OXFORD INDUSTRIAL DECARBONISATION PROJECT

Technology Analysis and Prioritisation

AN ERM REPORT FOR THE ZERO CARBON OXFORD PARTNERSHIP

FEBRUARY 2025

Introduction to this report, authors, and disclaimer

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About this document

This document reports the findings from WP3 of the ZCOP Local Industrial Decarbonisation Roadmap (LIDP) project, investigating and prioritising the technologies available to decarbonise Oxford's industrial sector.

Link to other work packages

The report builds upon the findings of the Oxford's Industrial Landscape & Baseline (WP1) report by considering the relevance of the technologies assessed to the types of industrial processes and sites in Oxford City. The analysis was also informed through several stakeholder engagement activities (WP2).

This report informs the approach to the Scenario Modelling (WP4) work, which ultimately informs the Oxford's Industrial Decarbonisation Roadmap and Action Plan (WP6).

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Department for Energy Security & Net Zero

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Executive Summary

A broad range of technologies exist to support decarbonisation of industrial emissions

Previous technology reviews

In the 2018 ZCOP Roadmap, **industrial emissions were modelled to decrease 84% by 2040**. This is achieved primarily by:

- "fabric improvements, the electrification of heat, site-level solar PV, … the electrification of processes, and process efficiency".
- gas grid blending with biogas (2%) and hydrogen (20% vol).
- insetting or GHG removals for residual emissions.

The previous roadmap identified the need for detailed work to understand relevance and potential deployment levels of different technologies.

This reports approach

A broader technology list was considered based on literature review, ZCOP member engagement, and previous experience from similar industrial roadmaps.

Deep decarbonisation technologies were reviewed in a detailed template to enable comparability and prioritisation.

Complementary and emerging technologies were assessed with respect to their potential roles in enabling decarbonisation in Oxford.

Decarbonisation technologies were reviewed against several key technical characteristics: **Technology Readiness Level (TRL), Cost, Process applicability, and Site applicability**.

Abatement Technology List	Example Equipment	
Deep-Decarbonisation		Reviewed in detail in this project
Electric Heating	*E-boilers, Ovens, Dryers, Kilns/Furnaces*	
Heat Pumps	*Ground Source, Air Source, Water Source, Industrial*	
Heat Networks	*Waste heat utilisation, Heat pump upgrading*	
On-site Renewables	*Rooftop Solar, Car Park Solar, Urban & Onshore Wind*	
External Renewable Supply	*Direct Wire to Local Renewables, Physical PPA*	
Carbon Capture	*Post-combustion, Pre-combustion, Oxyfuel*	
Hydrogen Fuel Switching	*Blending, Boilers, Dryers*	
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Energy Storage	*Flow Batteries, Thermal, Kinetic, Hydro, Smart/MicroGrids*	
Carbon Offsets		
Emerging		
Alternative Energy Production	*Micronuclear, Geothermal Heat*	
Innovative Fuels	*Green Ammonia, E-fuels, Green Methanol, Syngas*	
Innovation on Existing Renewables	*Perovskite Solar Panels, AeroMine*	

A holistic approach was used to assess technologies suited to Oxford considering technical factors, barriers, and stakeholder views

Decarbonisation technologies were reviewed against several key technical characteristics:

- **TRL (Technology Readiness Level) -** assesses the current and future technical maturity of the decarbonisation solutions on the industry standard 1-9 scale.
- **Cost –** a review of the key upfront and operational cost drivers to inform the current and future potential for different technologies to be used in Oxford.
- **Process applicability –** red-amber-green assessment for the applicability of technologies to the prevalent industrial processes in Oxford, considering the technical feasibility and technology competition.
- **Site applicability -** red-amber-green assessment for the applicability of technologies to different types of sites seen in Oxford, considering key enablers and barriers to deployment.

The barriers for the decarbonisation technologies were reviewed against six categories: Policy, Environmental, Social, Technological, Regulatory, and Market.

Other key considerations in the detailed review of the decarbonisation technologies are **synergies between technologies, opportunities to collaborate with the decarbonisation of other sectors, and co-benefits**.

Workshop engagement and industrial surveys were used to complement the technology literature review by gathering stakeholder opinions on both the local barriers to deployment and the technical applicability of each technology to industry in Oxford.

Technology prioritisation was developed across the range of industrial emission sources identified in Oxford; electricity consumption, low temperature indirect heating, and complex heating (referring to > 100 °C or direct heating processes). Prioritisation is **based on the outcomes of the technical, barrier, and stakeholder reviews** and ensures the combined technology selection is able to decarbonise all the processes relevant to industry in Oxford.

Barrier to deployment considered

- Market
- Policy
- Regulatory
- Environmental
- Social
- Technological

Cost competitive and technically mature solutions are emerging to support industrial decarbonisation in Oxford

- Key technologies are already available to decarbonise industry in Oxford. **Mature heat pump and e-boiler technologies can deliver most indirect heat demand** (e.g., space heating, hot water, and steam) for industry in Oxford.
- **Electrification technologies are generally CAPEX intensive, but high efficiencies can lead to OPEX savings,** depending on the comparative price of electricity and natural gas.
- On-site renewables generally have short pay-back periods but are CAPEX intensive. As an alternative, external renewable supply has no CAPEX and can be price competitive with grid electricity but often requires commitment to long-term contracts.
- Heat networks and biofuel switching have been demonstrated in other sectors, however industrial applications are less mature in the UK.
- **Hydrogen fuel switching and small-scale, modular carbon capture technologies are less mature technologies**, can require more complex site/process modifications, and rely on wider energy infrastructure systems.
- **The cost of fuel switching technologies is primarily driven by the fuel OPEX itself**. Biomethane and hydrogen supply remain more expensive than natural gas, however biomethane benefits from no CAPEX requirements for process modifications.
- The cost of carbon capture for even the larger industrials sites located in Oxford is expected to be high, especially with additional transport and storage fees.
- Energy storage (primarily batteries), emerging low carbon energy/fuel pathways, and innovation for existing renewable technologies should all play a role in the medium term to enable electrification, diversify energy supply, and reduce costs.

Assessment summary of technologies against key criteria

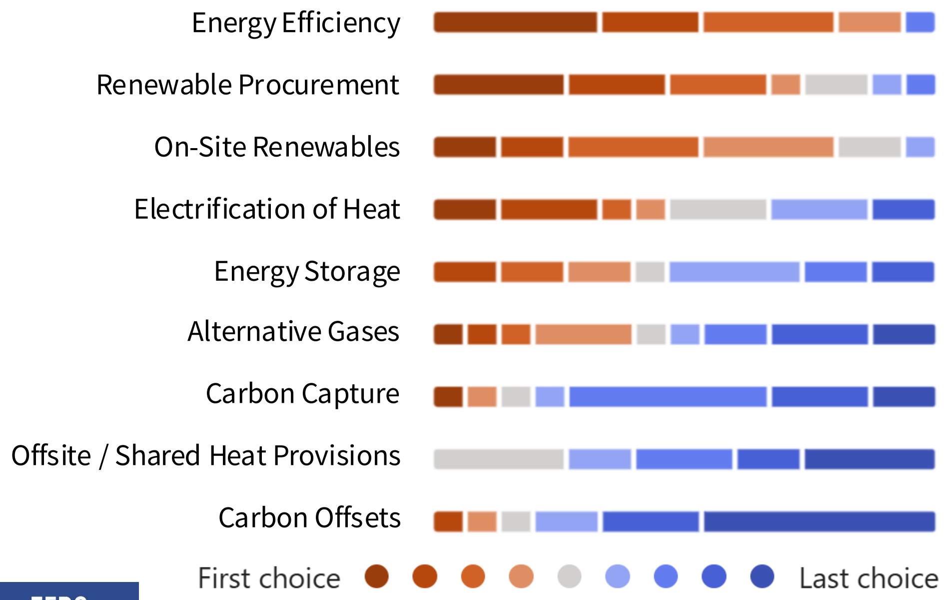
Technology	TRL*	CAPEX	OPEX	Stakeholder Interest	Applicability to Oxford
On-site renewables	7-9	↑	↓	🟢	🟢
External renewable supply	9	→	→	🟢	🟢
Heat Pumps	6-9	↗	↘	🟢	🟢
Heat Networks	8-9	→	↘	🟡	🟢
Electric Heating	5-9	↘	↗	🟡	🟢
Biofuel Switching	7-9	→	↗	🟡	🟡
Hydrogen Fuel Switching	5-8	↗	↗	🔴	🟡
Carbon Capture	6-8	↑	↗	🔴	🔴

*TRL = technology readiness level. TRL 1-3 refers to concept, TRL 4-6 refers to prototype, TRL 7-8 refers to demonstration, and TRL 9 refers to commercial adoption

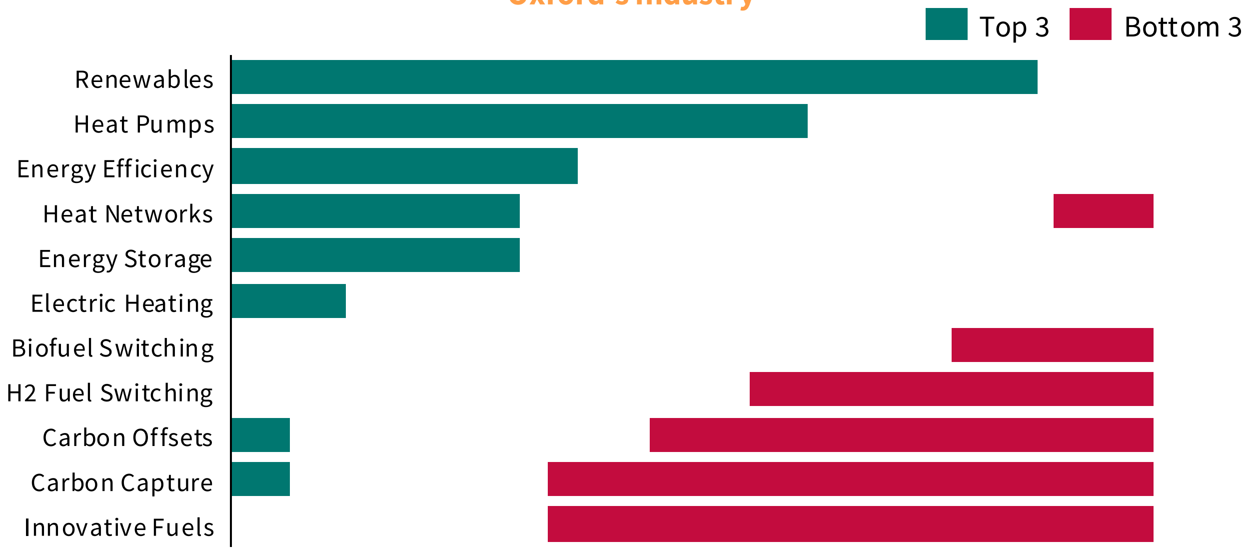
Stakeholder engagement indicated electrification technologies are the most applicable and interesting technologies for Oxford

- **Workshop and survey engagement in this project showed strong support for all electrification technologies,** despite widespread concerns regarding the ability of the electricity grid to support increased demand.
- **Heat networks were also perceived positively in the workshop engagement,** with attendees keen to learn more about the potential for waste heat recovery – however, the survey showed considerably less interest in shared heating provisions, potentially highlighting the need for further communication and knowledge sharing on the potential benefits of heat networks.
- **Alternative gases and carbon capture were not seen as key technologies** for industry in Oxford because of high costs and substantial energy infrastructure requirements that will be dependent on national policy decisions and roll-out.
- Carbon **offsets were also recognised as a low priority solution** to decarbonising industry.

Stakeholder survey responses on the most applicable technologies to their site



Workshop feedback on the most and least suitable technology for decarbonising Oxford's industry*



* Based on 14 responses for the top 3 technologies and 8 responses for the bottom 3 technologies. The results are scaled for comparability

Stakeholder engagement identified that grid constraints, the dispersed nature of industry, and electricity prices may inhibit decarbonisation

Barriers to industrial decarbonisation

Decarbonisation technologies face a broad spectrum of barriers to deployment in Oxford due to the city's location, current industrial landscape, and available infrastructure:

- **Grid constraints and connections:** Already a major issue in Oxford, grid constraints are posing a barrier to new renewable generation and offtake connections for electrification technologies. The issue may well worsen with electrification of domestic heating, transport, and industry. Grid upgrades are expensive and can delay projects by several years. Energy efficiency, on-site renewables, and energy storage can help alleviate grid constraint concerns.
- **Cost:** High CAPEX requirements for decarbonisation technologies are currently prohibitive for smaller industrials who must use external financing or funding. Nationally, the cost of electricity compared to the price of natural gas remains a key barrier to electrification. Oxford's industrial SMEs will struggle to benefit from significant economies of scale and the city's location reduces the potential to benefit from government funded, infrastructure projects.
- **Support / incentives for small scale industry:** Government's current focus on the large, emissions-intensive industrial clusters has led to a prioritisation of investment, strategy, and incentives to technologies less suited to Oxford's dispersed SME industry. The availability and accessibility (considering resource and financial constraints) of targeted fiscal support, especially for electrification, is a key policy lever to accelerate decarbonisation of small-scale industry.
- **Challenges for infrastructure deployment in a dispersed industrial landscape:** Infrastructure heavy technologies, such as heat networks or hydrogen transport networks, are challenging to deploy in Oxford's dispersed industrial landscape of SMEs. Nevertheless, shared infrastructure can reduce the burden on SMEs trying to develop their own decarbonisation solutions. Property owner-tenant relationships can also make implementing technologies difficult as landlords must invest but the tenant receives most benefits.

Technology and Sector Synergies

- **Industrial heat pump deployment could benefit substantially from cost reductions** based on deployment in residential and commercial buildings.
- Variable renewable generation profiles will not match the baseload electricity demand from industry so **batteries will play an important role in enabling baseload supply and flexibility**.
- **Industry may also be able to connect to heat networks** developed primarily for wider building stock demand.
- **The use of hydrogen or biofuels for transport** may prompt greater production and supply chain capacity enabling economies of scale and wider reaching supply, resulting in lower-cost for industrial users.
- Low carbon **gas blending into the gas grid** could partially decarbonise emissions from sites before they move away from natural gas.

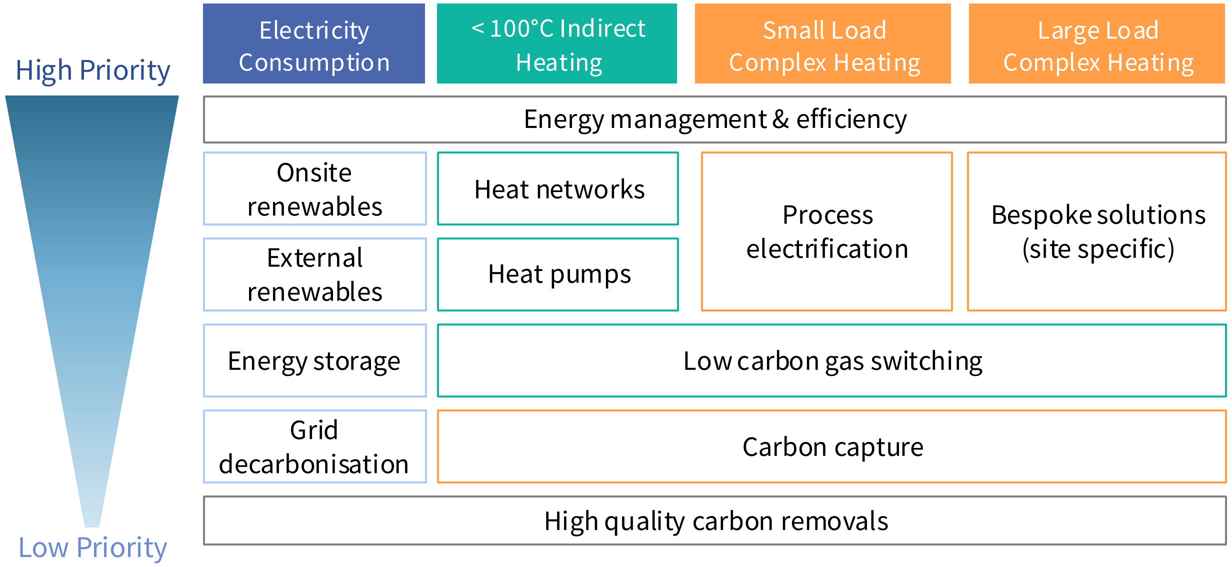
Local renewables, heat pumps, heat networks and process electrification are priority technologies for Oxford industrials

Individual technology assessments were used to prioritise technologies (based on technical considerations, economic factors, wider barriers in Oxford, and stakeholder views) for the range of industrial emission sources identified in Oxford. This includes electricity consumption, low temperature indirect heating (gas boilers), and complex heating* (e.g. ovens and kilns).

High priority solutions for Oxford industrials were identified as:

- **Energy management & efficiency measures,** which will be critical across all processes and technologies, especially innovative and digital/smart solutions to help reduce peak demand and alleviate grid constraints.
- **Onsite renewables** with energy storage for electricity supply (if space and capital are available) or **external renewables** via renewable energy procurement (if onsite renewables are not possible).
- Accessing a **decarbonised heat network** or installing a **heat-pump** to provide low temperature indirect heating (e.g., space heating).
- For complex heating at small loads, replacing natural gas equipment with an **electrified alternative** (e.g., e-boilers or microwave ovens) in cases where technologies are commercially available and where grid constraints are not a barrier. For complex heating at larger loads, the chosen solution is expected to be bespoke to the site.
- **Emerging technologies** will play a crucial role across the full spectrum of solutions to increase feasibility, reduce cost, and enable integration of low carbon technologies.

Overview of technology prioritisation across industrial processes



Lower priority solutions include:

- Waiting and being reliant on **grid decarbonisation,** as UK-wide developments in electricity supply are outside of the Oxford Industrial Cluster's control.
- **Carbon capture** is deprioritised since it is not expected to be economical for Oxford industrials, and the region is not a focus for CO_2 transport infrastructure development.
- **High quality carbon removals** are deprioritised since Oxford Industrial Cluster's focus is on first achieving direct decarbonisation where possible.

*Complex heating refers to processes at >100°C or direct heating technologies.

Higher priority technologies for decarbonising Oxford's industrials

High priority technologies are those that are likely preferred solutions for industrials in Oxford this decade. Reasons for being a preferred solution include lower costs, commercial availability, higher maturity, and limited barriers.

High Priority

Medium Priority

Electricity Consumption	< 100°C Indirect Heating	Complex Heating	

Energy efficiency: Oxford has already strategized the importance of energy efficiency across all sectors and industry is no different. An efficiency first approach enabled by **emerging smart/digital energy management solutions**, such as automated meter readings, is crucial to decrease total energy demand, immediately reduce emissions, and to minimise the subsequent cost of decarbonisation technologies.

Electricity Consumption

Onsite renewables: Localised renewable deployment (either onsite or within a business park) can provide benefits of lower cost electricity whilst alleviating demands on the electricity grid. To achieve the greatest emission reductions, this should be combined with **energy storage**.

Renewable procurement: If renewables cannot be deployed onsite, renewable electricity can be procured via a physical or virtual PPA. This is less likely to provide cost savings compared to onsite deployment and may not alleviate grid constraints. The emission savings from renewable PPAs may be less reliable due to demand 'matching' uncertainties.

< 100°C Indirect Heating

Heat networks: Heat networks are the preferred indirect heating mechanism below 100°C due to their ability to re-use waste heat, their economies of scale, and the limited demands placed on the electricity grid (assuming heat sources are carefully located to avoid grid constraints). They initially require collective action and may face barriers associated with capital investment, operational costs, and infrastructure development. Infrastructure may not be developed to sites or business parks around which there is not sufficient demands to justify network deployment.

Onsite heat pumps: Heat-pumps are commercially available, and their high-efficiency limits the impact on the grid, although grid-constraints may remain an issue for larger sites. Barriers faced include high upfront CAPEX and disruption.

Complex Heating

Small Loads

Process electrification: For small-scale complex heating processes, electrification technologies are the preferred solution. **Electric boilers or heat pumps** can generate high-temperature steam, and a range of **radiative heating** technologies are commercially available (e.g., ovens, dryers). Electric technologies may provide efficiency benefits, but face barriers of upfront CAPEX and high electricity prices. Process electrification could be co-deployed with onsite renewables to reduce operational costs. Technology readiness may be a barrier.

Large Loads

Bespoke solution: There are few sites in Oxford with large demands for high-temperature or direct heating. The best solution for these sites will be bespoke to their circumstances but could include:

- **Electric boilers & radiative heating:** These technologies are commercially available but may face grid constraints challenges and very niche processes may face readiness barriers.
- **High-temperature heat-pump:** by upgrading lower temperature heat, emerging technologies can reach higher temperatures.

+ Important supporting role of innovation across all technologies: Novel low carbon energy production technologies, innovative approaches to energy efficiency and grid management, and ongoing improvements to existing renewable generation will play a role in the medium-long term to enable electrification, diversify energy supply, and reduce costs.

Lower priority technologies for decarbonising Oxford's industrials

Low priority technologies are those that are deemed less applicable or less impactful solutions for industrials in Oxford this decade. These technologies may currently have feasibility challenges, higher costs, technical uncertainties, or other barriers.

Medium Priority

Electricity Consumption	< 100°C Indirect Heating	Complex Heating: Small Loads	Complex Heating: Large Loads

Electricity Consumption

Energy storage: Batteries and thermal energy storage can provide grid balancing services and support smoothing of variable renewable supply to constant baseload demand. **Smart, integrated, control systems** can deliver emissions and cost savings by storing lower cost and emission electricity for peak times.

UK grid decarbonisation: The UK government has a target to decarbonise the grid by 2030. Waiting for this target to be reached limits near-term abatement, increases uncertainty, and does not alleviate grid constraints or provide savings.

< 100°C Indirect Heating / Complex Heating

Low Carbon Gas Switching:

- Partial **blending of biomethane and hydrogen** into Oxford's gas grid may occur as part of wider national decarbonisation efforts or due to synergies with other sector decarbonisation strategies. This is subject to significant uncertainty on national strategy and network operator developments.
- Hydrogen blending is expected to be limited to less than 20 vol% offering limited decarbonisation.
- Larger sites may be able to access a **dedicated hydrogen supply** for 100% fuel-switching – this could be from on-site or local hydrogen electrolysers or imported from large-scale projects. However, the high-cost of hydrogen means heat-pumps or heat-networks are a higher priority solution for indirect heating.
- Use of **biomethane** as a drop-in natural gas replacement may be attractive for some sites, but barriers exist with the availability of sustainable feedstock and the necessary supply infrastructure to go beyond low percentage blending.

Carbon capture: Economically, carbon capture is more applicable to large-scale, hard-to-decarbonise processes which are not found within Oxford's industrial sectors. There are major barriers to the transport of captured CO_2 from Oxford to the UK's developing offshore CO_2 storage sites which are not likely to be resolved in the near-term, as well as wider socio-environmental concerns. **CO_2 utilisation** is a potential option, but such applications are still relatively novel and would still require large CAPEX investment, additional energy demands, and stable offtake markets.

Low Priority

High quality carbon credits: High-quality carbon removal credits can be used to "neutralise" the final 5-10% of hard-to-abate emissions once industry has decarbonised the rest of its operations. Removals should only be utilised for the residual emissions and therefore are not prioritised.

+ Important supporting role of innovation across all technologies: Novel low carbon energy production technologies, innovative approaches to energy efficiency and grid management, and ongoing improvements to existing renewable generation will play a role in the medium-long term to enable electrification, diversify energy supply, and reduce costs.

Methodology

A broad range of technologies exist to support decarbonisation of industrial emissions

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Deep decarbonisation technologies were reviewed against several key technical characteristics

Technology Readiness Levels

Assesses the technical maturity of the technologies through the technology readiness level (TRL) scale developed by NASA and used by UK Government assessments and widely across industry.[1,2]

In the core review only technologies currently at TRL 5 or above are included, with assessment of future TRLs for those still in development.

Emerging, lower maturity options are also discussed where relevant.

TRL	Description
9	Full commercial deployment
8	Full technology demonstration
7	Operational prototype
6	System demonstration in relevant environment
5	Component validation in relevant environment
< 5	Lab demonstrations and research concepts

Cost

The key cost drivers were reviewed to inform the potential for different technologies to be used in Oxford.

The cost impact can be driven by upfront, capital investment for major equipment (e.g., electric boilers) or by operational energy costs for fuel switching options. The review notes which technologies are likely in increase or decrease both CAPEX and OPEX.

Where **notable cost reductions are expected in the next 5-10 years this is noted**, including the main driver of these cost improvements.

Important cost factors that may increase or decrease costs in Oxford compared to other UK locations are highlighted; such as poor economies of scale at smaller sites or greater transport costs due to the distance to the major UK industrial clusters.

Process and Site Suitability

As characterised in the industrial baseline review, Oxford industry can be defined by five main processes types and three key site archetypes*.

The **suitability of each technology to these process categories was assessed** to inform those that are most relevant across Oxford.

A **RAG assessment considers the technical feasibility, technology competition, and both enablers and barriers to deployment**:

- ● Technology is mature and likely the strongest candidate for the process/site type with limited barriers.
- ● Technology is applicable to the process/site type but may face some barriers or competition.
- ● Technology is not applicable to the process/site type.

1 Technology Readiness Levels – NASA 2 Industrial Energy Transformation Fund - Phase 2: Autumn 2022 Guidance

* Process types: low temperature direct heating, high temperature direct heating, low temperature indirect heating, high temperature indirect heating, and electric. Site types: Single dispersed site, large site, business park site.

Six categories were used to review the barriers for the decarbonisation technologies

Market
Includes supply and demand dynamics, general and sectoral growth, ability to pay, government fiscal support, and cashflow demand.

Regulation
Broad range of compliance/regulations governing aspects such as health and safety, planning permissions, and environmental permitting.

Social
The people perspective covering features such as the local skills market, supply chain constraints, public opinion/opposition, or job market impacts.

Policy
The impact of local, regional, national, and international policy decisions on the feasibility, cost-effectiveness, and scalability of decarbonisation technologies.

Environmental
The environmental trade-offs from different decarbonisation technologies from upstream resource demands, novel process pollutants/ emissions, and downstream waste products.

Technological
Constraints on the feasibility and scalability of decarbonisation technologies due to technical immaturity, limitations on the deployment of requisite infrastructure, or cost reduction barriers.

Barriers are subdivided into two categories to highlight their potential impact in Oxford:

- **Significant barriers:** Potential show-stoppers and long-term barriers than could significantly delay or increase the cost of decarbonisation
- **Further considerations:** Less impactful or short-term issues that should be more readily overcome with expected progress

Workshop engagement and industrial surveys were used to complement the technology review

Extensive stakeholder engagement was utilised to complement and validate findings in the technology review.

Survey:

- A detailed survey was sent to industrial companies across Oxford to gather inputs for several aspects of the roadmap.
- The survey included a large section on the options for decarbonising to understand stakeholder attitudes towards and awareness of different decarbonisation technologies, existing and anticipated barriers for different decarbonisation technologies, and the state of current and planned technology deployments.

Workshops:

- Workshops were held in March and April 2024 to gather stakeholder views and feedback on the technology review.
- Engagement activities in the workshops, such as polls and Word Clouds, were used to gather data from stakeholders around their opinion of the most and least important decarbonisation technologies and key barriers to deployment in Oxford.
- Views where primarily gathered through group discussions with directed prompt questions relevant to the project objectives.

Please rank which technologies you believe would be most applicable to your industry/site?

What do you consider to be the major barriers to decarbonising your industry/site?

Have you installed or have plans to install any of these technologies at your site?

Have you identified useful solutions to overcome any barriers that may be applicable to other sites in Oxford?

Prioritisation is achieved via a multi-criteria analysis coupled with a process coverage assessment

The findings from the individual technology assessments were used to prioritise technologies for the range of industrial emission sources identified in Oxford. This includes electricity consumption, < 100°C indirect heating, and complex heating (referring to > 100°C or direct heating processes)*.

The **prioritisation considered technical and economic factors alongside wider barriers specific to Oxford (such as grid constraints) and stakeholder views**. In some cases, distinctions were made in priority levels based upon the type of site (scale, location) where this influenced the feasibility of a technology option or the extent to which a barrier would apply.

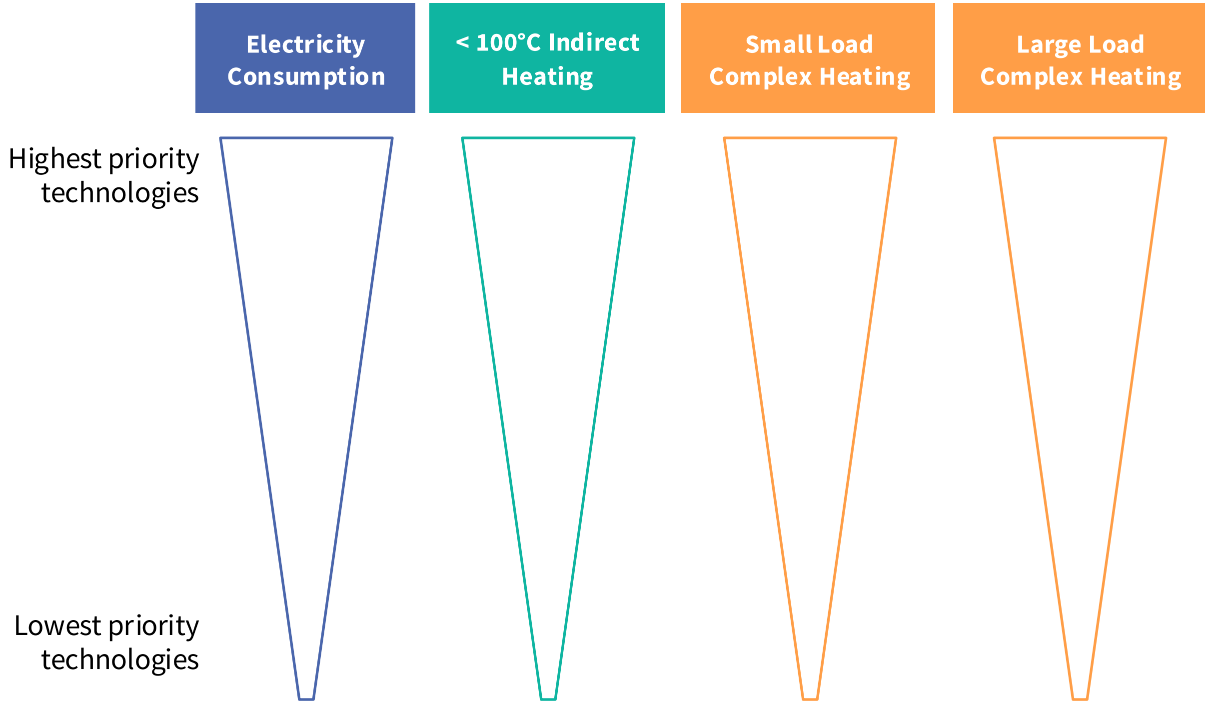
Although all factors investigated were considered, the most influential factors in the prioritisation of technologies were:

- **Technical feasibility**
- **Technology costs**
- **Infrastructure barriers**
- **Emission impact & uncertainty**

High priority technologies are those that are likely preferred solutions for industrials in Oxford, especially in the near term – such as those with lower costs, commercial availability, higher certainty, and limited barriers.

Low priority technologies are those that are deemed less applicable or less impactful solutions for industrials in Oxford but may have an impact in the medium-long term – such as those with technical challenges, high costs, or more barriers.

Findings were used to prioritise technologies for different emission sources



* **Direct heating**; flame in open air that passes directly over the target (e.g. furnaces, kilns). **Indirect heating**; a system where the combustion flue is separated from the system with the target (e.g. heat supply from CHP/boilers).

Key Insights on Decarbonisation Options

Many of the key decarbonisation technologies are already available to support the decarbonisation of industry in Oxford

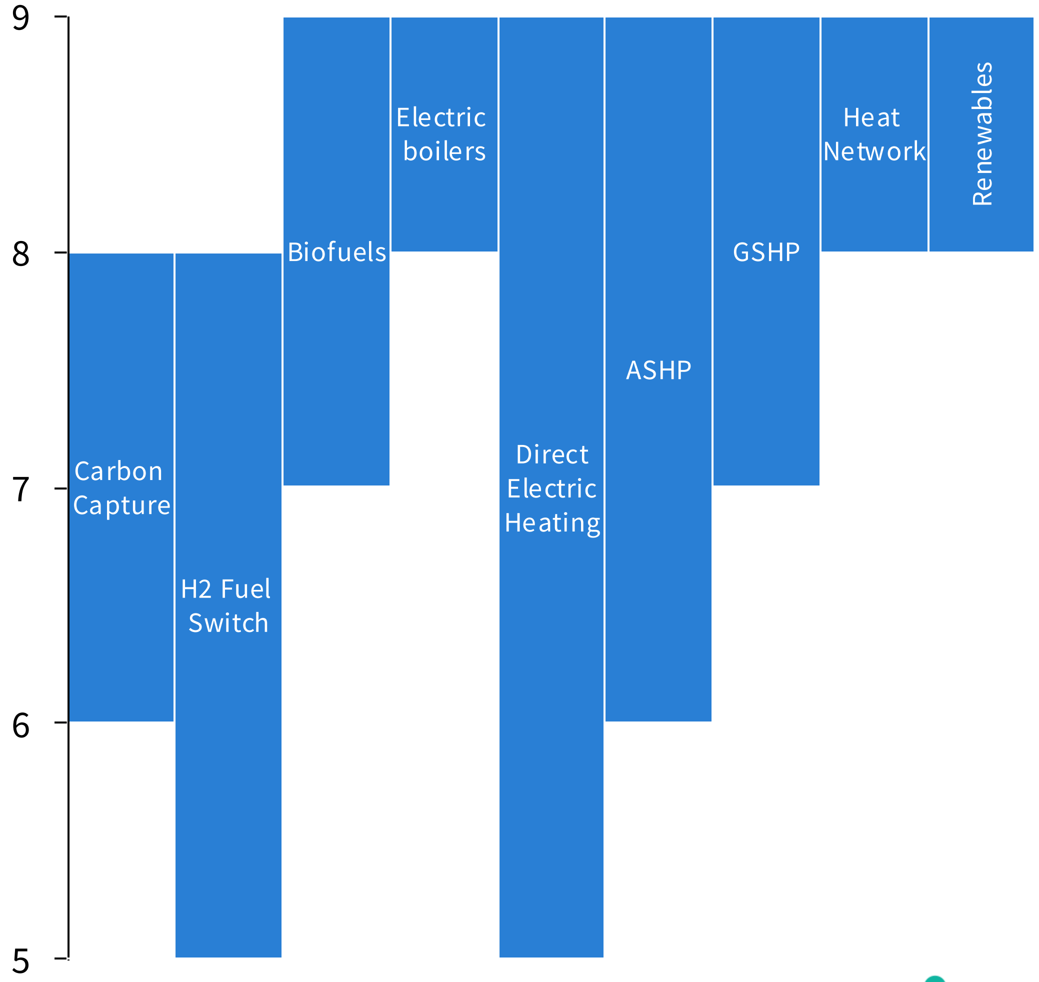
The decarbonisation technologies reviewed are generally at, or nearing, commercial deployment for the industrial processes present in Oxford:

- Mature heat pump and e-boiler technologies are already capable of delivering indirect heat for industry, such as space heating, hot water, and steam.
- Larger and high temperature heat pumps for industrial applications are still maturing, as are some high temperature direct electric heating technologies.
- Heat networks have been demonstrated in the domestic and commercial sectors; however industrial applications are less mature.
- Fuel switching to biofuels as a drop-in replacement for natural gas has limited technological barriers to overcome whereas hydrogen fuel switching can require more complex burner and process modifications.
- The small-scale, modular carbon capture technologies are still in development and a full transport and storage system is yet to be commercialised in the UK.

Electricity storage with batteries is mature with advances expected to increase round-trip efficiency and focus on relieving resource constraints. Emerging thermal energy storage solutions may provide an alternative option for industrial heating processes.

Emerging low carbon energy pathways are in development; such as micronuclear, green methanol, or deep geothermal heat; **as well as ongoing innovation to improve existing renewable technologies**, such as perovskite solar panels. These technologies could play a role in the medium-long term to diversify energy supply and reduce cost; Oxford should support the early deployment of innovative technologies developed by the local research institutions.

Current technology readiness level (TRL) ranges of decarbonisation technologies



The economic impact of technologies is a balance between upfront investment, technology efficiencies, and changing energy prices

Electrification

Electric heating, such as e-boilers, is generally the least expensive electrification technology to install and capital cost competitive compared to natural gas heating systems.

Heat pumps reduce operational expenditure (OPEX) due to high efficiencies, but increase upfront, capital expenditure (CAPEX) with the capacity and temperature of the required output:

- Higher temperature heat pumps are generally more expensive and less efficient so reduce operational electricity costs less.
- Ground-source heat pumps are more capital intensive expensive than air-source heat pumps so may require external investment to manage costs.

Heat networks are medium CAPEX solutions but limit OPEX costs by utilising waste heat and enabling flexibility across the network.

On-site renewable deployment is generally a CAPEX intensive option; however, it directly eliminates a portion of electricity OPEX by generating electricity for the site and avoids constraints from grid congestion.

External renewable supply can be price competitive with grid electricity but often requires commitment to long-term contracts whilst renewable electricity prices are expected to decrease.

Low Carbon Fuel Switching

The cost of fuel switching technologies is primarily driven by the fuel OPEX itself:

- Biomethane supply remains more expensive than natural gas supply but with no CAPEX requirements for process modifications.
- **Hydrogen production is significantly more expensive than natural gas.** Green hydrogen's cost will remain above the price of electricity (ignoring subsidies). In addition, there are CAPEX requirements for retrofitting/ replacing technologies to deploy 100% fuel switching and realise deep decarbonisation.

Carbon Capture

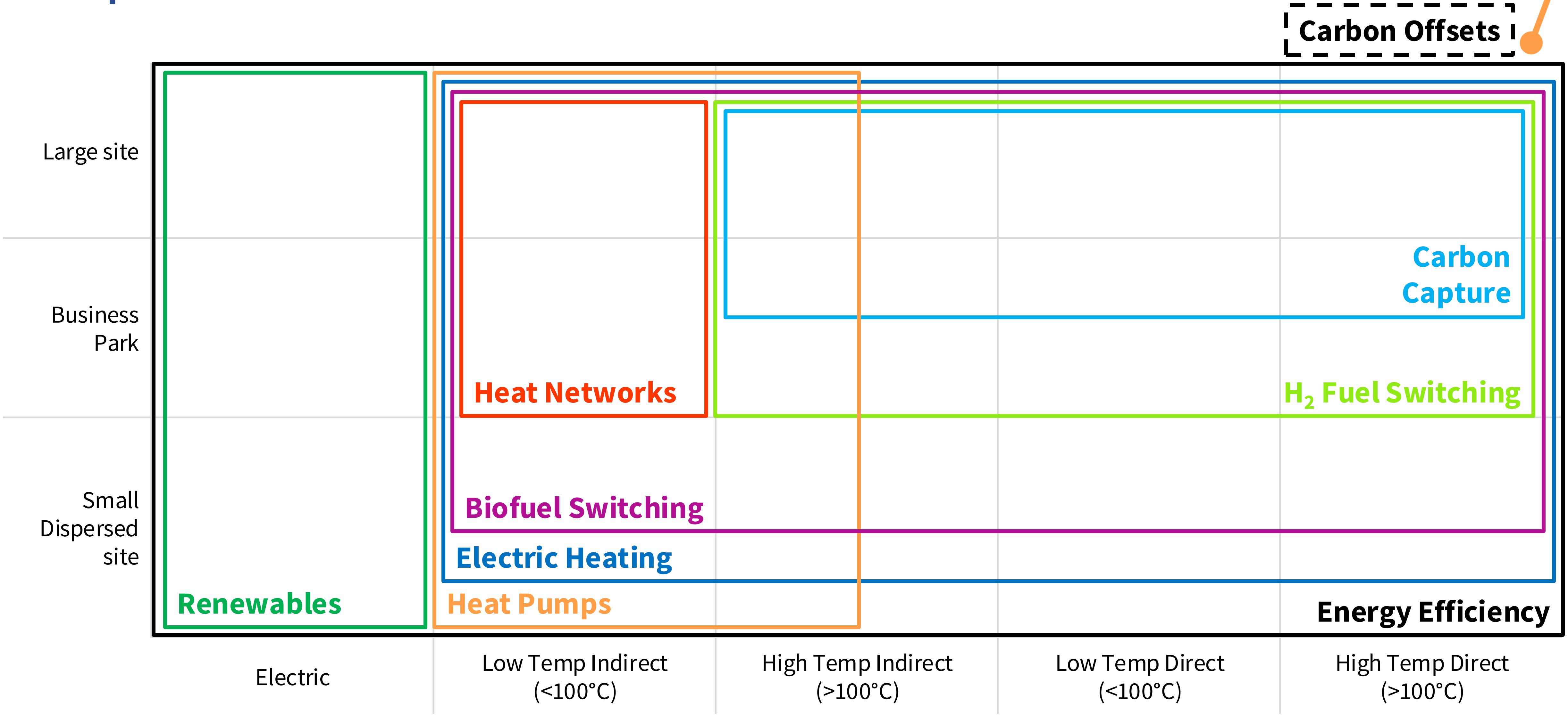
The **cost of capture varies substantially based on the scale and CO_2 concentration** of the flue gas stream.

Transport and storage will add additional costs to the total cost of CCS.

Comparative costs for decarbonisation options compared to existing technologies

Technology	CAPEX	OPEX
Carbon Capture	↑	↗
Hydrogen Fuel Switching	↗	↗
Biofuel Switching	→	↗
Electric Heating	↘	↗
Heat Pumps	↗	↘
Heat Networks	→	↘
On-site renewables	↑	↓
External renewable supply	→	→

The available decarbonisation technologies vary based on site type and process characteristics



* **Direct heating**; flame in open air that passes directly over the target (e.g. furnaces, kilns). **Indirect heating**; a system where the combustion flue is separated from the system with the target (e.g. heat supply from CHP/boilers).

Oxford's dispersed, SME industrial landscape poses challenges for infrastructure-heavy technologies to decarbonise industry

Support / incentives for small-scale industry

A lack of legislation holding smaller industrials and companies **financially accountable for carbon emissions** limits the potential to develop sustainable business cases for decarbonisation initiatives.

Government support and legislation is currently targeted at the most emissions intensive industries and the large industrial clusters which has led to a prioritisation of the decarbonisation technologies more suited to these situations such as carbon capture and hydrogen.

As such, there is a lack of government support for industrial electrification and support for smaller industries. Clear direction in the future support for these technologies is also lacking, creating hesitancy to invest if support may emerge in future.

Stakeholders in Oxford suggested that without regulated incentives or carbon pricing industrials are unlikely to be interested in pursuing decarbonisation due to the time and investment commitments.

> *"there's no legal incentive getting companies to be accountable for their carbon emissions"*
> Workshop participant

> *"inconsistency in terms of national level government policy creates a risky environment in which to take strategic long-term decisions"*
> Workshop participant

Challenges for infrastructure deployment in a dispersed industrial landscape

Infrastructure-heavy technologies, such as heat networks or carbon capture/hydrogen transport and storage, are challenging to deploy exclusively for Oxford's dispersed industrial landscape of SMEs. Heat networks or hydrogen supply chains are likely to be developed in collaboration with other sectors of Oxford's economy.

Industrial sites in Oxford are commonly leased from business parks and landlords. **Short-term lease agreements can make implementing decarbonisation technologies difficult** given limited incentive to decarbonisation the property.

CAPEX-heavy decarbonisation technologies, such as heat pumps or energy efficiency measures, are unappealing as landlords must provide initial investment but cost reductions are materialised for the tenant instead.

Speculative developments without confirmed tenants are also unlikely to invest in decarbonisation technologies that may increase their upfront investment risk or limit potential tenants from specialised industries with specific energy demands.

> *"tenants don't want to spend a lot of money on a building that is not theirs to decarbonise it, and they look at the landlord who is not going to make money out of those improvements"*
> Workshop participant

Grid capacity and electricity prices are the key barriers to widespread industrial electrification

Grid constraints and connections

Grid constraints are a major issue in Oxford that are already posing a barrier to new generation and demand connections in several parts of Oxford.

This issue is expected to persist and potentially worsen as electrification of domestic heating, transport, and industry increases demand.

Insufficient grid capacity and connections poses a major barrier to all electrification technologies. Grid upgrades are expensive and can delay projects by multiple years.

Several of the decarbonisation technologies investigated have the potential to alleviate grid constraint concerns:

- Energy efficiency measures can reduce total electricity demand.
- On-site renewables reduce the total electricity demand required through the grid.
- Process flexibility, micro/smart grids, and energy storage can be utilised to reduce peak consumption during periods of high demand on the grid.

Workshop poll results on the impact of grid constraints on decarbonising Oxford's industry

Cost

CAPEX requirements for emerging technologies remain prohibitive for smaller industrials without a large balance sheet to finance projects, leading to dependence on external financing which inflates costs.

The persistent **high cost of electricity compared to the price of natural gas remains a key barrier** to electrification for industrial customers.

Oxford's SMEs will **struggle to benefit from significant economies of scale** when deploying new equipment promoting the use of shared infrastructure where possible to reduce costs. Oxford's location away from the major industrial clusters reduces the potential to benefit from the foremost low-carbon infrastructure projects.

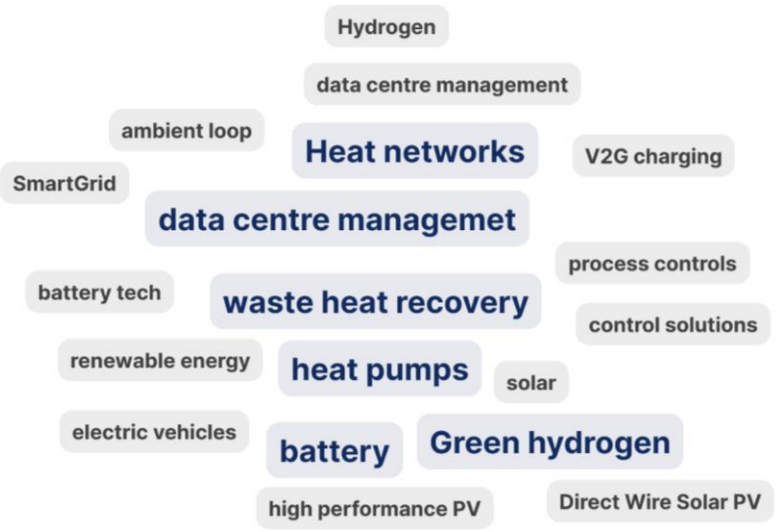
Deployment of electric equipment is likely to require supporting infrastructure due to local grid constraints, such as grid connection upgrades or battery storage, that may increase costs further.

Workshop feedback on the greatest single barrier to industrial decarbonisation

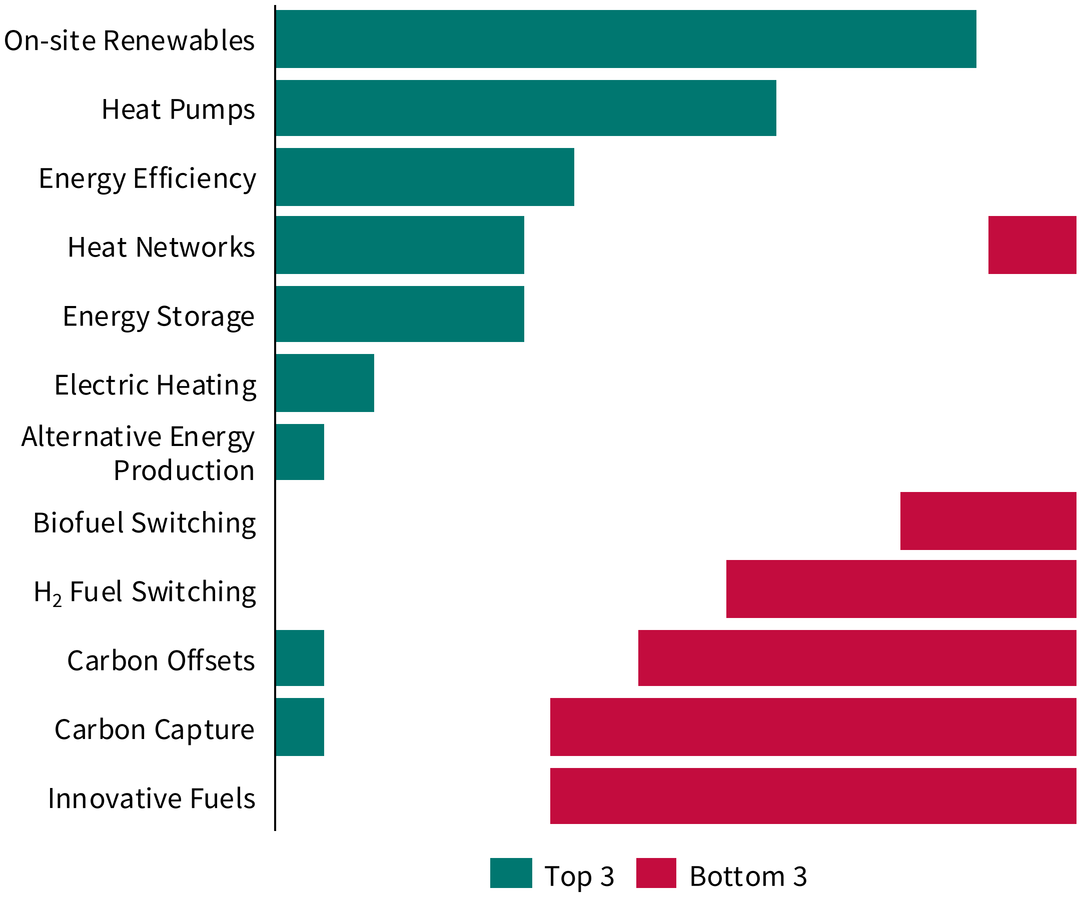
Stakeholder feedback highlighted grid constraints as the key barrier blocking the pursuit of industrial electrification technologies

- **Workshop engagement showed strong support for all electrification technologies despite widespread concerns regarding the ability of the grid to support increased demand.**
- **Heat networks were also perceived positively** with attendees keen to learn more about the potential for waste heat recovery.
- **Low-carbon gas switching options, including the most innovative fuels, and carbon capture where not seen as key technologies** for industry in Oxford because of high costs and substantial energy infrastructure requirements that will be dependent on national policy decisions and roll-out.
- **Carbon offsets were widely perceived as unsuitable for driving the decarbonisation of industry**, reinforcing their role to only neutralise the final percentages of emissions once deep decarbonisation has been implemented.

Workshop feedback on which technology participants were interested in learning more about



Workshop feedback on the most and least suitable technology for decarbonising Oxford's industry*

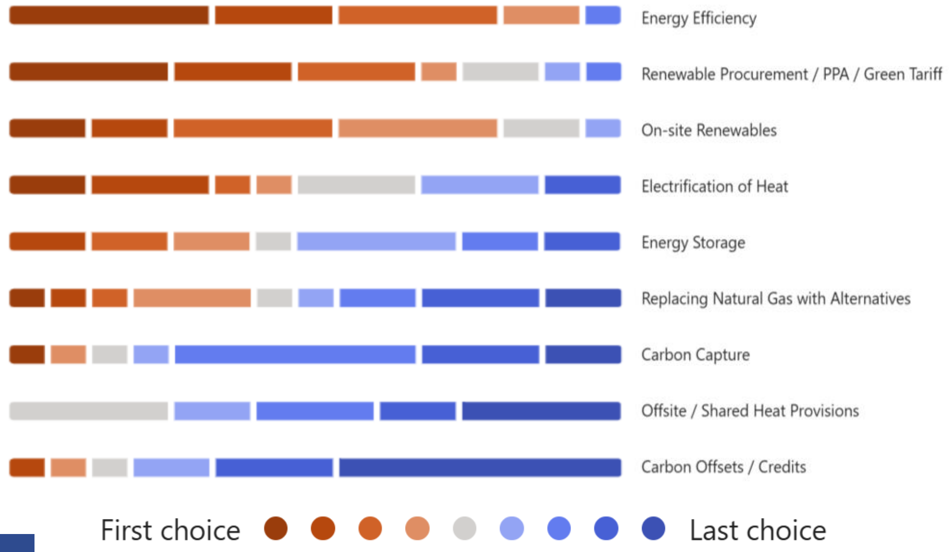


* Based on 14 responses for the top 3 technologies and 8 responses for the bottom 3 technologies. The results are scaled for comparability

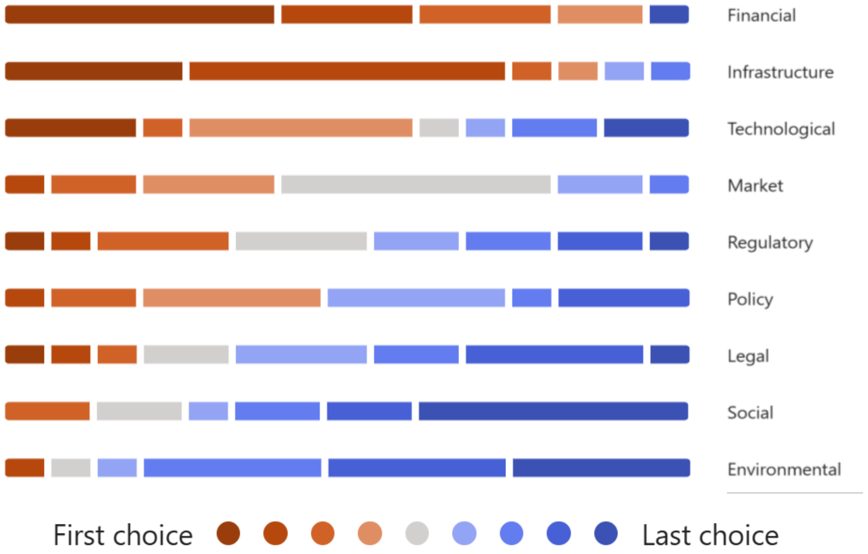
The industrial survey reinforces the desire to electrify but that costs and delayed infrastructure upgrades could stall progress

- **Workshop and survey engagement showed strong support for all electrification technologies,** despite widespread concerns regarding the ability of grid infrastructure to support increased demand.
- **Heat networks were also perceived positively in the workshop engagement,** however, the survey showed considerably less interest in shared heating provisions, potentially highlighting the need for further communication and knowledge sharing on the potential benefits of shared heat network infrastructure.
- **Low carbon gas switching options and carbon capture where not seen as key technologies** for industry in Oxford because of high costs and substantial energy infrastructure requirements that will be dependent on national policy decisions and roll-out.
- **Financing projects remains the key barrier** stakeholders perceive to decarbonising their footprint. **Technological barriers were also expressed as a significant concern despite the availability of technically mature solutions** for the large majority of industrial processes in Oxford highlighting the need for continue capacity building in Oxford's SMEs.

Stakeholder survey responses on the most applicable technologies to their site



Stakeholder survey responses on the greatest barriers to decarbonising their site



Synergies with the buildings and transport sectors, and between low carbon technologies may enable accelerated industrial decarbonisation

Buildings

- Decarbonisation of the residential, commercial and institutional heating sector is a significant challenge. The 2021 ZCOP Roadmap[1] identifies heat pumps, heat networks, and energy efficiency improvements as the key levers to accelerate decarbonisation.
- **Industrial heat pump deployment**, especially for space heating and low temperature processes, **could benefit substantially from learnings and economies of scale based on deployment in other buildings.**
- **Industry may also benefit from connecting to heat networks developed primarily for other buildings**, with heat pumps providing the potential to upgrade these heat sources for industrial processes. Industry could also act as an energy source for heat networks.

Transport

- The 2021 ZCOP Roadmap[1] suggests decarbonisation of the transport sector will be primarily driven by electrification and use of hydrogen/biofuels for heavy-duty vehicles.
- The use of **hydrogen or biofuels for transport may start to prompt greater production and supply chain capacity,** potentially enabling some economies of scale and wider reaching supply.
- Industrials often have heavy duty vehicles on site as part of vehicle fleets or onsite mobile machinery. Supply of low-carbon fuels for these vehicles may encourage additional uptake in industrial sectors.

Technologies

There are also key synergies between technologies that could accelerate the decarbonisation of industry:

- In an electrification focussed decarbonisation pathway several technologies will be required to generate, store, and utilise electricity.
  - **On-site and imported renewables will be necessary to complement electric heating technologies**, primarily heat pumps and e-boilers.
  - Variable generation profiles will not match the baseload energy demand for industrial processes so **energy storage will play an important role**.
- Heat networks generally provide low temperature heat for space heating. Industrial processes will likely require heat upgrading with heat pumps to reach higher process temperatures.
- **Hydrogen and biomethane blending into the gas grid could act as an interim decarbonisation lever** and reduce residual emissions from sites without alternatives to grid natural gas supply.

1 2040 Net-Zero Action Plan – ZCOP

Prioritisation of Decarbonisation Options for Oxford

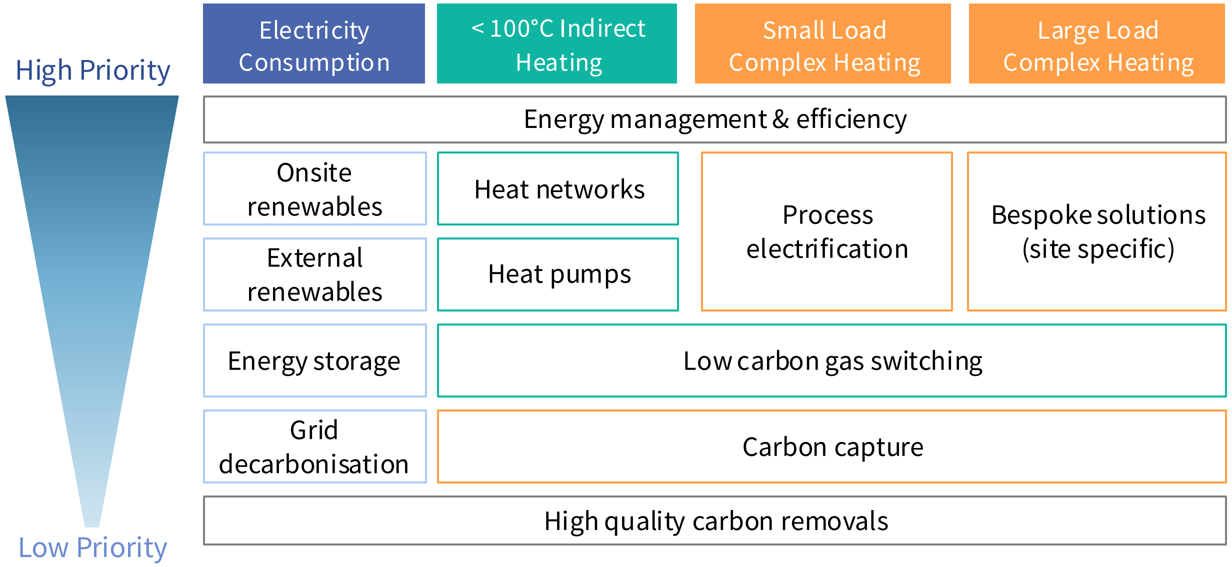
Priority decarbonisation technologies were identified for each category of industrial emissions in Oxford

Individual technology assessments were used to prioritise technologies (based on technical considerations, economic factors, wider barriers in Oxford, and stakeholder views) for the range of industrial emission sources identified in Oxford. This includes electricity consumption, low temperature indirect heating (gas boilers), and complex heating* (e.g. ovens and kilns).

High priority solutions for Oxford industrials were identified as:

- **Energy management & efficiency measures,** which will be critical across all processes and technologies, especially innovative and digital/smart solutions to help reduce peak demand and alleviate grid constraints.
- **Onsite renewables** with energy storage for electricity supply (if space and capital are available) or **external renewables** via renewable energy procurement (if onsite renewables are not possible).
- Accessing a **decarbonised heat network** or installing a **heat-pump** to provide low temperature indirect heating (e.g., space heating).
- For complex heating at small loads, replacing natural gas equipment with an **electrified alternative** (e.g., e-boilers or microwave ovens) in cases where technologies are commercially available and where grid constraints are not a barrier. For complex heating at larger loads, the chosen solution is expected to be bespoke to the site.
- **Emerging technologies** will play a crucial role across the full spectrum of solutions to increase feasibility, reduce cost, and enable integration of low carbon technologies.

Overview of technology prioritisation across industrial processes



Lower priority solutions include:

- Waiting and being reliant on **grid decarbonisation,** as UK-wide developments in electricity supply are outside of the Oxford Industrial Cluster's control.
- **Carbon capture** is deprioritised since it is not expected to be economical for Oxford industrials, and the region is not a focus for CO_2 transport infrastructure development.
- **High quality carbon removals** are deprioritised since Oxford Industrial Cluster's focus is on first achieving direct decarbonisation where possible.

*Complex heating refers to processes at >100°C or direct heating technologies.

Higher priority technologies for decarbonising Oxford's industrials

High priority technologies are those that are likely preferred solutions for industrials in Oxford this decade. Reasons for being a preferred solution include lower costs, commercial availability, higher maturity, and limited barriers.

High Priority

Medium Priority

Electricity Consumption	< 100°C Indirect Heating	Complex Heating

Energy efficiency: Oxford has already strategized the importance of energy efficiency across all sectors and industry is no different. An efficiency first approach enabled by **emerging smart/digital energy management solutions**, such as automated meter readings, is crucial to decrease total energy demand, immediately reduce emissions, and to minimise the subsequent cost of decarbonisation technologies.

Electricity Consumption

Onsite renewables: Localised renewable deployment (either onsite or within a business park) can provide benefits of lower cost electricity whilst alleviating demands on the electricity grid. To achieve the greatest emission reductions, this should be combined with **energy storage**.

Renewable procurement: If renewables cannot be deployed onsite, renewable electricity can be procured via a physical or virtual PPA. This is less likely to provide cost savings compared to onsite deployment and may not alleviate grid constraints. The emission savings from renewable PPAs may be less reliable due to demand 'matching' uncertainties.

< 100°C Indirect Heating

Heat networks: Heat networks are the preferred indirect heating mechanism below 100°C due to their ability to re-use waste heat, their economies of scale, and the limited demands placed on the electricity grid (assuming heat sources are carefully located to avoid grid constraints). They initially require collective action and may face barriers associated with capital investment, operational costs, and infrastructure development. Infrastructure may not be developed to sites or business parks around which there is not sufficient demands to justify network deployment.

Onsite heat pumps: Heat-pumps are commercially available, and their high-efficiency limits the impact on the grid, although grid-constraints may remain an issue for larger sites. Barriers faced include high upfront CAPEX and disruption.

Complex Heating

Small Loads

Process electrification: For small-scale complex heating processes, electrification technologies are the preferred solution. **Electric boilers or heat pumps** can generate high-temperature steam, and a range of **radiative heating** technologies are commercially available (e.g., ovens, dryers). Electric technologies may provide efficiency benefits, but face barriers of upfront CAPEX and high electricity prices. Process electrification could be co-deployed with onsite renewables to reduce operational costs. Technology readiness may be a barrier.

Large Loads

Bespoke solution: There are few sites in Oxford with large demands for high-temperature or direct heating. The best solution for these sites will be bespoke to their circumstances but could include:

- **Electric boilers & radiative heating:** These technologies are commercially available but may face grid constraints challenges and very niche processes may face readiness barriers.
- **High-temperature heat-pump:** by upgrading lower temperature heat, emerging technologies can reach higher temperatures.

+ Important supporting role of innovation across all technologies: Novel low carbon energy production technologies, innovative approaches to energy efficiency and grid management, and ongoing improvements to existing renewable generation will play a role in the medium-long term to enable electrification, diversify energy supply, and reduce costs.

Lower priority technologies for decarbonising Oxford's industrials

Low priority technologies are those that are deemed less applicable or less impactful solutions for industrials in Oxford this decade. These technologies may currently have feasibility challenges, higher costs, technical uncertainties, or other barriers.

Medium Priority

Electricity Consumption	< 100°C Indirect Heating	Complex Heating – Small Loads	Complex Heating – Large Loads

Energy storage: Batteries and thermal energy storage can provide grid balancing services and support smoothing of variable renewable supply to constant baseload demand. **Smart, integrated, control systems** can deliver emissions and cost savings by storing lower cost and emission electricity for peak times.

UK grid decarbonisation: The UK government has a target to decarbonise the grid by 2030. Waiting for this target to be reached limits near-term abatement, increases uncertainty, and does not alleviate grid constraints or provide savings.

Low Carbon Gas Switching:

- Partial **blending of biomethane and hydrogen** into Oxford's gas grid may occur as part of wider national decarbonisation efforts or due to synergies with other sector decarbonisation strategies. This is subject to significant uncertainty on national strategy and network operator developments.
- Hydrogen blending is expected to be limited to less than 20 vol% offering limited decarbonisation.
- Larger sites may be able to access a **dedicated hydrogen supply** for 100% fuel-switching – this could be from on-site or local hydrogen electrolysers or imported from large-scale projects. However, the high-cost of hydrogen means heat-pumps or heat-networks are a higher priority solution for indirect heating.
- Use of **biomethane** as a drop-in natural gas replacement may be attractive for some sites, but barriers exist with the availability of sustainable feedstock and the necessary supply infrastructure to go beyond low percentage blending.

Carbon capture: Economically, carbon capture is more applicable to large-scale, hard-to-decarbonise processes which are not found within Oxford's industrial sectors. There are major barriers to the transport of captured CO_2 from Oxford to the UK's developing offshore CO_2 storage sites which are not likely to be resolved in the near-term, as well as wider socio-environmental concerns. **CO_2 utilisation** is a potential option, but such applications are still relatively novel and would still require large CAPEX investment, additional energy demands, and stable offtake markets.

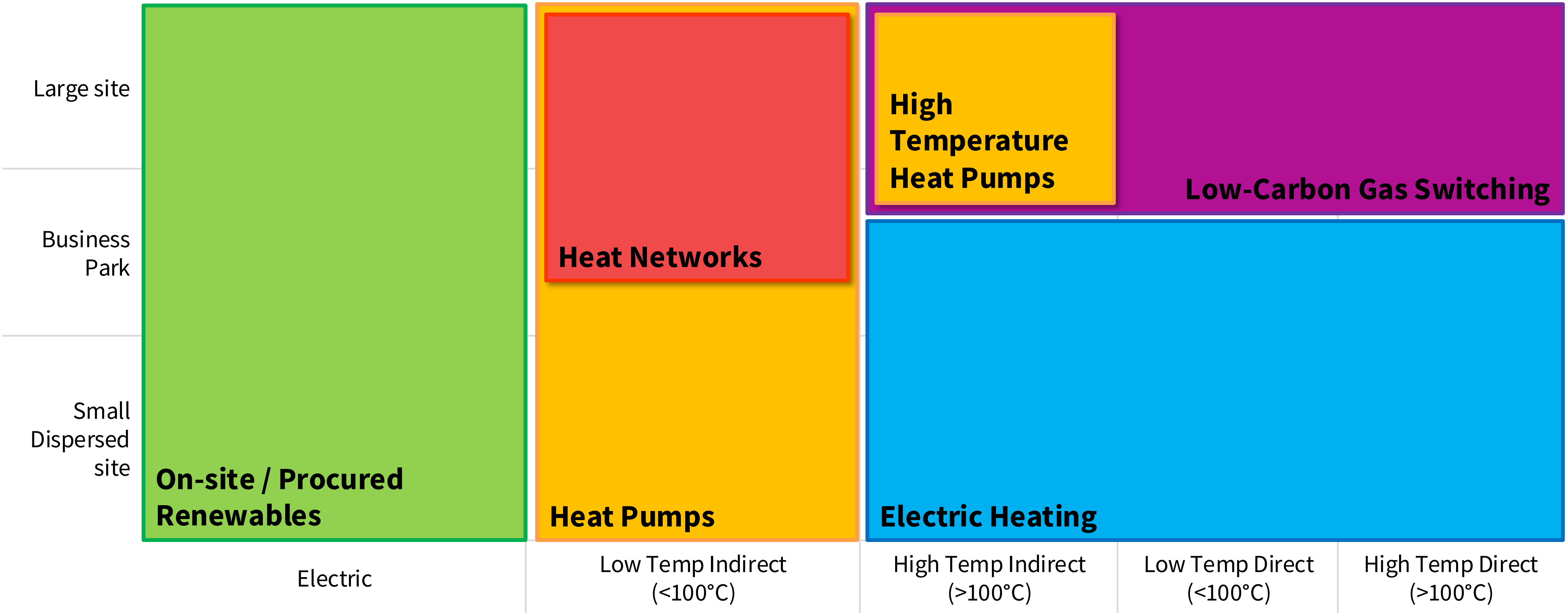
Low Priority

High quality carbon credits: High-quality carbon removal credits can be used to "neutralise" the final 5-10% of hard-to-abate emissions once industry has decarbonised the rest of its operations. Removals should only be utilised for the residual emissions and therefore are not prioritised.

+ Important supporting role of innovation across all technologies: Novel low carbon energy production technologies, innovative approaches to energy efficiency and grid management, and ongoing improvements to existing renewable generation will play a role in the medium-long term to enable electrification, diversify energy supply, and reduce costs.

The prioritised decarbonisation technologies still leave options for the full range of industry in Oxford

The graphic displays the highest priority deep decarbonisation technology option for each combination of industrial process/site considering the results of the technical feasibility and barrier analysis



Appendix – Detailed Technology Assessments

Technical characteristics highlight the strength of electrification and renewables to decarbonise industrial heat and electricity supply

Technology	TRL	Cost	Process Applicability	Site Type	Technology Synergies	Sectoral Synergies
On-site renewables	7-9	High CAPEX, OPEX decrease	Electric only	All	Electrification	General
Renewable Procurement	9	Minor OPEX increase	Electric only	All	Electrification	General
Electric Heating	5-9	Low CAPEX, OPEX increase	Most gas fired processes	All	Renewables	Buildings
Heat Pumps	6-9	High CAPEX, OPEX decrease	Most Indirect Heating	All	Heat Networks	Buildings
Heat Networks	8-9	OPEX decrease	Indirect Heating (with upgrading for high temp)	Only sites within network	Heat Pumps	Buildings
Biofuel Switching	7-9	OPEX increase	All gas fired processes	All	Hydrogen Blending	Transport
Hydrogen Fuel Switching	5-8	Major OPEX increase	Mostly high temperature	Demand hubs only	Biofuel Blending	Transport
Carbon Capture	6-8	High CAPEX, OPEX increase	Only hardest to abate	Large sites only	Limited	Limited

Poor performance

Good performance

Strong performance

Stakeholder engagement and barrier analysis indicate a limited role for hydrogen fuel switching and carbon capture technologies

Technology	Social	Technological	Regulatory	Environmental	Market	Policy	Stakeholder Engagement	Applicability to Oxford
On-site renewables							Positive	High
Renewable Procurement							Positive	High
Heat Pumps							Positive	High
Heat Networks	Disruption for installation						Neutral	High
Electric Heating		Grid constraints				Limited support	Neutral	High
Biofuel Switching			Sustainability regulations		Feedstock availability		Neutral	Medium
Hydrogen Fuel Switching			Strict HSE regulation	Leakage and resource demand		Policy uncertainty	Negative	Medium
Carbon Capture	Public opposition	Small scale applicability		Continued O&G extraction	Immature market / incentives		Negative	Low

Major barriers
Small barriers
Limited barriers

Technical Overview Template

Description

Brief technology introduction highlight key characteristics and technology configurations/variations.

Assessment of the **suitability of each technology to the key process categories in Oxford.** A **RAG assessment considers the technical feasibility, technology competition, and both enablers and barriers to deployment**:

Technology is mature and likely the strongest candidate for the process type with limited barriers

Technology is applicable to the process type but may face some barriers or competition

Technology is not applicable to the process type

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric

Cost

The key cost drivers that inform the potential for different technologies to be used in Oxford.

Where **notable cost reductions are expected in the next 5-10 years this is noted**, including the main driver of these cost improvements.

Important cost factors that may increase or decrease costs in Oxford compared to other UK locations are highlighted.

Retrofit	If a decarbonisation technology can be deployed as a retrofit
New build	If a decarbonisation technology can be deployed as a new build
CAPEX	Compared to the counterfactual if CAPEX costs are expected to be generally higher or lower
OPEX	Compared to the counterfactual if OPEX (mainly fuel) costs are expected to be generally higher or lower

TRL

Assesses the technical maturity of the technologies through the technology readiness level (TRL) scale.

In the core review only technologies currently at TRL 5 or above are included, with assessment of future TRLs for those still in development.

Emerging, lower maturity options are also discussed where relevant.

TRL	Description
9	Full commercial deployment
8	Full technology demonstration
7	Operational prototype
6	System demonstration project in relevant environment
5	Component validation in relevant environment
< 5	Lab demonstrations and research concepts

Suitability Assessment Template

Significant barriers

Further considerations

Barriers are subdivided into two categories to highlight their potential impact in Oxford:

- **Significant barriers:** Potential show-stoppers and long-term barriers than could significantly delay or increase the cost of decarbonisation. These barriers are indicated by a red icon and placed at the top of the section.
- **Further considerations:** Less impactful or short-term issues that should be more readily overcome with expected progress. These barriers are indicated by an orange icon and placed is the second part of the section.

The six categories of barrier are used to highlight the key themes for each technology:

- **Market**
- **Policy**
- **Regulatory**
- **Environmental**
- **Social**
- **Technological**

Applicability to Oxford

LOW / MEDIUM / HIGH

Assessment of the overall applicability of a technology to Oxford considering technical characteristics, local barriers, synergies with other technologies and other sectors, existing projects and infrastructure, site and process suitability, and co-benefits for the city.

Assessment of the suitability of each technology to the key site types categories in Oxford. A RAG assessment considers the technical feasibility, technology competition, and both enablers and barriers to deployment:

Technology is mature and likely the strongest candidate for the site type with limited barriers

Technology is applicable to the site type but may face some barriers or competition

Technology is not applicable to the site type

Small Dispersed Site	Large Site	Business Park Site
● (green)	● (red)	● (amber)

Electric Heating – Technical Overview

Description

There are four categories of electric heating equipment that can collectively replace current natural gas boilers and direct heating technologies (e.g. ovens, kilns)[1,2]:

- Heat Pumps (discussed separately in the next section)
- **Electric boilers**
- **Electromagnetic radiative heaters (e.g. microwave dryers)**
- Electric arc technologies (not scoped due to high temperature, niche applications)

There are two main categories of electric boilers; electrode and element boilers. In an electrode boiler, electric current passes through electrodes immersed in water whereas an element boiler heats a material submerged in the water.

Most industrial steam generation and low temperature process can be met with electric heating technologies today. Element boilers are often preferred for small-scale applications for their simplicity whereas electrode boilers are considered better for high temperature/pressure applications.

Radiative heating includes the use of radio, microwave, infrared, and induction heaters. Radiative heating can reach very high temperatures, but is also applicable to low temperature direct heating such as ovens or dryers.[3,4]

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric
●	●	●	●	●

Cost

Electric boilers have lower equipment installation costs than natural gas boilers but as a new build could still invoke additional costs unless aligned with the end of life of the existing boiler.

Despite greater efficiency (up to 99%) compared to the incumbent natural gas boilers, higher electricity prices still lead to increased fuel costs.

Long term cost reductions are likely to be driven by reduced electricity prices and gradual installed cost reductions via increasing scale and supply chains.

Retrofit	✗
New build	✓
CAPEX	↘
OPEX	↗

TRL

Electric boilers, both electrode and element, are already commercially available (TRL 9). Electric boilers can have capacity up to 70 MW_{th} (110 tph steam) and produce saturated steam up to 300°C. There remain limited deployments for the highest-pressure applications (>80 barg).

Radiative heating technologies can produce temperatures over 2000°C with efficiencies above 90%. Lower temperature applications such as dryers and ovens are already technologically mature with high temperature solutions developing to be available commercially available this decade.

E-boiler TRL
9

Radiative TRL
5-9

1 Future Opportunities for Electrification to Decarbonise UK Industry; ERM for DESNZ, to be published. 2 Research: Electrifying Industry | BZE 3 2023 Ambienta Lens – Electrifying Industrial Heat 4 Improving process heating system performance – US DOE

Electric Heating – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Electrification rapidly increases the load connected to the grid posing a substantial issue given Oxford's grid-constraints where projects may have to wait/pay for major upgrade works.
- The long-term cost of electrification is likely to be driven by the cost of electricity which remains high compared to natural gas in the UK due to the current market structure.

Further considerations

- Less mature electrified technologies for direct heating processes can require substantial process changes and electrified high temperature steam generation is relatively novel, with limited market penetration.
- Due to a lack of manufacturing capacity and instalment expertise the supply chain may not be able to cope with growing rate of deployment across industry and other sectors of the economy.
- The carbon benefit of electrification is dependent on a decarbonised grid or renewable coupling, which can increase cost and delay impact.
- Electrification will lead to increased mineral demand to upgrade grid infrastructure and batteries resulting in environmental impacts from the mineral supply chain.
- To date Government support and strategies have been primarily focussed on competitive pathways such as CCUS and hydrogen, especially in larger clusters. Fiscal policy support for the electrification of industrial heat is limited in the UK.
- Electrification is a new-build technology option and therefore a CAPEX burden that will be placed on landlords and not tenants.

Applicability to Oxford

HIGH

Electrified heating has several benefits including the potential to reduce issues of energy security from single-fuel dependency, reduction of all air pollutants, and to support Oxford's constrained grid by enabling wider power system benefits through flexible operation and the option to couple with batteries or thermal energy storage (TES).

Electrification technologies can provide more precise heating for Oxford's high-tech engineering and biosciences as well as the potential to eliminate waste heat from combustion.

Electrifying heat can be effectively coupled with on-site renewable deployment, renewable energy procurement, heat pumps, battery energy storage, and energy efficiency improvements to create an electrification heavy scenario.

Electrification builds on existing energy infrastructure that is readily accessible for industrials in Oxford, however it currently poses a major constraint on electrification build out due to grid constraints in Oxford.

Electrification of heat is the preferred pathway for decarbonising heat in buildings and the emerging pathway for mobility as indicated by the previous ZCOP Roadmap. This offers the potential for shared costs in infrastructure development.

Small Dispersed Site	Large Site	Business Park Site
●	●	●

Air-Source Heat Pump – Technical Overview

Description

There are three main types of ASHP:

1. **Air to Air Heat Pumps:** A space heating solution that takes heat from the external air and transfers it into the building, or vice versa for cooling.
2. **Air-to-Water Heat Pumps:** These systems are most common in the UK, and transfer heat from outdoor air to water, suitable for heating water in radiant floor heating systems or radiators.
3. **High temperature Air-to-Water Heat Pumps:** These systems heat water to temperatures in excess of 100°C, compared to typically around 55°C, allowing industrial uses requiring higher temperatures.

Installing ASHP requires outdoors space, typically at least a few m^2 of space, and wet heating system piping. Going from gas or other heating systems that already have wet heating system piping is easier.

ASHPs primarily facilitate space heating and cooling and can be used for both new construction and retrofits. They typically require a minimum standard of insulation to work well as the heat is released slower than with gas based central heating.

Other heating systems compete with Air-source heat pumps, for example gas or hydrogen boilers, or resistive electric heating. Heat pumps have the best efficiency of all, but the second highest upfront costs out of all single-building heating systems.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric

Cost

Air-source heat pump costs are currently decreasing with increasing maturity of the technology and supply chains.

Air-source heat pumps benefit from high efficiency, in the range of 300%, as they use ambient heat as a baseload and upgrade it to the required flow temperature.

They typically have a high CAPEX but can lead to OPEX savings so are more cost effective for high demand sites. The typical payback period can be around 10 years for mid-sized commercial building.

Government subsidy can help with the large upfront CAPEX associated with heat pumps.

Retrofit	✓
New build	✓
CAPEX	↗
OPEX	↘

TRL

While low temperature air-source heat pumps are a proven technology that has been rolled out to significant part of the building stock in some areas in the world (e.g. Scandinavia), the market shares in the UK is still low despite being commercially available through many suppliers like Daikin, Samsung, or Vaillant. Improvements are still being made in the production and installation phases, leading to cost reductions and increased efficiency.

High temperature air-source heat pumps are currently being demonstrated. They can reach higher operating temperatures, but the drawback is they have a lower efficiency as a result making them currently less commercially appealing.

Low T HP TRL
7-9

High T HP TRL
5-7

Air-Source Heat Pump – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Electrification increases the load connected to the grid posing an issue in grid-constrained areas. Nevertheless, the grid connection power requirement is about a third that of direct electric heating.
- The cost of electrification is driven by the cost of electricity which remains high compared to natural gas in the UK.
- Current heat pumps have high upfront CAPEX which limits uptake but lots of competition and entry of new manufacturers is leading to cost reductions.
- Landlord/tenant relationships make ASHP uptake difficult due to short term lease agreements and diminishes the value to landlords of ASHP as cost reductions are materialised for the tenant.

Further considerations

- Lack of expertise in installation leading to uncertainty with regards to best installers to procure and lower efficiency when poorly installed. This means energy costs will be higher and payback longer.
- Lack of appreciation of commercial heat pump temperature range, that are now capable of 150°C and climbing
- Carbon benefit is dependent on a decarbonised grid or renewable coupling, which can increase cost and delay impact.
- Government supports heat pumps uptake through schemes such as the boiler upgrade scheme, but this is focused on domestic and commercial applications. The Industrial Energy Transition fund provides support for industrials with high energy use to invest in energy efficiency and low carbon (heat pump) technologies.

Applicability to Oxford

HIGH

Air-source heat pumps are applicable to Oxford's wide range of industrial buildings and are one of the preferred decarbonised heat solutions due to their high efficiency.

Air-source heat pumps are most cost and emissions effective in new builds or existing sites with good thermal efficiency, as they can be used to pre-heat buildings, therefore helping spread the load on the electricity network. Time of use tariffs such as Octopus Agile incentivise this by selling off-peak electricity at a discount, meaning consumers can heat buildings at a fraction of the cost they currently do using gas.

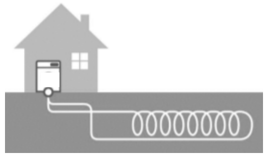
Additionally, if buildings have their own renewable energy generation, it can be used to power heat pumps.

Newer high-temperature heat pumps are becoming increasingly common and allow heat pumps to be used beyond just space heating, in new applications such as low temperature industrial processes that are abundant in Oxford.

Given the efficiency of heat pumps depends on the temperature difference between the return and working temperatures, there are significant synergies when waste heat from other industrial processes can be used and upgraded to the higher correct temperature for the application of interest.

Small Dispersed Site	Large Site	Business Park Site

Ground-Source Heat Pump – Technical Overview



Description

There are two main types of GSHP:

1. **Closed-loop GSHP:** These systems are most common, and transfer heat from the ground to a working fluid in a closed-loop, which can then be used for heating water in radiant floor heating systems or radiators
2. **Open-loop GSHP:** These systems are less common and require surface water to be pumped through the heat exchanger and returned to the ground. These are sometimes also referred to as water source heat pumps.

Installing GSHP can requires significant outdoor land space and wet heating system piping. Going from gas or other heating systems that do already have wet heating system piping is therefore easier.

GSHPs primarily facilitate space heating and cooling in residential, commercial, and industrial buildings. They can be used for both new construction and retrofits. They typically require a minimum standard of insulation to work well as the heat is released slower than with gas based central heating

Other heating systems compete with heat pumps, for example current gas or future hydrogen boilers, or resistive electric heating. Ground-source Heat pumps have the best efficiency of all, but also the highest upfront costs out of all single-building heating systems, due to the ground loop infrastructure required.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric
●	●	●	●	●

Cost

Ground-source heat pump costs are currently decreasing with increasing maturity of the technology and supply chains.

They benefit from high efficiency, in the range of 400%, as they use ground heat, which usually remains at a more constant temperature than air, as a baseload and upgrade it to the required flow temperature.

They typically have a high CAPEX but can lead to OPEX savings so are cost effective for high demand sites. The typical payback period can be around 10 years. Government subsidy can help with the large upfront CAPEX.

Retrofit	✓
New build	✓
CAPEX	↗
OPEX	↘

TRL

While ground-source heat pumps are a proven technology that has been rolled out to significant part of the building stock in some areas in the world (e.g. Scandinavia), the market shares in the UK is still very low despite being commercially available through suppliers like Kensa.

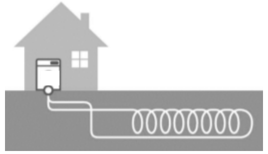
Improvements are still being made in the production and installation phases, leading to cost reductions and increased efficiency.

One limitation is the business case, which only makes sense for large demand sites, or aggregated small demand sites.

Current TRL

7-9

Ground-Source Heat Pump – Suitability Assessment



Market Policy Regulatory Environmental Social Technological

Significant barriers

- Electrification increases the load connected to the grid posing an issue in grid-constrained areas. The Grid connection power requirement for Ground-source heat pumps is about a quarter that of direct electric heating.
- Another key constraint is the large land requirement for the installation of the ground array, typically at least 100 m^2 for 10,000kWh of demand.
- The cost of electrification is driven by the cost of electricity which remains high compared to natural gas in the UK.
- Landlord/tenant relationships make GSHP uptake difficult due to short term lease agreements and diminishes the value to landlords of GSHP as cost reductions are materialised for the tenant.
- Current heat pumps have high upfront CAPEX which limits uptake. A lot of competition and entry of new manufacturers is leading to cost reductions. A lot of gas boiler companies are looking to expand into this market too.

Further considerations

- Lack of expertise in installation leading to uncertainty with regards to best installers to procure and lower efficiency when poorly installed.
- Carbon benefit is dependent on a decarbonised grid or renewable coupling, which can increase cost and delay impact.
- Government supports heat pumps uptake through schemes such as the boiler upgrade scheme, but this is focused on domestic and commercial applications. The Industrial Energy Transition fund provides support for industrials with high energy use to invest in energy efficiency and low carbon (heat pump) technologies.

Applicability to Oxford

MEDIUM

Ground-source heat pumps are applicable to limited set of buildings, due to their high infrastructure cost and space constraints which could be a major issue especially in the city centre.

Where several buildings share the ground loop array, the setup becomes like a small heat network; business parks could be well suited to the shared infrastructure potential but may struggle to fund the upfront investment and manage contractual relationships with numerous leaseholders.

Ground source heat pumps are most cost and emissions effective in new builds or existing sites with good thermal insulation, as they can be used to pre-heat buildings. This may be beneficial for future expansion of Oxford's industrial/business parks but is a barrier for older, existing industrial sites.

Ground source heat pumps are most applicable to (groups of) buildings with high heat demand, so OPEX savings compensate for the large CAPEX. Additionally, if buildings have their own renewable energy generation, it can be used to power heat pumps.

Given the efficiency of heat pumps depends on the temperature difference between the return and working temperatures, there are significant synergies when waste heat from other industrial processes can be used and upgraded. Open loop heat pumps may also be able to exploit the river as a source of heat.

Small Dispersed Site	Large Site	Business Park Site

Heat Network – Technical Overview

Description

Heat Networks (HN), also known as district heating (DH), are centralized heating systems that distribute heat from a central source to multiple buildings or facilities within a defined area through a network of insulated pipes. These systems provide a more efficient and sustainable way of delivering heat compared to individual heating systems in each building.

HNs vary in size and in the technology used to provide heat to the network. The most common heat sources are summarised below:

1. **Gas Combined Heat and Power (CHP):** gas boilers which simultaneously produce electricity and heat can be used, increasing overall energy efficiency
2. **Heat-pump:** Different types of heat pumps can be used to produce heat, making best use of available waste heat in the region, e.g. geothermal, rivers, or sewers.
3. **Waste-to-Energy:** waste-to-energy facilities where heat is generated from the combustion of municipal solid waste can then be used in a heat network.

Heat networks primarily facilitate space heating and hot water provision for residential, commercial, and industrial buildings within the serviced area. They can also support various industrial processes that require heat, such as drying, sterilization, and industrial heating.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric

Cost

HNs require a network of insulated pipes for heat distribution, along with heat exchangers, pumps, and control systems. The high infrastructure investment means that the network needs to deserve enough demand points and therefore offer significant OPEX savings for it to be financially viable. This is why HNs costs are very dependent on heat demand density.

Additionally, the cost to consumers also needs to be considered. Heat Networks are currently excluded from the Ofgem price cap, exposing its consumers to potentially unaffordable energy costs.

Retrofit	✓
New build	✓
CAPEX	→
OPEX	↘

TRL

While HNs are a proven technology that has been rolled out to significant part of the building stock in some areas in the world (e.g. Denmark, Poland), the total number of buildings on heat network in the UK is low.

High upfront cost and disruption during building of the schemes are the main factors limiting the rollout of HNs, as well as the risk that some demand centres that had committed to connect decide not to join the network, therefore reducing the number of consumers that share the infrastructure cost.

Current TRL

8-9

Heat Network – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Heat networks can cause significant disruption when being installed, as they will require existing buildings to be retrofitted with a heat exchanger instead of their current heating system and a pipe network to be built, typically following the road network. This is also reflected in long timelines from project conception to building and operation, from feasibility assessment, detailed project planning, planning permission application, fundraising, and construction .
- Landlord/tenant relationships make heat network update difficult due to short term lease agreements and diminishes the value to landlords of heat networks as cost reductions are materialised for the tenant.
- The cost of electrification is driven by the cost of electricity which remains high compared to natural gas in the UK.
- Heat network consumers are not protected by Ofgem price caps, which exposes them to price volatility and makes some consumers reject them.

Further considerations

- Heat networks have high upfront CAPEX which limits areas where it can be cost-effective to zones of high heat demand density.
- For heat networks to be decarbonised, their energy centres need to be using heat pumps. In this case, electrification increases the load connected to the grid posing an issue in grid-constrained areas.
- Heat networks can lead to significant energy and emissions savings because a large heat generation unit is significantly more efficient than many individual ones.
- Many schemes seek to facilitate the rollout and financing of Heat Networks, such as the Heat network zoning and the Green Heat Network Fund (GHNF) providing financial support at the different stages of the project conception (technical feasibility, project development, construction, etc).

Applicability to Oxford

HIGH

Heat networks are applicable to a significant proportion of buildings in Oxford, due to the high heat demand density from University, commercial, and municipal buildings.

Due to their high infrastructure cost and disruptive nature, conventionally they are better suited for new development than retrofitting. Nevertheless, given Oxford's aging building stock limits the applicability of heat pump technologies there is a potentially significant role for heat networks.

Heat networks, especially coupled with heat pumps, could be particularly useful for shifting peak demand to reduce grid constraints in Oxford, as they have large hot water tanks that allow storage of energy.

Industrials may require a temperature lift for their processes which can be achieved with an on-site heat pump, best complemented by their own renewable generation.

Heat networks are most likely to be developed by external infrastructure investors with industrials or business parks then joining the existing network as an offtaker.

A proposed heat network, by developer 1energy, is initially targeting institutional demand but may pass close to existing industrial hubs which could connect in future phases. This could also permit the use of industrial waste heat to feed the network.

Small Dispersed Site	Large Site	Business Park Site
●	●	●

On-site renewables – Technical Overview

Description

On-site renewables generation refers to the generation of electricity from renewable sources, typically solar photovoltaic (PV) panels, on an industrial site. This approach allows users to use their own electricity, thus reducing their costs, dependence on grid-supplied electricity, and carbon emissions.

One key limitation of renewable generation is its intermittency, requiring backup power either through a grid connection, energy storage, and other on-site dispatchable generation. Another limitation can be grid headroom capacity in the case where exports to the grid are expected.

The most common generation includes:

1. **Roof-Mounted Solar Panels**: PV panels installed on rooftops of buildings, utilising available roof space to generate solar electricity.
2. **Ground-Mounted Solar Arrays**: Solar panels installed on the ground within the property boundaries, suitable for larger installations where roof space is limited or unsuitable.
3. **Solar Carports**: Parking structures with solar panels installed on the roof, providing both shade for vehicles and solar electricity generation.
4. **Wind**: Wind is not common due to national level planning permission issues and a perceived higher level of visual and sound impact on local communities.
5. **Solar thermal**: Solar thermal is not common in the UK due to high costs compared to renewable energy available.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric

Cost

Solar PV is one of the cheapest forms of electricity generation. It has a significant CAPEX cost but leads to savings during operation.

The typical payback period for solar PV systems is around 5-8 years, out of a panel lifetime of 20-30 years, offering a strong solution to decarbonise electricity for buildings with large electricity demand.

Export tariffs can be used to improve business cases of on-site renewables, allowing industrials to sell back to the grid in hours where generation exceeds demand.

Solar panel costs have fallen significantly with the strengthening of supply chains in China and this trend is expected to continue.

Retrofit	✓
New build	✓
CAPEX	↑
OPEX	↓

TRL

Solar PV is a very mature technology. The current limiting factors for solar PV rollout is mostly around financing, upfront cost, and grid connection availability and cost.

New solar cell technology is improving rapidly and can offer new opportunities, such as flexible, transparent or extremely lightweight solar, which can be integrated in new locations unsuitable for traditional Silicon-based solar.

Mature TRL

9

Emerging TRL

5-7

On-site renewables – Technical Overview

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Landlord/tenant relationships make installing PV difficult due to short term lease agreements and diminishes the value to landlords of PV as cost reductions are materialised for the tenant.
- Installation of PV requires significant surface available, either on roofs, carports, or neighbouring land. Not all roofs can support the weight of PV.

Further considerations

- Counter-intuitively, addition of renewables can be grid-limited even though it is meant to reduce grid load. Renewables required export headroom which is constrained in certain regions of Oxford.
- Solar PV is a key technology to effectively decarbonise electricity use in buildings. Because of its intermittent nature it needs to be combined with dispatchable power through grid connection and backup electric power, or on-site batteries, for industrial processes. Full life cycle including mining and recycling need to be accounted for in assessments.
- Some schemes exist to incentivise consumers to install PV, such as the Smart Export Guarantee, which ensures an export rate of electricity generated, and the Energy Company Obligation which provides grant funding.
- The cost-effectiveness of on-site generation depends on the cost of the electricity to consumers. Currently this cost being high makes business case for on-site PV more favourable.
- Solar PV cost has been decreasing and is expected to continue on that trend going forward, making it a very suitable choice for electricity generation. There are no supply chain issues at the moment or expected in the near future.
- Space constraints can limit the potential deployment of on-site renewable technologies within the city centre.

Applicability to Oxford

HIGH

On-site generation is very applicable to Oxford, as it is in an area of the UK with good solar resource availability. However, wind resources in the area are not as strong so offer more limited potential.

On-site renewables couple effectively with Oxford's wide range of industrial heating processes that could be electrified. Due to their high infrastructure cost, they are better suited for larger sites with high demand.

Using batteries can ensure that the energy produced by the PV array can be used when it is required, and effectively allows matching the generation and industrial demand profiles. Smart management of battery storage allows export arbitrage with additional electricity helping flatten network peaks and reduce grid congestion.

Industrials in Oxford's business parks often do not own their building and therefore cannot deploy on-site renewables with certainty they will benefit from the full payback time. Deployment in Oxford City is also fallible to space constraints with larger sites unable to match their demand with sufficient generation capacity.

The business case for solar PV is often supported by being connected to the grid for export, but as parts of Oxford are known to have grid constraints this may limit deployment due to prohibitively large costs associated with grid upgrades.

Small Dispersed Site	Large Site	Business Park Site
●	●	●

External Renewable Supply – Technical Overview

Description

Offsite renewable supply includes local renewable developments (potentially with direct wire) and purely contractual mechanisms to procure renewable energy supplied through the grid.

Power Purchase Agreements (PPAs) are a contract between a generator and offtaker to buy an amount of energy at a fixed price. There are three types of PPA:

- A **private wire PPA** involves a direct connection between the generator and the offtaker.
- A **physical PPA** is an agreement between the generator, offtaker, and a utility for use of the grid to transfer power.
- A **virtual PPA** is a financial arrangement for the transfer of renewable energy certificates or Renewable Energy Guarantees of Origin (REGOs), rather than actual power.

Renewable electricity is crucial to decarbonise existing electric equipment and to maximise emissions savings from the use of electric heating pathways.

PPAs are vital to support renewable build out, helping overcome high CAPEX costs by providing income certainty to de-risk the financing of the large initial investment.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric
red	red	red	red	green

Cost

PPAs have recently fallen in price as renewable asset deployment has increased.[1,2]

Utilisation of PPAs removes any CAPEX for the industrial whilst exploiting economies of scale to drive down energy cost.

Cost is influenced heavily by the type and "shape" of the PPA, which determines whether risk falls with the producer or offtakers. Costs are expected to track wholesale grid energy price projections and generators and offtaker hedge against future price volatility.

Retrofit	✓
New build	✗
CAPEX	→
OPEX	→

TRL

PPAs are a mature contractual mechanism that have been used widely across industrial and utility-scale projects for many years.

The underlying renewable energy generation technologies are also commercially mature.

Innovative commercial arrangements are targeted to better manage risks and production variability. Increasingly regulation is requiring more granular supply-demand matching which may influence the contracting mechanisms used.

Current TRL

9

1 Berkeley Lab's latest "Utility-Scale Solar" report analyzes record deployment and higher value in 2021
2 European_PPA_Market_Outlook_2024 – PexaPark

External Renewable Supply – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Physical PPAs require the necessary grid capacity and connections if they are being used in conjunction with industrial electrification technologies and therefore placing additional electricity demand on the grid.
- Without half hourly temporal matching PPAs can ignore the impact of additional peaking plant utilisation although this is yet to become common practice. Increasingly regulations are requiring half-hourly matching of renewable supply and demand to maximise whole system benefits which will increases costs.
- Uncertainty in price evolution can lead to hesitancy in signing long-term contracts due to ongoing variability in the energy markets influenced by international event and government policy.

Further considerations

- Although direct wire PPAs encounter the least environmental concerns their deployment could be limited be space constraints and community opposition to development in the local area.
- Virtual PPAs do not consider the variations in emissions intensity for different grids.
- There is limited space in Oxford city for large scale renewable developments to provide private-wire connections.
- Fiscal policy support is targeted for renewable generators with limited incentive for offtakers. Recently announced support[1] may not be applicable to light industry in Oxford; pushing industry towards PPAs.
- Local distribution and variability management will be complicated for shared PPAs, such as PPAs, such as at a business park.

Applicability to Oxford

HIGH

PPAs can support the development of local/shared renewable energy generation projects around Oxford that may be able to help decarbonise other sectors in Oxford as they electrify.

Renewable electricity procurement is crucial to complement on-site renewable generation to allow full decarbonisation of electricity supply in the period before the UK grid decarbonises. Electric heating equipment is dependent on renewable energy supply to deliver maximal decarbonisation benefits.

PPAs are generally large contractual agreements that would favour large industrial sites where private wire PPAs are feasible, this may be challenging in Oxford.

Oxford's business parks may struggle with long term commitments compared to tenancy's; energy procurement is also commonly the tenant's responsibility.

Oxford's landscape of dispersed sites are more likely to rely on physical or virtual PPAs from renewable energy projects that have already acquired financing.

If private wire PPAs can be established to local renewable generation this avoids potential concerns over temporal matching, grid emission intensity imbalances, space constraints for onsite renewable deployment in the city centre, reduces grid transmission fees, and relieves Oxford's issues with grid congestion.

Small Dispersed Site	Large Site	Business Park Site
● (amber)	● (green)	● (green)

1 British Industry Supercharger gives huge boost to UK businesses

Hydrogen Fuel Switching – Technical Overview

Description

Hydrogen (H_2) fuel switching can replace natural gas combustion in industrial processes, with potential to decarbonise heating, notably high temperature, demands. Hydrogen combustion produces no point source carbon emissions.

Low-carbon H_2 can be blended with natural gas for use in existing equipment or with some burner/process modification most natural gas equipment could combust 100% H_2 streams.

Hydrogen is most likely to be supplied via grid blending, a fully converted gas grid, or directly by a local electrolyser. This will depend on national policy decisions and on local gas DNO developments.

H_2 is also used as a feedstock in several industrial processes (mainly chemicals) where renewable supply will be necessary in future; here we focus on H_2 as a fuel.

Different types of low-carbon H_2 include:[1]

- **Electrolytic (green) H_2**, produced via water electrolysis using dedicated renewable sources.
- **CCS-enabled (blue) H_2**, produced via the reforming of natural gas in combination with CCS.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric
● (green)	● (green)	● (amber)	● (green)	● (red)

Cost

Low carbon H_2 is not yet competitive against natural gas prices. Long-term production costs are expected to fall, but not until the mid-2030s.[2] Government funded business models will lower the retail price for H_2 in the meantime.

Low-cost electricity, such as from avoided curtailment, is necessary to reduce the cost of green hydrogen production but this can lead to higher CAPEX costs per unit production.

Retrofitting existing equipment reduces the CAPEX burden of hydrogen conversion. However, site conversion and transport fees further increase the system level cost of using H_2.[3]

Retrofit	✓
New build	✓
CAPEX	↗
OPEX	↗

TRL

Hydrogen boilers and dryers are considered TRL 7-8 whilst less mature direct heating equipment sit at TRL 5–6.[4] This is because the different combustion characteristics, temperature and emissivity, of H2 from natural gas is challenging for direct heating applications.

With continued H2 burner R&D activity and rapid commercialisation of H2 equipment, many technologies could reach full commercial availability (TRL 9) before 2030.

Low-carbon H2 production is TRL 7-9 with scaled deployments increasing in number.[4]

Current TRL
5-8

Future TRL
7-9

1 Element Energy for HICP - MPR Study 2 Hydrogen production costs 2021. 3 Hydrogen Transport and Storage Cost Report
4 ETP Clean Energy Technology Guide – Data Tools - IEA

Hydrogen Fuel Switching – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- A significant near-term barrier for industrial is the supply on low carbon hydrogen as large-scale production is still yet to be demonstrated at commercial scale in the UK and enabling H_2 transport infrastructure is yet to be established
- Policy support is focussed on developing major hydrogen clusters, through the cluster sequencing program, which will therefore be the first to develop large scale supply and transport solutions
- It is unclear if gas-grid conversion will be approved as part of the hydrogen for heating decision in 2026 which could greatly reduce the potential for hydrogen deployment for small industry in Oxford.
- Hydrogen remains expensive compared to natural gas and dependent on fiscal policy support. High capital costs for 100% H2-enabled equipment and on-site infrastructure can discourage industrial investment.
- Health, safety and environmental concerns from the public about the potential for hydrogen leakage during transport and storage of the combustible gas. Strict HSE and COMAH regulations require changes to site permitting.

Further considerations

- Low-carbon H_2 production and subsequent combustion is inherently inefficient and therefore energy and resource intensive.
- Electrolysis requires substantial water and renewable supply and CCS-enabled H_2 depends on upstream gas and downstream CCS value chains.
- Different flame characteristics lead to variations in direct heating processes and products that can impact quality and require regulation

Applicability to Oxford

MEDIUM

Hydrogen supply to Oxford is most likely to be electrolytic, green hydrogen produced locally and coupled to nearby renewable generation. Whereas CCUS-enabled H_2 is more likely to emerge in the coastal industrial CCS clusters where access to gas supply and CO_2 storage is easier.

H_2 transport and storage costs are likely to promote regional production unless the gas grid is converted (for blending). Hydrogen blending could provide intermediate decarbonisation of domestic heating and may lead to full conversion of the grid.

There are plans to develop a UK wide transmission system for hydrogen however this is initially focused on the large industrial clusters.[1] The earliest individual industrials in Oxford might be able to connect to such as system would be well after 2035.

Local production plans are limited to RWE's electrolyser in Didcot, which received government funding in 2022 for a Front End Engineering Design study.[2,3] Niche high temperature industrial applications may rely on such small-scale production sites.

H_2 is seen as a potential solution for heavy-duty transport requirements, permitting potential synergies and economies of scale if deployed in alignment with industrial fleets or on-site mobile machinery switching to hydrogen fuelling.

Small Dispersed Site	Large Site	Business Park Site

1 Project Union – National Gas 2 RWE hydrogen activities in UK 3 Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 1 (April 2022) competition

Biofuel Switching – Technical Overview

Description

Biofuels span a range of biological products that can be combusted as an alternative to fossil fuels:

- **Biomass** - Biological material used as a fuel supply, can include waste-derived fuels which may only contain a portion of biomass amongst non-biological waste.
- **Biogas** - A mixture of gases produced from the anaerobic digestion of biomass, containing methane and carbon dioxide.
- **Biomethane** - Upgraded biogas that can be used as a direct replacement for natural gas. Biomethane can also be produced from gasification of biomass.
- **Biodiesel** - Used to replace conventional transport fuels for on-site mobile machinery and vehicle fleets but is not the primary focus of this review[1].

Biofuels, biomethane especially, are widely applicable to industrial processes that run on natural gas as a drop-in replacement, this also permits the potential for gas grid blending.

Combustion of biofuels results in on-site CO_2 emissions, but they can be discounted if sustainably sourced without negatively influencing high biodiversity land areas, soil carbon stocks, or forest environments.[2]

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric
●	●	●	●	●

Cost

Cost will be heavily influenced by the available supply, with waste streams and local supply chains substantially improving the economics of biofuel production.

Current biomethane supply from upgrading of AD biogas costs £60-80/MWh and may fall gradually. Costs are expected to be around £80/MWh for gasification technologies once they reach commercial scale.[2]

Biomethane injection into the gas grid is currently supported by the Green Gas Support Scheme tariffs at £35-65/MWh however support for direct industrial use is less clear.[3]

Retrofit	✓
New build	✗
CAPEX	→
OPEX	↗

TRL

Use of biomethane as a replacement for natural gas in industrial processes does not represent a major technical challenge.

Upgrading of biogas produced via anaerobic digestion is a demonstrated commercial process (TRL 9) which is already widely utilised in industry.[4]

Advanced gasification is a less mature production pathway with several pilot projects, but no complete system has yet been demonstrated at commercial scale in the UK.[5,6]

Biogas Upgrading TRL

9

Gasification TRL

6-8

1 Industrial Non-Road Mobile Machinery Decarbonisation Options: Techno-Economic Feasibility Study 2 Biomass Strategy 2023 3 ENGIE – Biogas potential and costs in 2050 3 Green Gas Support Scheme and Green Gas Levy | Ofgem 4 Negative Emissions Technologies: Feasibility Study - Final Report 5 Advanced Gasification Technologies – Review and Benchmarking: Review of current status of advanced gasification technologies 6 ETP Clean Energy Technology Guide – Data Tools - IEA

Biofuel Switching – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Availability of biofuels for industry may be limited by environmental regulations limiting feedstocks, long-term contractual obligations to Energy from waste (EfW) plant operators, and competition from mobility applications.
- Biomass can only be considered carbon neutral when sourcing meets strict sustainability and regulatory requirements. Supply will need to be verified using stringent MRV practices across an integrated biomass supply chain, requiring sectoral and international policy alignment.

Further considerations

- The biogas upgrading process presents an opportunity to capture a concentrated stream of biogenic CO_2. Integration of CCS on biogas upgrading is yet to be demonstrated at scale in the UK but could enable delivery of carbon-negative fuels.
- Potential competition with other land use may affect other sectors of the economy, such as food supply or solar farm deployment.
- Environmental concerns emerge with increasing demand for biomass resulting in intensive farming practices, deforestation, and environmental degradation.
- Biofuel combustion on-site results to continued CO_2 emissions and pollution at point of use.
- Utilisation of wastes and waste-derived fuels can require consenting and permitting variations for the industrial site.
- Policy support is currently focused on gas grid blending and transport applications with limited support available for industrial biofuel switching.

Applicability to Oxford

MEDIUM

Biomethane blending into the gas grid could complement and precede hydrogen blending in Oxford. Blending would also support decarbonisation of commercial and residential heating.

Biofuel utilisation is expected to be supply constrained with competing use cases:

- EfW plants making use of waste-derived fuels, and especially those that retrofit CCS, may represent significant competition for feedstock. Ardley ERF already utilises at least 95% of Oxfordshire's residual municipal waste as part of a 25-year contract with the county council.[1]
- Biofuels represent a potential solution for decarbonising heavy-duty vehicles where electrification may not be applicable.
- Hydrogen production with biomass could also emerge as a long-term competitor for feedstock supply.

Where available from sustainable or waste sources, biofuels could be most valuable to off-grid, dispersed, small-scale industrial sites with limited alternatives. Supply constraints may limit the potential for biofuels to support larger sites. Industries that generate their own organic process residues, such as food & drink, could convert these waste to biofuels.

Small Dispersed Site	Large Site	Business Park Site

1 Ardley ERF - Viridor

Carbon Capture – Technical Overview

Description

CCUS is the technology that chemically captures CO_2 to prevent it being released from point sources into the atmosphere. Carbon capture includes three distinct approaches:[1]

- **Post-combustion capture** is widely applicable and the most mature approach with numerous developers, especially chemical absorption with amine solvents.
- **Pre-combustion capture** refers to cases where CO_2 is removed before combustion, rather than from the post-combustion flue gases.
- **Oxy-fuel capture** involves burning a fuel using pure oxygen rather than air; this gives a relatively pure CO_2 stream for further processing and compression.

CCS is commonly thought to be most important to decarbonise large-scale, "hard-to-abate", high temperature or process emissions.

Captured carbon can either be:

- Utilised in existing industries (e.g. food & drink) or emerging applications (e.g. sustainable fuels), although this does not result in site-level emission reductions.
- Permanently stored requiring a complex value chain with transport via trailer or pipeline and storage in aquifers or depleted offshore O&G fields.

Direct Heating (<100°C)	Direct Heating (>100°C)	Indirect Heating (<100°C)	Indirect Heating (>100°C)	Electric

Cost

The most applicable and cost-effective retrofit CCS technology can vary depending on a range of factors relating to the flue gas and the site's surrounding infrastructure.[2,3]

CCS is a traditional industrial process - CAPEX intensive and benefits from economies of scale. Therefore, small scale applications, such as those required by Oxford's industrials, quickly become prohibitively expensive.

Most SME sites in Oxford would likely require novel modular technologies where capture-as-a-service agreements can reduce CAPEX intensity.

Retrofit	✓
New build	✗
CAPEX	↑
OPEX	↗

TRL

There are several technology developers targeting the small-scale capture market, often with modular solutions to achieve cost benefits at scales of 2-100 ktCO_2/yr, which are most applicable to Oxford.

Modular technologies are now being validated in pilot facilities and are expected to reach a maturity in the late 2020s.[1,4,5]

Emerging technology vendors for modular systems include Carbon Clean, Aker, Linde-BASF, Entropy, and C-Capture; they broadly range from TRL 5-8.[6]

Large-Scale TRL
7-9

Modular TRL
5-8

1 Element Energy for HICP MPR Study 2 Deep-Decarbonisation Pathways for UK Industry 3 Cost of CO2 Storage – GCCSI
4 State of the Art CCS Technologies 2023 - GCCSI 5 Cluster sequencing Phase-2: Track-1 project negotiation list, March 2023 6 Next generation carbon capture technology

Carbon Capture – Suitability Assessment

Market Policy Regulatory Environmental Social Technological

Significant barriers

- Small scale, modular systems are still technically and commercially immature so will likely not be available until the mid-2030s.
- Public opposition to CCS is prevalent due to view that it allows continued fossil fuel exploitation and has been used as a greenwashing tool.
- Continued environmental impact resulting from ongoing upstream fossil fuel production, parasitic energy/heat demand, and residual emissions.
- CCS regulation, environmental permitting, and consenting processes are still emerging so may place limitations on the rate of deployment.
- Carbon capture remains a high CAPEX and OPEX solution with limited financial incentives or a stable, investable market price for carbon.

Further considerations

- Carbon capture requires careful management of potential toxic capture chemicals emissions. Nevertheless, CCS can reduce other pollutant emissions given the need to limit contaminants in the capture unit.
- Policy support is focussed on developing four major CCS clusters through the cluster sequencing program, especially for T&S solutions.
- Lack of clarity around the liability for long-term CO_2 storage and the requirements for monitoring, reporting, and verification of CO_2 storage pathways.
- The CCS supply chain still suffers from cross chain risk between capture, transport, and storage providers.
- The deployment costs likely fall on the landlord, but the current market structure will reward tenant industrials for emissions reductions.

Applicability to Oxford

LOW

Carbon capture is most applicable to large point source emissions, typically Mt-scale, to achieve economies of scale in capture and transport processes.

Carbon capture may be used in the power sector to retrofit existing gas-fired power stations, but this is unlikely to be collocated with industry in the city of Oxford. CCS is unlikely to be used in other sectors of Oxford's economy and has limited synergies with other proposed industrial decarbonisation technologies.

Carbon capture is not well suited to the small scale and light industry in Oxford which would result in increased costs of decarbonisation and therefore prohibits widespread use of the technology in Oxford.

Modular CCS systems may increase the viability of small-scale capture in space constrained environments, but will not be commercially viable in the near-term.

Transport and storage costs will also be elevated in Oxford based on a lack of proximity to UK storage sites. As an alternative the local utilisation of captured carbon in existing sectors, such as food and drink or pharmaceuticals, may reduce system level emissions. Technologies may also emerge through Oxford's innovation to utilised captured carbon, such as e-fuel production.

Small Dispersed Site	Large Site	Business Park Site
● (red)	● (amber)	● (red)

Appendix - Complementary & Emerging Technologies

Energy efficiency can reduce emissions, fuel demand, grid constraints, and the costs of deep decarbonisation

Energy efficiency is often used to describe a wide range of technologies and measures. It commonly refers to any **process change which reduces the required energy input whilst still delivering the same product output**.

Energy efficiency can **deliver significant emissions reduction by reducing electricity/fuel demand.**

- Energy efficiency is the single largest measure to reduce energy demand in the IEA Net Zero Emissions by 2050 Scenario.[1]
- The previous **ZCOP Action Plan modelled a 30% demand reduction in industry as a result of energy efficiency measures by 2030,** mainly from lighting improvements.[2]

Numerous energy efficiency measures are available to industry, with some options highlighted to the right.[3,4]

Energy efficiency improvements are often at low or even negative cost. Instead, barriers to deployment are often human in nature; such as organisational structures, lack of knowledge, or tenancy relationships. Capital constraints, limited financing options/support, and a lack of effective targeted policies all reduce the deployment of energy efficiency technologies.

Crucially energy efficiency can also help alleviate grid constraints and reduce investment in other decarbonisation technologies by reducing the peak capacity or total energy demand.

Digital and smart solutions will play an increasingly important role as energy management and control utilises improving monitoring and optimisation software to reduce energy demand. For example, emerging artificial intelligence solutions may be able to optimise flexible energy tariffs, PPAs, and on-site renewable energy generation to reduce emissions, costs, and grid constraints.

Waste heat utilisation could play an important role for low temperature heating. Heat networks could allow this energy to be used at different sites and upgrading with heat pumps can provide higher temperatures.

Demand reduction

Fabric insulation, heat recovery systems, demand shifting from peak periods

Technology improvement

LED lighting, energy efficient motors, combined heating and power (CHP) units

Sector specific process change

Improved process design, adoption of best practice equipment designs

Digital system management

energy management tracking and systems, integrated energy systems, smart energy storage

Smart process controls

improved process monitoring, AI process optimisation

Behaviour change

Improved maintenance, material/feedstock sourcing and recycling

1 Energy Efficiency - Energy System – IEA 2 ZCOP 2040 Net-Zero Action Plan
3 Cross_Sector_Summary_Report 4 Reducing-CO2-emissions-from-heavy-industry

Energy storage will play a crucial role in the future energy system to mitigate the intermittency of renewable energy production

Variable generation profiles will not match the baseload energy demand often seen for industrial processes so energy storage will play an important role in enabling deep decarbonisation and flexibility.

Battery energy storage (BES) is mature with several technologies commercially available today (TRL 9) and being deployed at scales of 1-100s MWs in the UK. Lithium-ion batteries are the most widely used battery technology, representing more than 90% of global battery storage markets.[1] Innovative battery technologies are emerging to increase round-trip efficiency and relieve resource constraints by utilising new materials.

BES can be complemented by smart/microgrids and process flexibility to further increase the flexibility and stability of electricity demand. Another key component of these systems is the deployment of on-site renewables to provide low cost, behind-the-meter electricity supply, reducing flows through the grid.

Forecasts indicate that BES will dominate the energy storage market until at least the early 2030s, due to their price competitiveness and track record[2]. Barriers for adoption of BESs include a lack of regulation and constrained supply chains for raw materials, such as lithium.

Energy storage can be achieved with batteries but also **various other systems such as pumped hydro, kinetic energy storage, compressed air energy storage, and thermal energy storage.**[2]

Emerging thermal energy storage (TES) solutions may provide alternative energy storage options when coupled with industrial heating processes because **firming heat is more energy-efficient than firming power** when the final demand is heat.[3]

There are three main processes used to store heat: **sensible, latent, and thermo-chemical heat storage.** TES technologies can operate at MW scale capacity, have already reached **high TRLs (7-9)**, cover **temperatures from sub-zero (including cooling) to over 2000°C, and deliver storage for hours to several months**.[3,4]

TES can be especially beneficial where waste heat utilisation is an enabling factor, especially for non-continuous processes or potential synergies between different processes.

Key benefits of energy storage for industrial sites and wider system

- Peak shaving to reduce grid constraints
- Demand shifting to match intermittent renewable supply with continuous energy demand
- Grid services (frequency response, dynamic containment, fast-acting reserve)
- Ability to price arbitrage
- Back-up & guaranteeing continuity of energy supply
- Integration of variable/intermittent renewable supply
- Reduce curtailment of on-site generation

1 MIT Energy Lab 2018 2 BloombergNEF Global Energy Storage Outlook 2021 3 Net-zero heat: Long duration energy storage to accelerate energy system decarbonization 4 Innovation outlook: Thermal energy storage

Carbon removal credits can be used to "neutralise" the final 5-10% of hard to abate emissions

Credits types:

- **Emission Reductions**[1] – Credits generated by **preventing CO_2 emissions** to the atmosphere. Examples include avoided deforestation and renewable deployment.
- **Removals**[2] – Credits generated through the active **removal of existing atmospheric CO_2**. Removals are generally categorised as either nature-based or technological solutions each with different advantages and drawbacks. Examples include afforestation, ecosystem restoration, direct air capture and storage, biochar, and enhanced weathering.

Impact and Claim Integrity:

- The integrity and impact of carbon credits have been repeatedly criticised. Several **initiatives have emerged to align on a standard definition and implementation of integrity in the voluntary market**, namely ICVCM[3] and VCMI[4].
- Current Science Based Target Initiative[5] rules state **only after a company decarbonises, the remaining 5-10% can be "neutralised" with removal credits** only to reach net zero. Any other credits the company may buy is considered extra voluntary contribution and cannot be deducted from their emissions.
- The recently updated **Oxford Offsetting Principles**[1] specify the constraints on net zero aligned credit use to transition towards durable carbon removals.

Carbon markets:

- **Voluntary carbon markets[6]:** Companies purchasing credits voluntarily to compensate for their carbon footprint, motivated by corporate social responsibility and market advantages. Credits are commonly sold through marketplaces that use independent standards, such as Verra[7] or Puro Earth[8], to verify credits. Prices in the VCM remain low, however this is primarily for reduction credits whilst removal credits garner much higher prices[9].
- **Compliance carbon markets:** Companies are legally mandated to use credits to compensate for their emissions to meet mandatory limits of their emissions. Regulated through international, national, and regional carbon reduction schemes such as the Clean Development Mechanism under the Kyoto Agreement[10] or Internationally transferred mitigation outcomes (ITMOs) under Article 6 of the Paris Agreements[11].

Examples of VCM standards

CLIMATE ACTION RESERVE

puro · earth

VERRA

1 Revised Oxford principles for net zero aligned carbon offsetting 2 Carbon Dioxide Removal Primer 3 ICVCM - Build integrity and scale will follow 4 VCMI - Delivering high-integrity carbon markets 5 Ambitious corporate climate action - Science Based Targets 6 VCM Market Map 7 Methodologies - Verra 8 Puro.earth - carbon removal standard and registry 9 CDR.fyi 10 CDM: About CDM 11 Webinar I_Overview of Art.6 of the Paris Agreement

Emerging technologies can diversify the energy mix and reduce the cost of decarbonisation in the medium-term

Advanced Renewable Generation

Ongoing **innovation to improve existing renewable technologies** could deliver cost savings in the medium-long term.

Perovskite solar panels can absorb light more effectively than the standard solar panel technology today. They also offer flexibility, semi-transparency, and lightweight properties, making them suitable for various applications. However short lifetimes currently limits the commercial deployment of the technology as it is not possible to recover the initial investment.[1]

There are also **developmental wind technologies** gaining commercial deployments seeking to increase efficiency, lessen noise pollution, reduce footprint, and improve durability compared to existing wind turbine options.[2]

Digital monitoring and smart/local grid controls will play an increasingly important role in maximising the impact of renewable energy generation capacity and limiting the impact of persistent grid constraints.

Alternative Energy Production

Numerous novel low carbon energy production pathways are in development that may be able to diversify local energy supply and mitigate grid constraints.

Micro/small nuclear power – Micro and small nuclear technologies can provide low-carbon heat and electricity to industry. They avoid some of the challenges around grid constraints, whilst having a relatively small footprint for their power output (typically ~10MW). Whilst the science is mature, they are not proven at scale so are not expected to be readily commercially available until the mid-2030s. There are also significant regulatory hurdles to be overcome before reactors can be installed outside of current nuclear licensed sites.[2]

Geothermal heat – Deep geothermal technologies are able to supply medium-high temperature heat for industry.[3] However, initial investigation have indicated limited potential for deep geothermal heat supply in the Oxford area.[4]

Innovative Fuels

Alongside hydrogen there are several other fossil fuel replacements in development. These may be important in niche, high-tech industry where process control is crucial.

Synthetic fuels (or e-fuels) combine hydrogen and CO_2 or nitrogen to produce fuels such as green methanol and ammonia that can be used in industrial and transport applications. Current high prices for low carbon hydrogen and the limited supply of (biogenic) CO_2 restricts the potential for these technologies to reach price competitiveness with alternatives.

There are also **less mature biofuel pathways** to produce alternative fuels that are emerging. Many of these technologies are initially targeting applications in the transport sector but could scale in the medium term to reach scales relevant to industrial applications. Bioengineered algae and used cooking oil are also becoming an emerging source of transport fuels but will struggle to scale feedstocks.

1 Perovskite Solar Cells | Department of Energy 2 What is a Nuclear Microreactor? | Department of Energy 3 Home – Areomine Technologies 3 Geothermal technologies - British Geological Survey 4 Scientists discover regions of the UK with greatest potential to use heat from deep thermal waters- British Geological Survey

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