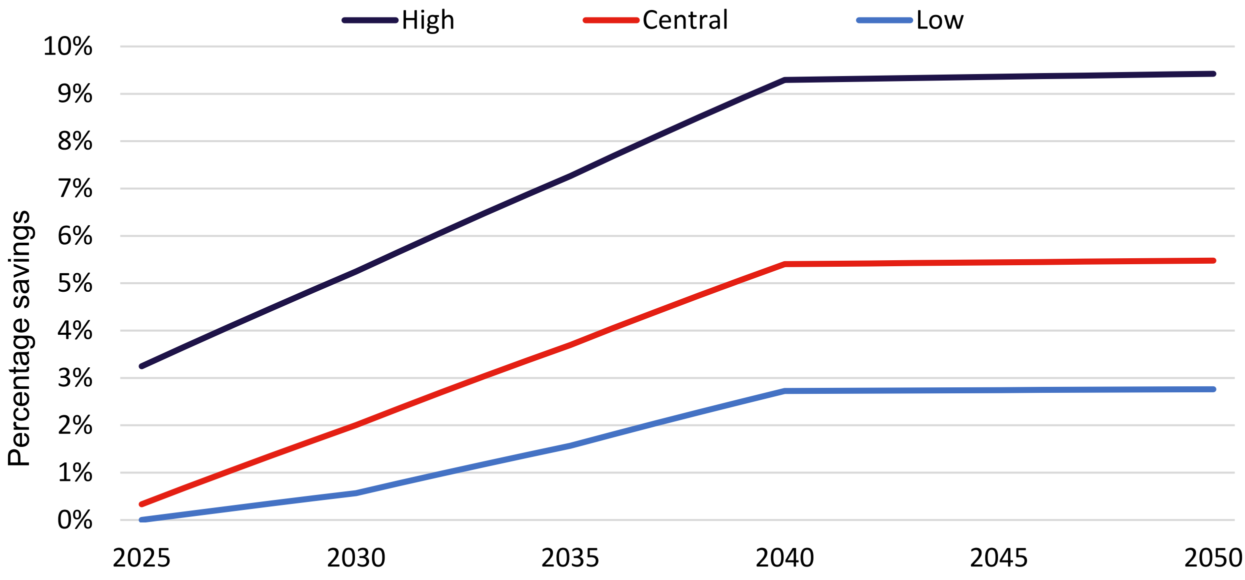
	High	Low
Adoption	Central Value x 0.8	Central Value x 1.2
% Energy Savings	Central Value x 1.2	Central Value x 0.8

The variables of adoption and percentage energy savings for each measure (as applied to category energy use) are considered to be those with the greatest inherent uncertainty and, therefore, those whose value will have the greatest impact upon the results. Although the level of uncertainty of these variables is different across EE measures, application of a plus or minus 20% sensitivity is considered an appropriate range which accounts for this uncertainty and broadly fits within the range of input given by industry stakeholders.

5.8.9.1 BAU Fuel for heat

The range of BAU Fuel for heat savings by 2050 is 3% – 9%.

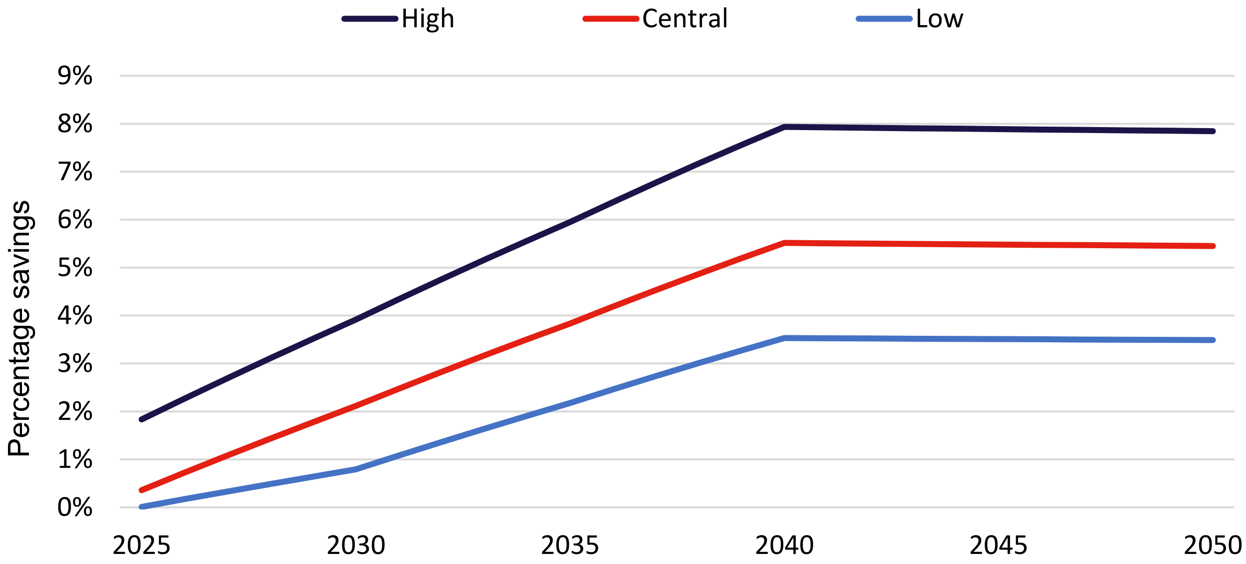
Figure 59: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, BAU



5.8.9.2 BAU Electricity

The range of BAU electricity savings by 2050 is 3% – 8%.

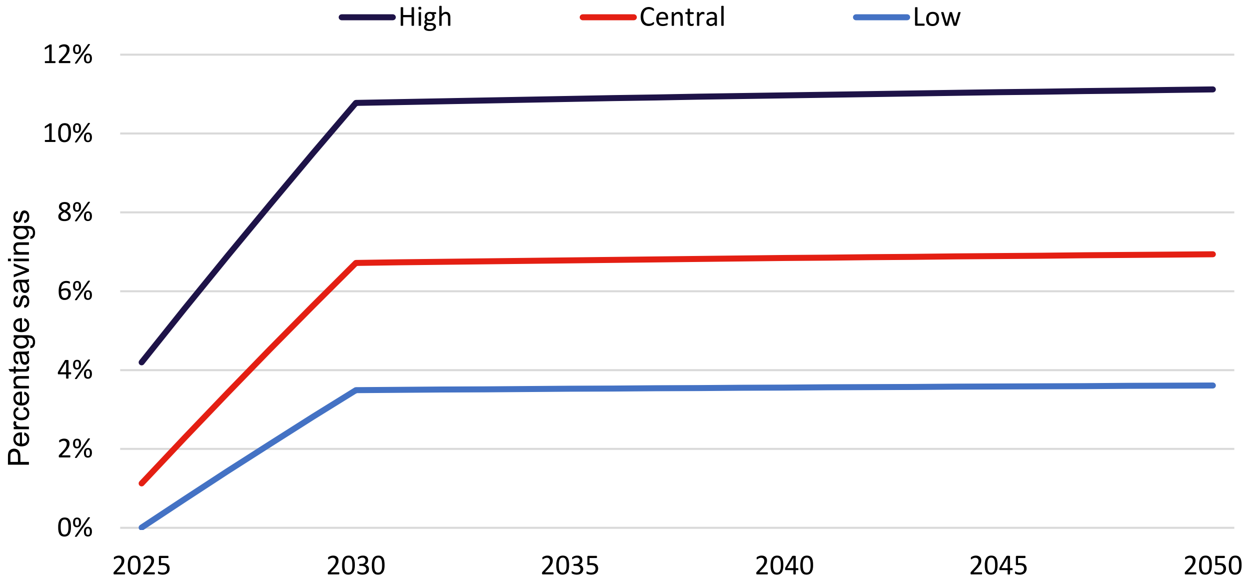
Figure 60: Sensitivity of results for High, Central and Low scenarios applied to Electricity, BAU



5.8.9.3 Max Tech Fuel for heat

The range of Max Tech Fuel for heat savings by 2050 is 4% – 11%.

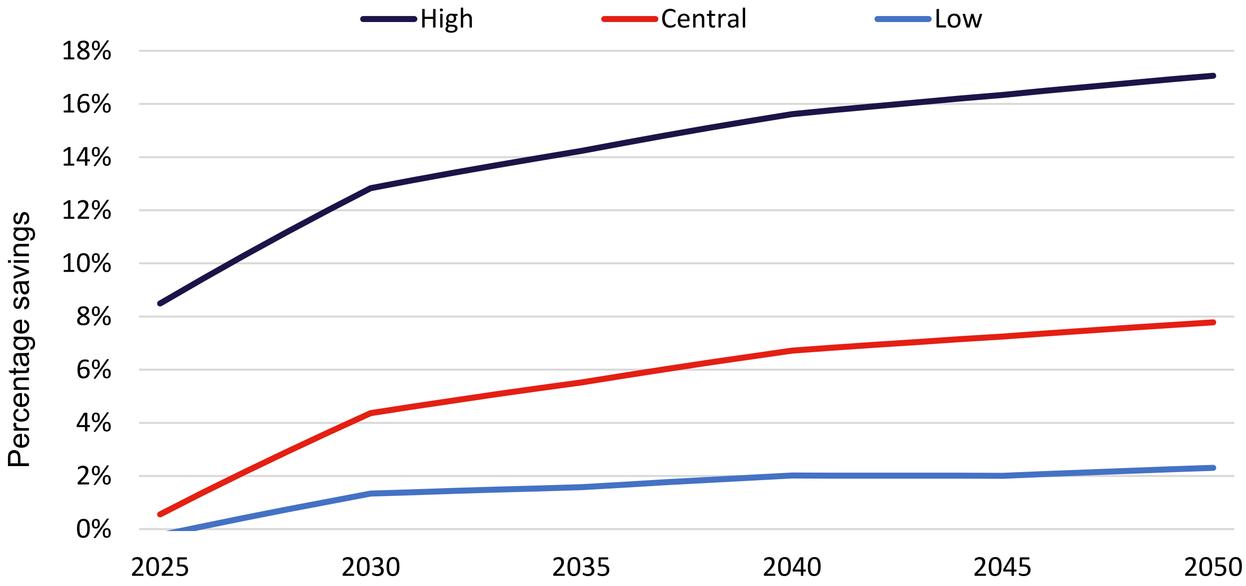
Figure 61: Sensitivity of results for High, Central and Low scenarios applied to Fuel for heat, Max Tech



5.8.9.4 Max Tech Electricity

The range of Max Tech electricity savings by 2050 is 2% – 17%.

Figure 62: Sensitivity of results for High, Central and Low scenarios applied to Electricity, Max Tech



5.8.10 Limitations

Direct engagement with OM sub-sectors was only possible for some (plastics, rubber, lime, gypsum, motor manufacturers) and this engagement was confined to interviews. There was no workshop, so the breadth of evidence is not as great as for the main sectors.

Interviews were confined to Sector Associations (SAs) and input from actual operators was usually (but not always) absent as there was limited time to follow up for OM sector input. As such, opinions of the SAs are prevailing for OM, unlike the situation for the seven main sectors where both SAs and operators provided evidence.

Leaving aside the specific measures looked at in plastics, lime and gypsum, the implicit assumption is that a relatively small number of cross-cutting measures capture a meaningful proportion of the EE potential across OM. While this may be considered a stretch, the measures were selected to address energy consumption processes which are significant and common across industry, and so the approach is considered proportionate for this project.

The adoption for the OM subsectors not engaged directly is taken as the average for the sub-sectors engaged. In so far as the sub-sectors engaged directly tend to be the larger energy consumers, where attention to EE may be higher, this could represent an over-estimate of current adoption leading to an underestimate of the overall EE potential for OM.

Unlike the situation with the seven main sectors, the adoption into the future was not directly consulted upon but inferred from the paybacks of the EE measures. This assumes a uniform attitude towards payback across the sub-sectors when considering the likelihood of measure implementation. This may not be the case, and therefore there is a large degree of uncertainty surrounding the OM results, more so than for the seven main sectors covered in this report.

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Food & Drink	Thermal characterization of a high-temperature industrial bread-baking oven: A comprehensive experimental and numerical study	Link	Yves Mansour, Olivier Rouaud, Rayan Slim, Pierre Rahmé	2024
Food & Drink	Thermal energy management in the bread baking industry using a system modelling approach	Link	Joe Paton, Zinedine Khatir, Harvey Thompson, Nik Kapur, Vassili Toropov,	2013
Glass	A review of decarbonization options for the glass industry	Link	Michael Zier, Peter Stenzel, Leander Kotzur, Detlef Stolten,	2021
Glass	Best Available Techniques (BAT) Reference Document for the Manufacture of Glass	Link	Scalet Bianca Maria, Garcia Muñoz Marcos, Sissa Aivi Querol, Roudier Serge, Delgado Sancho Luis	2013
Glass	Decarbonizing the glass industry: A critical and systematic review of developments, sociotechnical systems and policy options	Link	Dylan D. Furszyfer Del Rio, Benjamin K. Sovacool, Aoife M. Foley, Steve Griffiths, Morgan Bazilian, Jinsoo Kim, David Rooney	2022
Glass	Detailed comparison of physical fining methods in an industrial glass melting furnace using coupled CFD simulations	Link	Georg Daurer, Juraj Raič, Martin Demuth, Christian Gaber, Christoph Hochenauer	2023
Glass	Emerging energy efficiency and carbon dioxide emissions reduction technologies for the glass industry	Link	Cecilia Springer1 and Ali Hasanbeigi	2017
Glass	Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry	Link	Ernst Worrell Christina Galitsky Eric R Masanet Wina Graus	2008

Sector	Title	URL	Author	Year
Glass	Energy efficiency potentials in the Eu industry: impacts of deep decarbonisation technologies	Link	Kermeli, K., Crijns-Graus, W., Johannsen, R.M. et al.	2022
Glass	Industrial decarbonization pathways: The example of the German glass industry	Link	Michael Zier, Noah Pflugradt, Peter Stenzel, Leander Kotzur, Detlef Stolten	2023
Glass	Modelling of the controlled melt flow in a glass melting space — Its melting performance and heat losses	Link	Marcela Jebavá, Petra Dyrčíková, Lubomír Němec	2015
Glass	Performance evaluation of industrial glass furnace regenerator	Link	Samy M. El-Behery, A.A. Hussien, H. Kotb, Mostafa El-Shafie	2017
Glass	Reducing industrial energy demand in the UK: A review of energy efficiency technologies and energy saving potential in selected sectors	Link	Jahedul Islam Chowdhury, Yukun Hu, Ismail Haltas, Nazmiye Balta-Ozkan, George Jr. Matthew, Liz Varga	2018
Glass	Supercritical CO2 and air Brayton-Joule versus ORC systems for heat recovery from glass furnaces: Performance and economic evaluation	Link	Piero Danieli, Sergio Rech, Andrea Lazzaretto	2019
Glass	Technological Energy Efficiency Improvements in Glass-Production Industries and Their Future Perspectives in Italy	Link	Cantini, A., Leoni, L., Ferraro, S., De Carlo, F., Martini, C., Martini, F., Salvio, M.	2022
Glass	The materiality of transparency: An environmental analysis of the architectural flat glass industry since 1945 in Europe, France and Belgium	Link	Jean Souviron, Ahmed Z. Khan	2021
Glass	The Use of CFD for the Design and Development of Innovative Configurations in Regenerative Glass Production Furnaces	Link	Cravero, C., De Domenico, D.	2019
Iron & Steel	A digital life-cycle management framework for sustainable smart manufacturing in energy intensive industries	Link	Malarvizhi Kaniappan Chinnathai, Bugra Alkan	2023

Sector	Title	URL	Author	Year
Iron & Steel	A survey analysis of low carbon technology diffusion in China's iron & steel industry	Link	Xianbing Liu, Xue Gao	2016
Iron & Steel	ASEAN Technologies Customised List. Version 3.2 Part-1:EAF. Recommended technologies for energy saving, environmental protection and recycling in ASEAN iron and steel industry	Link	The Japan Iron and Steel Federation	2022
Iron & Steel	ASEAN Technologies Customised List. Version 4.1 Part-2:BF-BOF. Recommended technologies for energy saving, environmental protection and recycling in ASEAN iron and steel industry	Link	The Japan Iron and Steel Federation	2023
Iron & Steel	Best Available Techniques (BAT) Reference Document for Energy Efficiency	Link	European Commission	2009
Iron & Steel	Best Available Techniques (BAT) Reference Document for Iron and Steel Production & Ferrous Metals Processing	Link	Rainer Remus, Miguel A. Aguado-Monsonet. Serge Roudier, Luis Delgado Sancho	2013
Iron & Steel	Best Available Techniques (BAT) Reference Document for Large Combustion Plants	Link	Thierry Lecomte, José Félix Ferrería de la Fuente, Frederik Neuwahl, Michele Canova, Antoine Pinasseau, Ivan Jankov, Thomas Brinkmann, Serge Roudier, Luis Delgado Sancho	2017
Iron & Steel	Best Available Techniques (BAT) Reference Document for the Ferrous Metals Processing Industry	Link	Aries, E., Gómez Benavides, J., Mavromatis, S., Klein, G., Chronopoulos, G., Roudier, S.	2022
Iron & Steel	Centrifugal-Granulation-Assisted thermal energy recovery towards low-carbon blast furnace slag treatment: State of the art and future challenges	Link	Junjun Wu, Yu Tan, Peng Li, Hong Wang, Xun Zhu, Qiang Liao	2022
Iron & Steel	Current progress of process integration for waste heat recovery in steel and iron industries	Link	Abrar Inayat	2023

Sector	Title	URL	Author	Year
Iron & Steel	Decarbonisation options for the Dutch steel industry	Link	A. Keys, M. van Hout, B. Daniëls	2019
Iron & Steel	Design of Novel Flash Ironmaking Reactors for Greatly Reduced Energy Consumption and CO2 Emissions	Link	Hong Yong Sohn, De-Qiu Fan and Amr Abdelghany	2021
Iron & Steel	Development of new methodologies for industrial CO2-free steel production by electrowinning	Link	Arcelormittal Maizieres Research	2023
Iron & Steel	Digital industrial furnaces: Challenges for energy efficiency under VULKANO project	Link	Juan Carlos Antolín-Urbaneja, Asier González-González , Jose Manuel Lopez-Guede, Jesús M. López De Ipiña	2018
Iron & Steel	Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review	Link	R.Q. Wang, L. Jiang, Y.D. Wang, A.P. Roskilly	2020
Iron & Steel	Ferro Coke Production and Its Evaluation in Blast Furnace Utilization	Link	SATO Michitaka, FUKADA Kiyoshi, HASEGAWA Shinji	2022
Iron & Steel	From residual steel gasses to methanol	Link	I-Deals Innovation & Technology Venturing Services Sl	2021
Iron & Steel	Industrial cyber-physical system driven intelligent prediction model for converter end carbon content in steelmaking plants	Link	Cai-Jun Zhang, Yan-Chao Zhang, Yang Han	2022
Iron & Steel	Industrial Thermal Energy Recovery Conversion and Management	Link	Brunel University London	2021
Iron & Steel	Integrated Process Control based on Distributed In-Situ Sensors into Raw Material and Energy Feedstock	Link	Lulea Tekniska Universitet	2017
Iron & Steel	Iron and Steel Technology Roadmap Towards more sustainable steelmaking	Link	International Energy Agency	2020
Iron & Steel	Novel integrated refurbishment solution as a key path towards creating ecoefficient and competitive furnaces	Link	Fundacion Circe Centro De Investigacion De Recursos Y Consumos Energeticos	2019

Sector	Title	URL	Author	Year
Iron & Steel	Policy and pricing barriers to steel industry decarbonisation: A UK case study'	Link	Clare Richardson-Barlow, Andrew J. Pimm, Peter G. Taylor, William F. Gale	2023
Iron & Steel	Potential applications of thermoelectric generators (TEGs) in various waste heat recovery systems	Link	Kuan-Ting Lee, Da-Sheng Lee, Wei-Hsin Chen, Yu-Li Lin, Ding Luo, Young-Kwon Park, Argel Bandala	2022
Iron & Steel	Potential Decarbonization Strategies and Challenges for the U.S. Iron & Steel Industry	Link	Sachin Nimbalkar	2016
Iron & Steel	Pursuing Zero-Carbon Steel in China. A Critical Pillar to Reach Carbon Neutrality	Link	Ji Chen, Shuyi Li, Xiangyi Li, Ye (Agnes) Li	2021
Iron & Steel	Reducing industrial energy demand in the UK: A review of energy efficiency technologies and energy saving potential in selected sectors	Link	Jahedul Islam Chowdhury, Yukun Hu, Ismail Haltas, Nazmiye Balta-Ozkan, George Jr. Matthew, Liz Varga	2018
Iron & Steel	Reducing industrial hydrogen demand through preheating with very high temperature heat pumps'	Link	Andrew J. Pimm, Tim T. Cockerill, William F. Gale	2023
Iron & Steel	Resource-efficient Machine for the Recycling of coal dust into High-calorie Briquettes	Link	C.A. Group GMBH	2019
Iron & Steel	SCOPE21 Coke making Process, Best Available Techniques (BAT) Reference Document for Iron and Steel Production	Link	Kazuya Uebo, Yukihiro Kubota, Hideki Fujikawa, Kazuhide Doi, Kenji Tanizawa Makoto Matsuura, Masaki Sasaki, Hiroki Nakai, Toshihiko Noguchi	2020
Iron & Steel	Stacked autoencoder for operation prediction of coke dry quenching process	Link	Jian-Guo Wang, Yu Wang, Yuan Yao, Bang-Hua Yang, Shi-Wei Ma	2019
Iron & Steel	Techno economical investigation of energy harvesting from MIDREX® process waste heat using Kalina cycle in direct reduction iron process	Link	ina Salemi, Morteza Torabi, Arash Kashani Haghparast	2022

Sector	Title	URL	Author	Year
Iron & Steel	Technology and material efficiency scenarios for net zero emissions in the UK steel sector	Link	Alice Garvey, Jonathan B. Norman, John Barrett	2022
Iron & Steel	Ten megawatt scale vapor compression heat pump for low temperature waste heat recovery: Onsite application research'	Link	Bin Hu, Hua Liu, Jiatong Jiang, Zhiping Zhang, Hongbo Li, R.Z. Wang,	2022
Iron & Steel	Turning industrial waste gases (mixed CO/CO2 streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings	Link	Covestro Deutschland AG	2021
Iron & Steel	Turning waste from steel industry into a valuable low cost feedstock for energy intensive industry	Link	Francisco Cabello Núñez, Javier López Sanz, Fritz Zaversky	2019
Iron & Steel	Ultra Low Carbon Dioxide Steelmaking (ULCOS) - top gas recycling blast furnace process (ULCOS TGRBF)	Link	European Commission: Directorate-General for Research and Innovation	2014
Iron & Steel	Waste energy recovery and energy efficiency improvement in China's iron and steel industry	Link	Qi Zhang, Xiaoyu Zhao, Hongyou Lu, Tuanjie Ni, Yu Li	2017
Iron & Steel	Waste heat recovery in iron and steel industry using organic Rankine cycles	Link	Mohammad Ja'fari, Muhammad Imran Khan, Sami G. Al-Ghamdi, Artur J. Jaworski, Faisal Asfand	2022
Pulp & Papers	Analysis of energy efficiency and carbon dioxide reduction in the Chinese pulp and paper industry	Link	Lihong Peng, Xiaoling Zeng, Yejun Wang, Gui-Bing Hong	2015
Pulp & Papers	Assessment of emerging energy-efficiency technologies for the pulp and paper industry: a technical review	Link	Lingbo Kong, Ali Hasanbeigi, Lynn Price	2016
Pulp & Papers	Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board	Link	Michael Suhr, Gabriele Klein, Ioanna Kourti, Miguel Rodrigo Gonzalo, Germán Giner Santonja, Serge Roudier, Luis Delgado Sancho	2015

Sector	Title	URL	Author	Year
Pulp & Papers	Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options	Link	Dylan D. Furszyfer Del Rio, Benjamin K. Sovacool, Steve Griffiths, Morgan Bazilian, Jinsoo Kim, Aoife M. Foley, David Rooney	2022
Pulp & Papers	Development of technology-explicit energy saving bandwidths: A case study for the pulp and paper sector	Link	Christophe G. Owttrim, Matthew Davis, Amit Kumar	2022
Pulp & Papers	Energy conservation and emission reduction of a new pulp mill by improving production processes	Link	Yijing Li, Tian Zhu, Shijia Qin, Guangzai Nong, Yongjun Yin	2023
Pulp & Papers	Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector	Link	Christophe G. Owttrim, Matthew Davis, Hafiz Umar Shafique, Amit Kumar	2022
Pulp & Papers	Energy efficiency challenges in pulp and paper manufacturing: A tutorial review	Link	Yijing Li, Tian Zhu, Shijia Qin, Guangzai Nong, Yongjun Yin	2021
Pulp & Papers	Energy efficiency improvement potentials through energy benchmarking in pulp and paper industry	Link	Imran Shabbir, Mojtaba Mirzaeian, Farooq Sher	2022
Pulp & Papers	Energy strategies in the pulp and paper industry in Sweden: Interactions between efficient resource utilisation and increased product diversification	Link	Maria T. Johansson, Sarah Broberg, Mikael Ottosson	2021
Pulp & Papers	Evaluating energy efficiency improvement of pulp and paper production: Case study from factory level	Link	Lingbo Kong, Jingyi Zhao, Jiahao Li, Rui Lou, Yao Zhang	2020
Pulp & Papers	Integrated chemical looping combustion in pulp mill for high energy efficiency and low carbon emission	Link	Yi Man, Song Hu, Jieqi Gao, Jigeng Li, Mengna Hong	2020
Pulp & Papers	Integrating a Fischer Tropsch process into a pulp mill - A techno-economic assessment	Link	Daniel Klüh, Matthias Gaderer	2023
Pulp & Papers	Integrating process optimization with energy-efficiency scheduling to save energy for paper mills	Link	Zhiqiang Zeng, Mengna Hong, Jigeng Li, Yi Man, Huanbin Liu, Zeeman Li, Huanhuan Zhang	2018

Sector	Title	URL	Author	Year
Pulp & Papers	Investment costs and CO2 reduction potential of carbon capture from industrial plants – A Swedish case study	Link	Stefanía Ósk Garðarsdóttir, Fredrik Normann, Ragnhild Skagestad, Filip Johnsson	2018
Pulp & Papers	Novel mechanical vapor recompression-assisted evaporation process for improving energy efficiency in pulp and paper industry	Link	Kim Y, Lim J, Cho H, Kim J.	2021
Pulp & Papers	Optimal operation of the evaporator and combustion air distribution system in a pulp mill to maximize biomass recycling and energy efficiency	Link	Jiye Park, Yurim Kim, Jonghun Lim, Hyungtae Cho, Junghwan Kim	2022
Pulp & Papers	Performance and cost of CCS in the pulp and paper industry part 2: Economic feasibility of amine-based post-combustion CO2 capture	Link	Kristin Onarheim, Stanley Santos, Petteri Kangas, Ville Hankalin	2017
Pulp & Papers	Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden	Link	Satu Lipiäinen, Katja Kuparinen, Ekaterina Sermyagina, Esa Vakkilainen	2022
Pulp & Papers	Pulp and Paper Sector - Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan	Link	Confederation of Paper Industries	2017
Pulp & Papers	Techno-Economic Analysis of CO2 Capture from Pulp and Paper Mill Limekiln	Link	Amod Parkhi, Selen Cremaschi, Zhihua Jiang	2022
Pulp & Papers	The Potential Energy Efficiency Improvements for the Italian Pulp and Paper Industry	Link	Simone Maggiore, Corine Nsangwe Businge, Marco Borgarello, Anna Realini, Elena Gobbi, Claudio Zagano, Francesca Bazzocchi	2019
Pulp & Papers	UK Paper Sector Decarbonisation Roadmap	Link	Confederation of Paper Industries	2023
Refineries	A review on boilers energy use, energy savings, and emissions reductions	Link	M.C. Barma, R. Saidur, S.M.A. Rahman, A. Allouhi, B.A. Akash, Sadiq M. Sait	2017
Refineries	A rigorous simulation-based procedure for retrofitting an existing Egyptian refinery distillation unit	Link	Mamdouh A. Gadalla, Omar Y. Abdelaziz, Dina A. Kamel, Fatma H. Ashour	2015

Sector	Title	URL	Author	Year
Refineries	A techno-economic review of gas flaring in Iran and its human and environmental impacts	Link	Mohammad Shahab-Deljoo, Bijan Medi, Monzure-Khoda Kazi, Mostafa Jafari	2023
Refineries	An innovative techno-economic analysis for the selection of an integrated ejector system in the flare gas recovery of a refinery plant	Link	Soroush Eshaghi, Farzad Hamrang	2021
Refineries	Application of retrofitted design and optimization framework based on the exergy analysis to a crude oil distillation plant	Link	Chenglei Yan, Liping Lv, Shun'an Wei, Ali Eslamimanesh, Weifeng Shen	2019
Refineries	Assessing deployment pathways for greenhouse gas emissions reductions in an industrial plant – A case study for a complex oil refinery	Link	Niels Berghout, Hans Meerman, Machteld van den Broek, André Faaij	2019
Refineries	Assessment of efficiency improvement and emission mitigation potentials in China’s petroleum refining industry	Link	Fu Zhao, Ying Fan, Shaohui Zhang	2021
Refineries	Assessment of the impacts of process-level energy efficiency improvement on greenhouse gas mitigation potential in the petroleum refining sector	Link	Alireza Talaei, Abayomi Olufemi Oni, Mohammed Ahiduzzaman, Pritam Sankar Roychaudhuri, Jeff Rutherford, Amit Kumar	2020
Refineries	Benefits of Using Advanced Electrostatic Fields in Crude Oil Dehydrators and Desalters	Link	Erik Sellman, Gary W. Sams, S. Pavan Mandewalkar	2012
Refineries	Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas	Link	Pascal Barthe, Michel Chaugny, Serge Roudier, Luis Delgado Sancho	2015
Refineries	CO2 emission reduction by zero flaring startup in gas refinery	Link	Nasibeh Hajilary, Mashallah Rezakazemi, Aref Shahi	2020
Refineries	Comparative techno-economic evaluation of potential processing schemes for petroleum crude oil distillation	Link	Sunil Kumar, Avinash S. Mhetre	2022
Refineries	Data-driven multi-period modelling and optimization for the industrial steam system of large-scale refineries	Link	Tiantian Xu, Tianyue Li, Jian Long, Liang Zhao, Wenli Du	2023

Sector	Title	URL	Author	Year
Refineries	DECARBONISATION OPTIONS FOR THE DUTCH REFINERY SECTOR	Link	C. Oliveira, K.M. Schure	2020
Refineries	Decarbonizing the oil refining industry: A systematic review of sociotechnical systems, technological innovations, and policy options	Link	Steve Griffiths, Benjamin K. Sovacool, Jinsoo Kim, Morgan Bazilian, Joao M. Uratani	2022
Refineries	Dynamic modelling of adiabatic reactor for hydrocracking of VGO by using of the continuous lumping approach	Link	Ignacio Elizalde, Fabián S. Mederos, Violeta Y. Mena-Cervantes, Raúl Hernández-Altamirano, José A.D. Muñoz	2016
Refineries	Eco-efficiency analysis of desalination by precipitation integrated with reverse osmosis for zero liquid discharge in oil refineries	Link	Flávia M. Ronquim, Hugo M. Sakamoto, J.C. Mierzwa, Luiz Kulay, Marcelo M. Seckler	2020
Refineries	Effect of flue gas condensing waste heat recovery and its pressure drop on energy saving and carbon reduction for refinery heating furnace	Link	Lianbo Mu, Suilin Wang, Junhui Lu, Guichang Liu, Liqiu Zhao, Yuncheng Lan	2023
Refineries	Effects of excess air and preheating on the flow pattern and efficiency of the radiative section of a fired heater	Link	Erfan Khodabandeh, Mahdi Pourramezan, Mohammad Hossein Pakravan	2017
Refineries	Energy configuration and operation optimization of refinery fuel gas networks	Link	Li Zhou, Zuwei Liao, Jingdai Wang, Binbo Jiang, Yongrong Yang, Wenli Du	2015
Refineries	Energy Conservation	Link	Yaşar Demirel	2018
Refineries	Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries	Link	Ernst Worrell, Mariëlle Corsten, Christina Galitsky	2016
Refineries	Energy efficiency improvement in oil refineries through flare gas recovery technique to meet the emission trading targets	Link	Gabriele Comodi, Massimiliano Renzi, Mosè Rossi	2016
Refineries	Energy Performance of Italian Oil Refineries Based on Mandatory Energy Audits	Link	Herce, C., Martini, C., Salvio, M., Toro, C.	2022

Sector	Title	URL	Author	Year
Refineries	Energy recovery in oil refineries by means of a Hydraulic Power Recovery Turbine (HPRT) handling viscous liquids	Link	Mosè Rossi, Gabriele Comodi, Nicola Piacente, Massimiliano Renzi	2020
Refineries	Energy recovery in oil refineries through the installation of axial Pumps-as-Turbines (PaTs) in a wastewater sewer: a case study	Link	Massimiliano Renzi, Pavel Rudolf, David Štefan, Alessandra Nigro, Mosè Rossi	2019
Refineries	Energy saving measures from their cradle to full adoption with verified, monitored, and targeted performance: a look back at energy audit at Catalytic Naphtha Reforming Unit (CCR)	Link	Variny, M., Blahušiak, M., Mierka, O. et al.	2019
Refineries	Energy, exergy and economic analysis of a novel solar driven CCHP system powered by organic Rankine cycle and photovoltaic thermal collector	Link	Ahmad Zarei, Saeed Akhavan, Marzie Babaie Rabiee, Sohail Elahi	2023
Refineries	Exceeding Pinch limits by process configuration of an existing modern crude oil distillation unit – A case study from refining industry	Link	Omar S. Bayomie, Omar Y. Abdelaziz, Mamdouh A. Gadalla	2019
Refineries	Feature selection based root cause analysis for energy monitoring and targeting	Link	Kulcsar T., Balaton M., Nagy L., Abonyi J.	2014
Refineries	Flare gas reduction: A case study of integrating regeneration gas in flash gas compression network	Link	Majid Sarkari, Behnaz Jamshidi, Milad Ahmadi Khoshooei, Farhad Fazlollahi	2022
Refineries	Fully integrated CO2 mitigation strategy for an existing refinery: A case study in Colombia	Link	Édgar Yáñez, Hans Meerman, Andrea Ramírez, Édgar Castillo, Andre Faaij	2022
Refineries	Hybrid Separation Process of Refinery Off-gas toward Near-Zero Hydrogen Emission: Conceptual Design and Techno-economic Analysis	Link	Bingyuan Ma, Chun Deng, Hongnan Chen, Meiqian Zhu, Minbo Yang, and Xiao Feng	2020
Refineries	IEA Energy Efficiency 2022 report.	Link	Interntional Energy Agency	2022
Refineries	Improving energy efficiency in a complex natural gas refinery using combined pinch and advanced exergy analyses	Link	Mohsen Mehdizadeh-Fard, Fathollah Pourfayaz, Mehdi Mehrpooya, Alibakhsh Kasaeian	2018

Sector	Title	URL	Author	Year
Refineries	Industrial Energy Efficiency Accelerator (IEEA): successful projects (2023)	Link	Department for Energy Security & Net Zero	2023
Refineries	Integration of organic Rankine open cycles to alkanes’ fractional distillation: Process design and techno-economic assessment	Link	Adel Boualouache	2023
Refineries	Leakage of gasoil from side cut piping in crude distillation unit of a petroleum refinery	Link	Chidambaram Subramanian	2023
Refineries	Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors	Link	Energy Transitions Commission	2018
Refineries	Modulated AC/DC Crude Desalting Technology Application & Best Practices	Link	White, Ramsey , Mulas, Simone , Domini, Pier , Lopez, Miguel , and Faris Abusittah	2021
Refineries	New directions in the implementation of Pinch Methodology (PM)	Link	Jiří Jaromír Klemeš, Petar Sabev Varbanov, Timothy G. Walmsley, Xuexiu Jia	2018
Refineries	Optimal Operation of an Industrial Natural Gas Fired Natural Draft Heater	Link	Richard Yentumi, Bogdan Dorneanu, Harvey Arellano-Garcia	2022
Refineries	Paraffin-based crude oil refining process unit-level energy consumption and CO2 emissions in China	Link	Feng-Rui Jia, Wan-Ting Jing, Guang-Xin Liu, Qiang Yue, He-Ming Wang, Lei Shi	2020
Refineries	Pathways to industrial decarbonisation	Link	Australian Industry Energy Transitions Inititiative	2023
Refineries	Power generation as a useful option for flare gas recovery: Enviro-economic evaluation of different scenarios	Link	Mahya Nezhadfard, Amirhossein Khalili-Garakani,	2020
Refineries	Progressive crude oil distillation: An energy-efficient alternative to conventional distillation process	Link	Shankar Nalinakshan, V. Sivasubramanian, Vineesh Ravi, Aneesh Vasudevan, M.S. Ramya Sankar, K. Arunachalam	2019

Sector	Title	URL	Author	Year
Refineries	Retrofit of heat exchanger networks by graphical pinch analysis – a case study of a crude oil refinery in Kuwait,	Link	Ibrahim H. Alhajri, Mamdouh A. Gadalla, Omar Y. Abdelaziz, Fatma H. Ashour	2021
Refineries	Retrofit of steam power plants in a petroleum refinery	Link	Cheng-Liang Chen, Chih-Yao Lin, Jui-Yuan Lee	2013
Refineries	Review of Methods Used for Selecting Pumps as Turbines (PATs) and Predicting Their Characteristic Curves	Link	Amelio, M., Barbarelli, S., Schinello, D	2020
Refineries	Technical evaluation and optimization of a flare gas recovery system for improving energy efficiency and reducing emissions	Link	Javad Asadi, Esmaeil Yazdani, Yasaman Hosseinzadeh Dehaghani, Pejman Kazempoor	2021
Refineries	Techno-economic-reliability assessment of a combined NGL refinery and CCHP system driven by wasted energy of flare and flue gases	Link	Mohammad Tahmasebzadehbaie, Hoseyn Sayyaadi	2022
Refineries	The Cost Benefit of Refinery Effluent Pretreatment Upstream of Membrane Bioreactors	Link	Dizayee, K.K.H., Raheem, A.M., Judd, S.J	2023
Refineries	The Refinery of the Future	Link	James G. Speight	2020

Refineries literature was initially sought although analysis of the sector’s EE potential was produced in a separate study.