Department for
Energy Security
& Net Zero

Industrial Symbiosis – Drivers, Barriers, Benefits and Costs

Report prepared by Europe Economics

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Disclaimer

This report from Europe Economics was commissioned by the Department for Energy Security and Net Zero. It consists of evidence and research about industrial symbiosis. Any recommendations or positions in the report are not to be read as current or planned Government policy, but rather the advice of Europe Economics.

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Executive Summary

Europe Economics was commissioned by the Department for Energy Security and Net Zero (DESNZ) to research the potential for industrial symbiosis in the UK. Industrial symbiosis involves the exchange of waste and by-products between companies and industries to create mutual benefits, reduce waste, and keep resources in productive use for longer. By identifying and assessing the barriers, drivers, risks, costs, and benefits of industrial symbiosis – both in general and within the UK – this report aims to inform policy thinking on the value of industrial symbiosis to the UK and the most effective strategies to promote it.

The study included the following elements:

- The selection of six sectors which form the basis for deep-dive case studies.
- A literature review, both at a general level and for each of the six sectors we have chosen, of the potential for industrial symbiosis and the associated barriers, drivers, costs, benefits and risks. The literature also considers relevant UK legislation that may incentivise or act as a barrier to industrial symbiosis.
- Fieldwork, including 30 interviews with general experts and with companies and trade bodies from the six chosen sectors, and two focus groups.
- Comparative analysis of the drivers, barriers and risks associated with industrial symbiosis.

The six chosen sectors

Six sectors were chosen in which there is significant potential for industrial symbiosis and good availability of relevant information. Across the selected sectors, we also aimed to achieve a balance between established and emerging scope for industrial symbiosis, and a balance between sectors predominantly sending and receiving waste and by-products. The chosen sectors are also distributed across the UK. Our chosen sectors are:

- **Cement and concrete** (mainly receiving).
- **Glass** (mainly receiving).
- **Mining** (mainly sending).
- **Chemicals** (sending and receiving).
- **Food and drink** (mainly sending).
- **Agriculture** (sending and receiving).

Potential for industrial symbiosis

The literature shows that there are numerous opportunities for industrial symbiosis. The literature concerning the UK is relatively limited, with a greater number of sources relating to examples from other countries. Our stakeholder engagement has been valuable in highlighting examples of industrial symbiosis in the UK, both in terms of current and widespread practices, and in terms of opportunities that are either undertaken in a limited way or are still being researched and explored. The evidence also highlights different forms of industrial symbiosis, namely:

- Relatively **ad hoc exchanges** between companies across sectors, often (but by no means always) facilitated in some way by a third party.
- Individual companies within a sector seeking to **market their by-products** in a more formalised way and break into existing supply chains (rather than seeking out specific partners).
- By-products being sent through an **established supply chain** and widely used across a sector, often with intermediary processing companies.
- **Sector-wide process transformations** that are seeking to fundamentally change production techniques across a sector in conjunction with establishing new supply chains for by-products.

UK government policy can affect the potential for industrial symbiosis going forwards, such as through increases to the landfill tax or through policy changes that increase the carbon price under the UK ETS.

There are a number of **future trends** that may affect the potential for industrial symbiosis in the UK, both positively and negatively. These include an increasing focus on decarbonisation and the circular economy; a transition away from high-emitting manufacturing approaches that currently play a large role in industrial symbiosis; advances in digital technology, including artificial intelligence; and advances in renewable energy.

Drivers and enablers of industrial symbiosis

Based on the evidence from the literature and stakeholder engagement, we have identified six core categories of drivers and enablers of industrial symbiosis, namely financial, technological, information and knowledge-related, regulatory and policy-related, geographical, and organisational, social and cultural.

Our analysis shows that **financial drivers and enablers are considered the most important**, scoring ‘very high’ in our ranking. Essentially, companies will only consider industrial symbiosis if the benefits (in terms of various cost savings and revenue creation) justify the costs. Financial drivers are linked to other drivers in that many of these will have a cost element, for example geographic proximity is an enabler as it reduces the costs of transporting materials; and regulatory and policy-related factors can reduce or subsidise the costs of industrial symbiosis for firms, or drive them to pursue symbiotic networks as a way of reducing costs and taxes.

Some drivers and enablers **vary in their importance depending on the sector or nature of firms**. This is particularly the case with geographic proximity, which is key in sectors where materials are difficult or costly to transport; technological enablers, which are important in sectors that require innovative production methods to expand the use of by-products (such as chemicals and cement); and knowledge and informational enablers, which are particularly significant for smaller or less sophisticated firms and for sectors that are more diverse. Policy-related drivers are considered particularly important in encouraging industrial symbiosis in sectors where this is linked with sector-wide transformation of production processes to make use of by-products – for example, the provision of research funding and strategic policies in the chemicals and glass sectors.

Barriers to Industrial symbiosis

The literature shows that barriers to industrial symbiosis are present in the same categories as for drivers and enablers – indeed, in many cases the absence of a driver or enabler manifests as a barrier. Hence, key barriers are related to technology, knowledge and information, organisation and cultural, geography, financial impacts, and regulation / policy.

Within these categories, we have developed a more disaggregated set of barriers to capture the full range of barriers that exist and also to separate out those barriers likely to be the result of market or regulatory failures and those likely to be intrinsic to industrial symbiosis (or indeed relevant to any business and not specific to industrial symbiosis).

The evidence from the literature and stakeholders shows that the **most important barriers** are a lack of knowledge of industrial symbiosis in general and a lack of awareness of specific symbiotic opportunities in particular; suitable technologies or processes being unavailable, unproven or too expensive; and other general costs of industrial symbiosis such as set-up and capital investment costs, time, transportation costs, regulatory costs and the costs of purchasing the by-products themselves.

That said, stakeholders involved in facilitating industrial symbiotic networks have noted that often a number of barriers act together to disincentivise industrial symbiosis, and that many can be simultaneously important. This points to the potential value of having a coordinated industrial symbiosis strategy or facilitation that seeks to address multiple barriers together.

Risks of industrial symbiosis

Risks of industrial symbiosis include both risks to companies and risks to wider society. There is **relatively little evidence of risks** in the literature compared with the evidence available on drivers, barriers and impacts of industrial symbiosis. Stakeholders highlighted a number of risks, although in some cases these overlap with barriers to industrial symbiosis. For example, risks around the quality or environmental impact of waste can also act as a barrier to undertaking industrial symbiosis in the first place.

The most important risks highlighted in our research in terms of impact or likelihood are **fluctuations in the demand for or supply of by-products**, particularly where this undermines investment or disrupts supply chains; and the risk that the **by-products turn out to be unsuitable or environmentally damaging**. Stakeholders also mentioned risks associated with government policy – for example, where the viability of a symbiotic trade changes due to unforeseen changes in policy, or where the promotion of industrial symbiosis in one sector creates unintended consequences in another sector.

Costs and benefits of industrial symbiosis

The literature and stakeholder evidence indicate a wide range of benefits from industrial symbiosis.

- **Reduction in the use of primary materials,** reducing environmental degradation and emissions/energy resulting from extraction and/or processing of those materials.
- **Reduction in CO2 and other GHG emissions**, when replacement by-products generate fewer emissions in production processes.
- **Energy and water savings**, in cases where by-products require less energy or water in the production process or where water is re-used.
- **Avoided landfill**, and associated disposal costs, landfill tax payments and pollution.
- **Reduction in transportation costs**, and associated emissions.
- **Revenues generated** (for sending firms) and **cost savings** (for receiving firms, in cases in which the waste or by-product is cheaper than virgin materials).
- **Economic growth** and job creation (or safeguarding).
- **Innovation spillovers**, where technology enabling a synergy is used elsewhere.

Some of these benefits are particularly relevant to certain of our chosen sectors, as mentioned by stakeholders:

- **Energy savings** stemming from lower temperatures being needed in glass furnaces when using by-products (e.g. Calumite) or from a decrease in the production of high-energy Portland cement when supplementary cementitious materials (SCMs) are used instead were seen as key benefits for these sectors. In addition, the re-use of waste heat from production processes was also highlighted as important.
- Benefits associated with **reducing/eliminating the amount of waste** ending up in landfill were seen as particularly significant for the mining, cement, and food and drink sectors.
- **Carbon and emissions** savings were highlighted as a key benefit across all the sectors examined.

Evidence relating to the costs of industrial symbiosis is less readily available in the literature and from our stakeholder interviews than evidence relating to benefits. Stakeholders identified the following costs as particularly relevant, with some variation across sectors:

- The **time and resources** required to investigate and secure symbiotic partners and contracts.
- **Transportation costs**, which were seen as particularly significant where by-products are low value, bulky and/or difficult to transport, such as in the chemicals, agriculture, food and drink, and cement sectors. In addition, some stakeholders in the cement and mining sectors also mentioned a modal shift from rail to road transport (e.g. in the case of waste-derived fuels), which also contributes to higher emissions.
- Investment in **new equipment or production processes**, which can be substantial.
- The cost of obtaining **regulatory permits and approvals**, especially in terms of the significant time and resources required. These costs were highlighted as a key issue by most stakeholders across all the sectors examined.

1 Introduction

This is the final report for a study we carried out for the Department for Energy Security and Net Zero (DESNZ) on the potential for industrial symbiosis in the UK.

The aim of the research is to support policymakers in developing policies to encourage industrial symbiosis. The outputs of this work will guide policy teams towards the most effective interventions to encourage industrial symbiosis, including managing any risks, by providing information on the potential for industrial symbiosis and the associated drivers, barriers, risks, costs and benefits.

To enable us to carry out in-depth analysis within the scope of the project, our evidence gathering and analysis focuses on six sectors, namely cement, glass, mining, chemicals, food and drink, and agriculture.

1.1 Our Approach

1.1.1 Definition of industrial symbiosis

We draw on the definition of industrial symbiosis as set out in the CEN[1] Workshop Agreement to focus our literature review and wider research and analysis. This defines industrial symbiosis as "*the use by one company or sector of underutilised resources broadly defined (including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer.*"[2]

This definition draws out some key aspects of industrial symbiosis, such as: reusing under-utilised resources (e.g. waste); information opportunities (e.g. data on other organisations' resources or new technologies); and the importance of resource use duration. For the purposes of this study's scope, we restrict our analysis to certain resources, namely waste, by-products, residues, energy and water, and do not focus on other resources (e.g. surplus capacity and expertise).

Our working definition of industrial symbiosis includes recycling only to the extent that it is part of the process of transforming a waste- or by-product directly produced by one industry into a resource that can be used by another. The European Commission report (2018) states that industrial symbiosis can involve recycling, but it is much wider in scope that just recycling. For example, intermediate steps might be needed to prepare or treat some materials before a transaction or synergy can take place. Upgrading the materials, cleaning, refurbishment or sometimes recycling might be necessary before the by-products or flows are consumed again. Industrial symbiosis is not simply an alternative way of dealing with waste, but a systems

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[1] European Committee for Standardization.

[2] CEN Workshop Agreement. (2018). Industrial Symbiosis: Core Elements and Implementation Approaches. [link]

approach aimed at keeping resources within productive use for as long as possible.[3] In line with our sector approach to industrial symbiosis, our definition limits the application of recycling to waste- and by-products directly produced by an industry, and not – for example – the recycling of consumer or household waste to be used in a production process, as this does not involve direct cooperation or networking between the producer and user sectors.

1.1.2 Selection of sectors for investigation

We selected six sectors to form the core of our analysis, which enabled us to conduct in-depth research into industrial symbiosis whilst containing the overall scope of the study. These include sectors that predominantly[4] send by-products to other sectors; those that predominantly receive by-products; and those that do both.

- Cement (receiving)
- Glass (receiving)
- Mining (sending)
- Chemicals (both)
- Food and drink (sending)
- Agriculture, including controlled environment horticulture (both)

We selected the six sectors based on an initial review of data and literature, and discussions with DESNZ. At the outset of the project there was the possibility of a second phase to quantitatively model the potential for and impacts of industrial symbiosis (which was not undertaken due to insufficient data). Some of the selection criteria therefore relate to data availability. We created a long-list of potential sectors and applied the following criteria to select six sectors for detailed analysis:

- **Significant (and lasting) potential for industrial symbiosis**. Sectors with the biggest potential for industrial symbiosis in terms of scale of benefits (e.g. energy and emissions reductions, economic benefits) and deliverability.[5]
- **Good availability of information.** Sectors with a reasonable availability of literature, information and/or industry contacts to facilitate a deep dive case study.
- **Good mapping onto the Standard Industrial Classification (SIC).** Sectors which map well onto economy-wide data (e.g. on gross value added (GVA), energy consumption, emissions).

In addition, the overall selection of six sectors had to pass the following criteria:

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[3] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[4] There are typically opportunities for both sending and receiving across all sectors, but we focus on the predominant direction of resource flows.

[5] By way of example, our consideration of lasting might lead us not to select sectors where present material flows are likely to disappear over time (e.g. due to decarbonisation or changes in technology).

- **Balance of sending and receiving sectors.** The overall selection needed to include a balance of sectors that ‘send’ waste and by-products and that ‘receive’ them (noting that some may do both).
- **Balance of established and emerging scope for industrial symbiosis.** Sectors in which industrial symbiosis is reasonably established and proven as well as ‘newer’ sectors with anticipated potential.

1.1.3 Literature Review

We undertook a review of relevant literature (around 85 sources) to build a detailed understanding of the barriers and drivers, the technical potential, impacts, costs/cost savings and risks of industrial symbiosis. This was conducted in two parts:

- The first phase of the review covered industrial symbiosis at a general level, using examples from a range of sectors and use cases, drawn from the UK and overseas jurisdictions.
- The second phase focused on the six chosen sectors, with an initial review to identify the chosen sectors followed by an in-depth review to identify and collate evidence and data relating to actual or potential industrial symbiosis and associated drivers, barriers and impacts in those sectors.

We first identified a long-list of sources covering the research areas, and then refined these into a short list using the following criteria:

- In selecting the sources for the **general review** we focused on those with a robust analysis of drivers, barriers, technical potential, impacts and risks across a wide range of sectors, prioritising those that incorporate analysis of other papers (such as systematic reviews).
- For the **sector-specific papers** we prioritised those based on UK examples (although we considered other jurisdictions where UK evidence was limited); those as closely related to our chosen sectors as possible; and those with good data and information about the potential for industrial symbiosis, the costs, cost savings and other impacts.
- For **both parts** of the review we applied general selection criteria, namely that the literature must have been published in peer-reviewed journals or by trusted organisations, and that it must be recent (e.g. within the last 10 years). In areas where information was limited (e.g. a particular research theme for a certain sector), we also included sources older than 10 years.

1.1.4 Stakeholder engagement

We drew on academic and industry experts to gather further evidence on the research questions. The aim was to gather UK-specific evidence on industrial symbiosis given the relative lack of UK-specific sources in the literature.

General interviews. We held five interviews with academics and industry experts towards the beginning of the study to obtain an overview of the key issues relating to industrial symbiosis and guidance on our further research. These general interviews enabled us to gather views on industrial symbiosis from experts with practical experience of industrial symbiosis, providing a broader view than the six chosen sectors.

Sector-specific interviews. We conducted 25 interviews with trade associations, industry experts, research institutes and companies across the six chosen sectors to gather evidence across the research questions, with the number of interviews per sector as follows:

- Cement (4)
- Glass (3)
- Mining (4)
- Chemicals (6)
- Food and drink (4)
- Agriculture (4)

The aim was to gather practical information direct from companies on their involvement with industrial symbiosis, as well as broader views on actual and potential industrial symbiosis in their sectors.

Focus groups. We held two focus groups with academics and industry experts across a range of sectors to receive feedback on our emerging findings from the literature and interviews conducted to date.

- **Focus Group 1** covered our findings on the drivers, barriers and risks of industrial symbiosis. The material presented included our draft scores for the importance of drivers, barriers and risks, as well as our scores for the quality of the evidence available.
- **Focus group 2** covered our findings on the technical potential and costs and benefits of industrial symbiosis.

1.2 Structure of the report

The report is structured as follows:

- Chapter 2 provides an overview of the six chosen sectors.
- Chapter 3 presents the literature and stakeholder evidence on the opportunities for industrial symbiosis.
- Chapters 4 – 8 cover the literature and stakeholder evidence on the drivers, barriers, risks, costs and benefits of industrial symbiosis.
- Chapter 9 concludes.

2 Overview of the Chosen Sectors

2.1 Introduction

In this section we present a brief overview of the six chosen sectors. Together, these sectors account for a significant proportion of the UK's economic activity, resource use and emissions, as shown in the tables below.

Table 2.1: GVA and Employment for chosen sectors (2021/2022)

Sector	GVA (£m)	Employment (total jobs)
Cement and concrete[6]	3,604	74,000
Food and drink	35,918	418,800
Agriculture	17,546	513,000
Glass	1,600[7]	27,900[8]
Chemicals	17,621	52,200
Mining[9]	14,000	50,000 - 60,000

Source: Unless otherwise indicated, GVA: ONS Regional Gross Value Added (balanced) [link]; Employment: ONS Business Register and Employment Survey (2023) [link]

Table 2.2: Environmental Indicators for chosen sectors

Sector	Electricity used (Mtoe, 2022)[10]	Gas used (Mtoe, 2022)[11]	Oil used (Mtoe,2022)[12]	CO2 emissions (Thousand tonnes, 2021)[13]
Cement	0.390*	0.258	0.088	8,261
Food and drink	0.958	2.253	0.457	7,459
Agriculture	n/a	0.176	2.180	8,340

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[6] GVA and employment estimates for 2022 from MPA. (2023). Profile of the UK Mineral Products Industry. [link]

[7] Data from 2019 study in BEIS. (2022). Alternative Fuel Switching Technologies for the Glass Sector: Phase 3. [link]

[8] ONS employment for SIC code. (2023). 110-190. [link]. Note that British Glass estimated employment as 6,000 in 2019, most likely using a different sector definition. [link]

[9] Extractive Industries Transparency Initiative (EITI). Sector introduction. [link]

[10] DESNZ (2023) "Energy Consumption in the UK (ECUK): Final Energy Consumption Tables" Table C3 [link]

[11] ONS (2024): "Energy use by industry, source and fuel, 1990-2022" [link]

[12] ONS (2024): "Energy use by industry, source and fuel, 1990-2022" [link]

[13] ONS. (2024). Atmospheric emissions: greenhouse gases by industry and gas. [link]

Glass	0.390*	0.883	0.007	3,746
Chemicals	1.225	2.908	0.157	9,482
Mining	n/a	0.152	0.497	1,266

*Note: ONS data only available for SIC 23 “Manufacture of other non-metallic mineral products”

2.2 Cement and concrete

Our in-depth analysis focuses on the cement sector, but we also consider the role of concrete. The **cement and concrete sectors** play a crucial role in the UK economy, providing essential materials for infrastructure development, construction and various other sectors. There are currently ten manufacturing plants and two grinding and blending facilities producing cement in the UK. These facilities produce approximately 10 million tonnes of Portland cement (the most common type of cement) annually, about 78 per cent of the total cement sold in the UK market.[14] The industries are concentrated in the Midlands, Wales, North West England, Scotland, and Northern Ireland, with some presence in North East England.[15]

Box 2.1: Production of cement and concrete

Cement production uses naturally occurring calcareous deposits such as limestone, marl, or chalk which provide calcium carbonate. Raw materials are blended and exposed to high temperatures in a rotating kiln, triggering a chemical reaction that produces clinker while emitting CO2. For every tonne of pure cement produced, 0.6 tonnes of CO2 is emitted.[16] Around 60 per cent of these emissions result from the calcination of the raw materials, and 40 per cent from combustion of fuels to generate energy.[17] Following this, the clinker is cooled and finely ground, then combined with a small amount of gypsum to produce cement.

Cement serves as a binding agent, and when combined with water, sand and gravel (or other aggregates) it produces concrete.

2.3 Glass

The UK is a large producer of glass products, manufacturing approximately 3.5 million tonnes of glass products in 2019. Products include flat glass utilised in the construction and automotive sectors, container glass suitable for bottles and jars, glass fibre for reinforcement and insulation purposes, and specialised hollow glass products crucial for laboratories and medical research.[18] There are three major flat glass manufacturers and six glass container

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[14] Mineral Products Association. (2019). Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility. [link]
[15] Mineral Product Association. (2023). About Us. [link]
[16] Morgado, A., Hugues, P., & Vass, T. (2023). Cement. International Energy Agency. [link]
[17] Portland Cement Association. Carbon Footprint. [link]
[18] British Glass. Glass products. [link]

manufacturers in the UK, located in North East England, North West England and Scotland, with some presence in Northern Ireland.

Box 2.2: Glass production

Glass production uses primary input materials like silica sand, soda ash, limestone and dolomite, as well as cullet (recycled glass). Soda ash is the most energy intensive raw material used in the production process.[19] These materials are mixed together and melted in a furnace at temperatures of 1,500 degrees Celsius. The majority of carbon emissions (75 – 85 per cent) stem from the combustion of fossil fuels, predominantly natural gas, with the rest (15 – 25 per cent, depending on the recycled content) arising from the decomposition of raw materials.[20]

Glass is fully recyclable, with nearly a 100 per cent potential recycling rate. Waste glass in the UK has a 74 per cent recycling rate as of 2021, among the highest of any packaging material.[21] The use of recycled glass cullet (offcuts and broken glass) significantly reduces energy consumption compared to primary materials. Pre-consumer glass cullet, formed during the manufacturing process in other industries, are particularly significant for industrial symbiosis as these are directly produced by a manufacturing process rather than being end-of-life recycled waste.

2.4 Mining

The mining and quarrying sector encompasses both the mining of raw materials and the extraction of crude oil, petroleum, and natural gas, including: [22]

- Construction minerals, such as aggregates, brick clay and raw materials for cement (the largest bulk market among non-energy minerals).
- Industrial minerals, such as kaolin, ball clay, silica sand, gypsum, potash, polyhalite, salt, industrial carbonates, fluorspar and barytes.
- Metal minerals, such as tungsten and gold.
- Energy minerals, such as coal and natural gas.

We focus on the mining of raw materials, in particular metals and industrial minerals, in order to contain the scope of the case study. Choosing this area of focus helps to ensure that our research will continue to be relevant in the future, as there is likely to be increasing demand for industrial minerals and metals. It was also our intention to consider the opportunities associated with historical mining waste (e.g. the extraction of metals).

Within the UK, **tungsten** (wolfram) is the primary extracted metal mineral. England has the world's fourth-largest known tungsten deposit, about 10 per cent of the world's known

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[19] Hartwell, R., Coult, G., & Overend, M. (2022). Mapping the flat glass value-chain: a material flow analysis and energy balance of UK production. Glass Struct Eng, 8, 167–192. [link]
[20] BEIS. (2022). Alternative Fuel Switching Technologies for the Glass Sector: Phase 3. [link]
[21] Recycling rate refers to DEFRA 2021. (2023). Packaging waste recycling data, in UK statistics on waste. [link]
[22] Extractive Industries Transparency Initiative (EITI). Mining & Quarrying in the UK. [link]

reserves, situated at the Drakelands Mine near Plympton, Devon.[23] **Industrial minerals** extracted in the UK have diverse applications. For example, silica sand and limestone are primarily used in glassmaking, cement, and iron and steel manufacturing. Kaolin, ball clay and potash have significant international markets.

Box 2.3: Mining by-products

The various mining sectors yield a spectrum of by-products, including:

- quartz- and lignite-rich ball clay;
- intrabasaltic laterite;
- carbonate-rich tailings from fluorspar processing;
- shale and sandstone remnants from limestone quarrying;
- quartz- and mica-rich tailings originating from kaolin processing;
- residuals from sand and gravel processing;
- ultrafine quartz-rich tailings are a by-product of silica sand processing; and
- tailings from tungsten processing.

The majority of mineral waste generated by mining stays within the quarry or mine site where it is produced, and is commonly used to construct haul roads and screening bunds, and to fill voids and restore the site to fulfil the conditions of the mine's planning permission. In the UK, mineral waste is exempt from the Aggregates Levy provided it is not commercially used and remains on-site.[24]

2.5 Chemicals

The chemicals sector underpins a significant proportion of manufacturing, providing chemical materials and products to a range of industries such as aerospace, construction, automotive manufacture, pharmaceuticals and consumer products. The range of chemical outputs includes petrochemicals, polymers, agrochemicals, paints and personal care. In order to contain the scope of the research, we focus on the production of base chemicals, where replacing fossil feedstocks with waste products is a core opportunity for industrial symbiosis.[25]

The chemicals sector is very clustered, especially the upstream sector (manufacture of base-commodity organic chemicals) which is clustered around areas of the UK where core feedstocks such natural gas enter the UK. The clustering of the chemicals sector also reflects

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[23] Extractive Industries Transparency Initiative (EITI). Mining & Quarrying in the UK. [link]

[24] Mitchell, C., Bide, T., & Petavratzi, E. (2024). Fuelling the Foundation Industries: Discovering the Hidden Value of Mineral Waste in the UK. Materials Proceedings, 15(1), 80. [link]

[25] These subsectors correspond to the SIC codes 20.11 and 20.13 (excluding petrochemicals, pharma and fertilisers which fall under SIC codes 20.14 and 20.15).

the legacy of ICI, which built many sites and plants close together. The industry can be divided into three broad tiers, as follows.[26]

- **Tier 1** consists of companies processing feedstock into bulk commodity chemicals (e.g. ammonia, ethylene, propylene and BTX). The production of these high-volume basic chemicals is located in the North East and West of England, and in Scotland (Grangemouth).
- **Tier 2** consists of companies that take part in the intermediate step of the manufacturing process and often (but not always) use the basic chemicals from tier 1 to undertake further reactions. These processes take place across the UK.
- **Tier 3** activities include the manufacturing of high-value finished products such as pharmaceuticals and agrichemicals. These sites are prominent in the South and South-East.

Our sector focus (production of base chemicals) covers elements of Tier 1 and Tier 2.[27]

Box 2.4: Basic production of chemicals

The chemicals sector is the highest energy consuming industrial sector, which can be attributed to the fact that in around half of the chemical industry's subsectors energy input is consumed as feedstock.[28] Oil and natural gas are currently the main feedstocks used, as they are the sources of both carbon and hydrogen and are used to produce basic chemicals such as ethylene, propylene and ammonia. The initial stages of chemical manufacturing processes are typically the most energy intensive, as large volumes of raw material are extracted and converted into primary products.[29] The raw materials used to produce primary chemical products are crude oil, natural gas, metal and mineral ores, sodium chloride and animal or vegetable fats.[30]

2.6 Food and Drink

The food and drink industry is the UK's largest manufacturing sector by turnover, with GVA reaching £115.2 billion in 2021.[31] The sector has a range of subsectors, which include the processing and preserving of meat and production of meat products, the manufacture of grain mill products, and the production of soft and alcoholic drinks.[32] It is estimated that 97 per cent of UK food and drink manufacturing businesses are small to medium sized enterprises (SMEs), although SMEs only account for 22 per cent of the industry's turnover.[33]

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[26] Department for Energy Security and Net Zero (DESNZ). (2024). Unlocking Resource Efficiency – Phase 2 Chemicals. [link]

[27] The production of base chemicals corresponds to SIC codes 20.11 and 20.13.

[28] Cefic. Chemical Industry Snapshot. [link]

[29] Science Based Targets. (2023). Science Based Targets in the Chemicals Sector: Status Report. [link]

[30] The Manufacturers' Organisation. (2017). Sector Bulletin: Chemicals. [link]

[31] Department for Environment, Food and Rural Affairs. (2024). Food statistics in your pocket. [link]

[32] The subsectors correspond to the following Standard Industrial Code (SIC): 10-12. ONS data show that SIC code 10 "Manufacture of food products" is largest subsector, contributing 1.1 percent of UK GVA in 2021.

[33] Department for Environment, Food and Rural Affairs. (2024). Food statistics in your pocket. [link]

Food and drink manufacturing has a strong presence across the whole of the UK. Many of the largest food and drink manufacturers are located in London. Yorkshire and the Humber is the largest food and drink manufacturing region in the UK based on employees, and is the second largest based on turnover. Scotland is the third largest region by food and drink turnover and production.[34,35]

Box 2.5: Key inputs and by-products

Inputs to the sector include agricultural produce such as grains, fruits, vegetables, and livestock. These materials undergo various processing stages such as heating and cooling, processing (e.g. milling or baking) and refrigeration, which are energy intensive.[36] Carbon dioxide is also a key input, as an integral component of any carbonated drink. Food and drink manufacturing processes generate a range of waste and by-products such as food waste, meat processing and packaging waste, and other organic waste.[37]

2.7 Agriculture

This chosen sector covers agriculture as a whole, with an additional focus on Controlled Environment Horticulture (CEH) which is considered a particular candidate for industrial symbiosis. Agriculture is a key sector in the UK and produces a range of products including cereals, vegetables, fruits, dairy products and meat. The sector is comprised of companies ranging from small family-owned farms to large firms and agribusinesses.

In 2022, nearly a quarter of all agricultural holdings and a fifth of England's total farmed area was based in the South West.[38] Dairy, cattle and sheep farming are predominantly located in the South West due to the warm and wet climate. Additionally, the warm summers and flat land makes the east suitable for cropping, and 26 per cent of cereals and 64 per cent of sugar beet are grown here. Vegetables, horticulture and potatoes, and pigs and poultry also have high value outputs in the East.[39]

Box 2.6: Key inputs and by-products

The main inputs to the industry include materials such as seeds for animal feed, fertilisers, pesticides, manure and machinery, which are used to produce outputs such as food, livestock or other agricultural products for consumption.[40] Waste or by-products may include unused portions of crops, livestock, compost and packaging materials. Many of the inputs are sourced from non-renewable resources – for example, nitrogen for

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[34] Evolve UK. (2020). UK Food and Drink Manufacturing Sector — Overview, Trends and Opportunities. [link]

[35] The Manufacturers' Organisation. (2017). Sector Bulletin: Food and Drink. [link]

[36] Ladha-Sabur, A., Bakalis, S., Fryer, P.J., & Lopez-Quiroga, E. (2019). Mapping energy consumption in food manufacturing. [link]

[37] Ladha-Sabur, A., Bakalis, S., Fryer, P.J., & Lopez-Quiroga, E. (2019). Mapping energy consumption in food manufacturing. [link]

[38] Stewart, I., Uberoi, E., & Coe, S. (2023). Agriculture in the South West. UK Parliament. [link]

[39] DEFRA. (2022). Agriculture in the UK Evidence pack. [link]

[40] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]

inorganic fertilisers. Producing nitrogen fertilisers also uses large amounts of natural gas and coal, and can account for more than 50 per cent of total energy use in commercial agriculture.[41] Depending on the cropping system, oil accounts for between 30 and 75 per cent of the energy used in UK agriculture. However, the nutrients required for inputs such as animal feed and some fertilisers can be sourced sustainably from organic waste.

CEH is a sub-sector of agriculture, sometimes referred to as vertical or indoor farming. It entails the use of structures such as glasshouses, polytunnels or “plant factories” to create fully controlled environments for plant growth, sealing off the external environment, along with the provision of all necessary elements for growing crops such as water, appropriate temperature, humidity, ventilation, light, and CO_2.

In the UK, CEH involves cultivating high-value crops such as tomatoes, peppers, cucumbers, and berries in glasshouses and polytunnels, covering about 798 hectares for protected vegetables and 217 hectares for soft fruits. This sector, while only representing about two per cent of the total productive horticultural land, is vital for extending the growing season and contributed 262 thousand tonnes of produce with a market value of £374 million to the UK’s domestic market in 2021.[42]

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[41] Woods, J., Williams, A., Hughes, J.K., Black, M., & Murphy, R. (2010). Energy and the food system. Philosophical Transaction of the Royal Society. [link]

[42] DEFRA R&D Report. (2023). Foresight study to compare the relative gains, costs, feasibility and scalability of current and future ‘industrial horticulture’ models. [link]

3 Industrial Symbiosis Opportunities

In this section, we describe the opportunities for industrial symbiosis (both current opportunities and those that are new or under development), drawing on literature and stakeholder evidence for our chosen sectors. We begin with by giving an overview of what the general literature says on estimating the potential for industrial symbiosis, and later in the section present stakeholder views on trends that may affect the potential for industrial symbiosis in the future.

3.1 Estimating the potential for industrial symbiosis

Studies we have reviewed either measure current examples of industrial symbiosis or attempt to estimate potential industrial symbiosis. The literature tends to focus on specific examples of industrial symbiosis, such as for a single sector, material flow, or localised area like an industrial park. Aggregated estimates of industrial symbiosis – either existing or potential – across countries as a whole or across economic areas are less common.

3.1.1 Sectors with the highest potential

The SCALER project investigated potential synergies across Europe and highlighted the main sectors in which potential benefits can be achieved through industrial symbiosis. Among sectors that send waste and by-products to others, the steel sector (which sends slag and coke-oven gas) and the waste treatment sector (which sends prepared fuel) were identified as having significant potential. The cement industry (receiving from the steel sector) and various other sectors receiving prepared fuels from the waste treatment industry emerged as key receiving sectors.[43] In a systematic review by Neves et al., manufacturing was identified as the predominant sector in the 103 cases of potential symbiosis explored, accounting for 63 per cent of total cases across all sectors. Other sectors with a high number of cases of potential symbiosis were agriculture, forestry and fishing, electricity and water, and waste management and recycling. Within the manufacturing sector cases, the most commonly cited economic activities were chemicals, iron and steel, pulp and paper, construction materials, and wood and wood products.[44] The opportunities for industrial symbiosis are explored in more detail in the following sections on our chosen sectors. As described in Chapter 2 these sectors were selected against a number of criteria including, but not limited to, the potential for industrial symbiosis.

3.1.2 Aggregate estimates of industrial symbiosis potential

The SCALER report represents one such attempt to measure and quantify the broad potential for industrial symbiosis. It evaluated 38 of the most impactful potential synergies across Europe and estimated that, if they were fully implemented, they would involve over 300 million

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[43] Quintana, J., Chamkhi, R., Bredimas, A. (2020). Quantified potential of industrial symbiosis in Europe. SCALER. [link]

[44] Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., & Matias, J.C.O. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. Sustainability, 11(24), 7095. [link]

tonnes of material and would save 91 million tonnes of CO_2, 1.5m TJ of energy, and 2.5 billion cubic meters of water per year, and result in an of increase 24 billion PDF.m2.y (a measure for ecosystem quality). The report estimated that around 85 per cent of this potential has already been implemented.[45]

There are very few sources specifically quantifying the potential for industrial symbiosis across the UK (our sector-specific sections below report estimates for various sectors). Three key sources are summarised below.

The National Industrial Symbiosis Programme (NISP). During the programme's first five years of operation in England, it was estimated that over seven million tonnes of waste were diverted from landfill (including 0.363 million tonnes of hazardous waste), more than five million tonnes of CO_2 and just over 9.5 million tonnes of water were saved, while virgin material savings (measured in tonnes per year of raw materials saved by increased efficiencies/changes to a more sustainable material) were reported to be around 9.7 million.[46]

The West Midlands Industrial Symbiosis Programme (WMIS) has the aim of initiating industrial symbiosis opportunities in the West Midlands region. In the West Midlands, 7.4 million tonnes of waste are being sent to landfill each year, and it is estimated that the WMIS could help divert a minimum of 17,000 tonnes a year, as well as achieving CO_2 savings of 6,000 tonnes per year at a minimum. Additionally, between 1.2–2.0 million tonnes of water are expected to be saved annually as a result of the programme.[47]

A report for the **European Commission** (2018) on industrial symbiosis across the EU estimated a maximum potential annual saving of €72.7bn from landfill diversion (€7bn for the UK), or a maximum value from transactions of secondary materials of between €6.9bn and €12.9bn per year across the EU. The report notes that due to data limitations this estimate does not account for the upstream market potential of resources not becoming waste, such as by-products transactions and reuse/recirculation of materials [48]

3.1.3 Challenges in estimating the potential for industrial symbiosis

The literature highlights the challenges of estimating volumes of, and potential for, industrial symbiosis. For example, the report for the European Commission reviewed a wide range of sources and concluded that there is very little quantitative evidence on the potential for industrial symbiosis, in particular in relation to its potential value. The report finds that the estimates that do exist are for specific sectors or programmes (such as NISP), and that it is not possible to robustly scale these up to a national or international level given very different baselines and economic, environmental and industrial contexts.

Further challenges are noted in measuring the potential for industrial symbiosis, which include a lack of data on the flow and use of by-products before they are classified as waste; lack of

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[45] Quintana, J., Chamkhi, R., Bredimas, A. (2020) Quantified potential of industrial symbiosis in Europe. SCALER. [link]

[46] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report. [link]

[47] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Business Case.

[48] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

data on the costs and material losses involved in re-processing waste and by-products for re-use, and also on the technical and infrastructure-related limitations to the re-use of some waste and by-products; and fluctuations in the demand for and supply of waste and by-products not captured by the data.[49]

Furthermore, the sources we have reviewed that measure the volume and benefits of industrial symbiosis in different sectors are technical and focus on detailed material flows to examine how a waste- or by-product is produced, in what quantities it is available, its properties and qualities, how it could be re-used, and by which sectors that could use it, focusing on specific production processes. Life cycle assessment methodologies are often used which are specific to the specific material and context.[50]

3.1.4 Measurement metrics

The volume of, and potential for, industrial symbiosis is measured in the literature through the use of various metrics. For example, the European Commission (2018) estimates the **volume of waste** that could potentially be recovered through industrial symbiosis (and diverted from landfill or incineration), and estimates a monetary value for each waste stream. The SCALER project modelled (among other things) the **volume of materials that could be directed to re-use**, which has the advantage of capturing by-products before they are classified as waste.

Many of the sources we reviewed focused on metrics that are better described as benefits, such as **CO_2 and other GHG reductions**, **energy and water savings**, or (in some cases) the **monetary values** of exchanges.

The choice of metric for measuring and monitoring industrial symbiosis potential is likely to vary according to the purpose of the exercise. Metrics that measure the **volume of industrial symbiosis** – such as the reduction in waste landfilled or incinerated, or the volume of by-products re-used – would capture the core activity of industrial symbiosis in terms of keeping resources in use for longer and reducing waste. Metrics that measure the **impacts of industrial symbiosis**, such as GHG reductions, would provide a closer focus on other benefits of industrial symbiosis, which may be useful to policymakers to ensure that industrial symbiosis is delivering specific benefits rather than simply being an end in itself.

3.2 Cement and Concrete

This section summarises the opportunities for industrial symbiosis in the cement and concrete sector. The sector is predominantly a receiving sector. We distinguish between waste materials and by-products that can be used in cement production and waste materials that can partially replace cement in the production of concrete.

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[49] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[50] Life cycle assessment (LCA) is a standardized methodology used to address the potential environmental impacts throughout a life cycle extending from raw material extraction through production, use, end-of-life treatment, recycling, and final disposal.

3.2.1 Cement as a receiving sector

The literature and the stakeholders we interviewed identified a wide range of by-products that can be used in the production of cement.

Waste fuels can be used to replace some traditional fuels to fire the kilns. Dried sewage sludge, meat and bone meal and RDF (refused derived fuel) are all alternatives to conventional fuels in cement production, promoting sustainability and reducing environmental impact.[51] The mix of fuels used needs to be carefully calibrated as the mineral content of some of these fuels can affect the quality of the cement. A stakeholder notes that the substitution rate for waste-derived fuels in some UK cement plants can be around 75 per cent on average (with a substitution rate above 90 per cent at one plants), which is considered high by UK standards. Heidelberg Material successfully trialled a net zero fuel mix at their cement kiln, and found that the fuel could potentially reduce CO_2 emissions by nearly 180,000 tonnes annually compared with traditional coal usage.[52] In addition to ongoing research by companies, the industry as a whole is closely monitoring the emergence of new waste streams that could potentially be used, such as wind turbine blades, the ceramic content of car batteries, and photovoltaic (PV) panels.

The Mineral Products Association's (MPA) roadmap for the concrete and cement industry aims for net zero emissions by 2050. It plans to source 70 per cent of the sector's thermal input from waste biomass and 30 per cent from fossil fuels, reducing emissions by 16 per cent compared with 2018,[53] which equates to a reduction of 1.3Mt CO_2 per year.[54]

The sector currently uses two major **alternative materials** to act as SCMs: ground granulated blast-furnace slag (GGBS, a by-product of steel making) and fly ash (waste generated from coal fired power generation). SCMs reduce the use of clinker in cement production, allowing the clinker-to-cement mass ratio to be reduced below its historical level of 0.75.[55] As the process used to manufacture clinker is carbon-intensive, this significantly reduces embodied carbon.[56] However, the use of both of these materials are in decline as a result of steel producers switching to electric arc furnaces and a move towards renewable energy generation, and stakeholders stated that the cement sector is looking for alternatives.

Despite a global production of approximately 3.5 billion tonnes of SCMs in 2018, current use is relatively low and mainly restricted to GGBS and coal fly ash. This indicates a substantial potential for greater adoption of alternative SCMs to replace clinker in cement production

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[51] Ramsheva, Y. K., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. In 1st International Conference on Technologies & Business Models for Circular Economy, 35-54. [link]

[52] Heidelberg Materials. Hydrogen Trial. [online]

[53] Mineral Products Association. (2020). UK Concrete and Cement Industry Roadmap to Beyond Net Zero.[online]

[54] Mineral Product Association. (2023). Delivering Net Zero UK Cement. [CONFIDENTIAL – SENT BY DESNZ]

[55] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [online]

[56] Ren, Z., & Li, D. (2023). Application of steel slag as an aggregate in concrete production: A Review. Materials, 16(17), 5841. [online]

across different countries. In the UK, coal fly ash and GGBS currently constitute around 20 per cent of the mixture.[57]

Shah et al. (2022) found that UK has the potential to produce SCMs in quantities similar to or greater than its national cement production.[58] Shah et al. (2022) found that SCM mixtures can allow manufacturers to achieve an average clinker-to-cement mass ratio of 14 per cent globally, equating to a reduction of around 61 percentage points from 2018 levels, provided that the resulting binders are suitable for concretes and mortars production. Furthermore, a stakeholder expects rising CO_2 emissions prices to boost demand for alternative raw materials, making them more price-competitive than clinker and increasing their use.

The literature and stakeholder interviews have identified a wide range of alternative SCMs that are currently used in cement manufacturing. **Bauxite residue** is a by-product of primary aluminium production from bauxite ore, and can act as a substitute for additional clinker volumes in cement and concrete manufacturing, thereby reducing its carbon footprint.[59]

Box 3.1: Industrial symbiosis at a cement plant in Dunbar

A cement plant in Dunbar (UK) has symbiotic synergies with companies located in its region. The plant produces 1 million tons of cement per year. The plant valorises 20 thousand tonnes of scrap tyres from a tyre manufacturer and 22 thousand tonnes of recycled liquid fuel (RLF) from a waste processing facility as an alternative cement kiln fuel. The plant also utilises about 500 thousand tonnes of fly ash from the local power plant as a clinker substitute and reuses recycled glass/sand from a nearby glass producer as a secondary raw material.

Source: Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). Review of successful IS methods and systems for the cement industry. EPOS. [link]

One stakeholder highlighted the use of **waste sodium bicarbonate** from manufacturing industries as an alternative raw material. Historically, this has been employed in low volumes (typically a couple of thousand tonnes annually) to address low alkali levels in other raw materials used at some plants. The same stakeholder also indicated that it used **synthetic waste gypsum**, which is sourced from waste plasterboard and blended with rock gypsum onsite before being added to cement. In addition, desulfurization gypsum from power stations can substitute for natural gypsum in cement production.[60] However, the closure of coal-fired power stations will reduce this supply.

Another stakeholder mentioned that **basic oxygen furnace slag**, a calcium-rich material also obtained from steel manufacturing, can be used as a partial alternative to natural aggregates in

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[57] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [online]

[58] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [online]

[59] Sourmelis, S., Pontikes, Y., Myers, R. J., & Tennant, M. (2024). Business models for symbiosis between the alumina and cement industries. Resources, Conservation and Recycling, 205, 107560. [online]

[60] Ramsheva, Y. K., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. In 1st International Conference on Technologies & Business Models for Circular Economy, 35-54. [link]

the production of Portland cement concrete. The same stakeholder also stated that recovered **landfilled fly ash** is another by-product that can be used to replace cement.[61] An advantage of using landfilled fly ash is that the reactivation process enhances the carbon sequestration ability of the ash, with the stakeholder reporting a sequestration rate of five per cent. The stakeholder noted that the UK Quality Ash Association estimates that 100 million tonnes of landfilled fly ash can be used in cement and concrete production.

A cement manufacturer also stated that it used alternative raw materials instead of virgin alumina in its production processes. These alternative raw materials include **lagoon ashes** sourced from power stations. Furthermore, iron oxide waste has been recognised as an alternative to cement clinker.[62]

The industry is also exploring alternative SCMs that can be potentially used in the future. For instance, one stakeholder is exploring the possibility of utilising **incinerated bottom ash (IBA)** from waste incineration for energy generation. Research efforts are ongoing, both within industry and research institutions, to find viable applications for IBA.

Stakeholders have also suggested that there is a potential to use other by-products including:

- **Calcined clay**: Clay residue left over from quarrying activities, often treated as waste material.
- **Brick powder**: Residue from brick manufacturing processes.

Stakeholders also mentioned efforts to explore the use of waste from other quarrying sectors, particularly slate quarries which have high waste percentages (around 98 per cent). While not chemically identical to fly ash and shale, slate waste can serve as an alternative raw material to some extent.

Box 3.2: Project to assess the impact of recycled concrete fines

A stakeholder described an ongoing project aimed at reprocessing demolition waste to produce recycled concrete fines. The objective is to use these fines as substitutes for GGBS and fly ash in order to reduce clinker production. Currently, while aggregate from demolition waste is commonly reused, the fine powder component often ends up in landfills. Some companies have developed methods to extract concrete from this fine powder. The process typically involves subjecting the extracted concrete to CO_2 exposure, which strengthens it, followed by calcination to further enhance its properties and contribute to cement strength.

Although there has been some initial exploration in this area, further research is needed to fully understand the properties of recycled concrete fines. It is believed that the temperatures required for calcination may be lower than those needed for clinker production, potentially leading to reduced CO_2 emissions. However, the actual CO_2 savings from this process are currently uncertain, unlike the other two options (GGBS

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[61] This also means that an requires an additional level of collection and processing compared to fly ash obtained from steel production.

[62] Ramsheva, Y. K., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. In 1st International Conference on Technologies & Business Models for Circular Economy, 35-54. [link]

and fly ash) which do not generate CO_2 during production. Nonetheless, diverting this material from landfills contributes to waste reduction efforts.

Source: Stakeholder interview

By-products from different industries can also partially replace cement and aggregates in concrete manufacturing. Iron silicate, a by-product of copper smelting, can replace stone aggregate and clinker, thereby reducing the global warming potential of concrete production.[63] Glass powder, derived from finely ground glass, can partially replace cement, improving the strength of concrete while enhancing its workability. Similarly, recycled glass cullet can serve as a partial replacement for cement, although the literature highlights concerns around the proportion of glass material added, as adding too much could reduce the overall strength of the concrete.[64]

The table below summarises by-products that can be received by the cement sector from other sectors through industrial symbiosis. The table highlights what inputs are being replaced in the cement and concrete manufacturing process. For instance, GGBS replaces some amount of clinker in the final cement product, whereas recycled concrete fines replaces some amount of cement in concrete manufacturing. We highlight where symbiosis is already taking place ("ongoing") and where opportunities are still being developed and/or scaled ("potential").

Table 3.1: By-products that can be received by the cement and concrete sector from other sectors

Replacement Material	Input Replaced	Sending Sector	Status
Basic oxygen furnace slag	Clinker	Iron and steel manufacturing	Ongoing
Bauxite residue	Clinker	Alumina production	Potential
Ground granulated blast-furnace slag (GGBS)	Clinker	Iron and steel manufacturing	Ongoing, in decline
Iron oxide	Clinker	Iron manufacturing	Ongoing
Sodium bicarbonate	Clinker and slag	Manufacturing process	Ongoing
Coal fly ash	Clinker and shale	Coal-fired power stations	Ongoing, in decline
Lagoon ash	Clinker and shale	Power stations	Ongoing
Desulfurization gypsum	Natural gypsum	Power stations	Potential
Waste-derived fuels (e.g. dried sewage sludge, RDF, waste tyres)	Fuel	Water processing and waste management	Ongoing
Meat and bone meal	Fuel	Animal caracasses	Ongoing

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[63] International Copper Association. (2022). No Resources Lost: The Circular Opportunity of Industrial Symbiosis. [online]

[64] Rahman, S., & Uddin, M. N. (2018). Experimental investigation of concrete with glass powder as partial replacement of cement. Civil Engineering and Architecture, 6(3), 149-154. [online]

Paper sludge	Fuel	Recycling factories	Ongoing
Calcined clay	Clinker and cement	Quarrying	Potential
Silica fume	Clinker and cement	Silicon production	Potential
Surplus soil	Stabilise cement	Construction sites	Potential
Brick powder	Cement	Construction sites	Potential
Landfilled fly ash	Cement	Landfill	Ongoing
Recycled concrete fines	Cement	Concrete sector	Potential
Slate	Cement	Slate quarries	Potential

Source: Europe Economics analysis.

3.2.2 Cement as a sending sector

The cement sector also has potential as a sending sector. In particular, by-pass dust, a finely powdered material gathered from the air filtration systems in cement kilns, offers significant potential for industrial symbiosis. This is because it has a high potassium and lime content, and can therefore serve as an alternative to traditional fertilizers and lime, making it valuable for agricultural use.[65] DESNZ (2023) found that no kiln bypass dust is sent to landfills, and is rather returned to the kiln as feedstock, or sold for secondary applications such as agricultural liming, soil stabilization, concrete mix, chemical treatment, and ceramic and brick manufacturing.[66] That said, a cement manufacturer we interviewed noted that it does not currently sell its kiln bypass dust given the costs associated with selling it, although it would be open to exploring such opportunities in the future.

There is also potential for cement manufacturers to send waste heat to other sectors, although the literature notes that re-using heat internally is typically preferred by cement manufacturers as this is the most cost- and energy-efficient use. One exception is the use of excess heat to generate electricity, which can then be transported over greater distances with minimal losses. The benefits of doing this would differ depending on contextual factors such as electricity prices and demand from other sectors.[67]

Cement manufacturers also have the potential to send water from their manufacturing sites to local authorities and industries. For example, Aalborg cement in Denmark was expected to circulate cold water from its own quarry lake to a new regional hospital for district cooling. [68]

The table below summarises by-products that can be sent from the cement sector to other sectors through industrial symbiosis in the UK.

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[65] Cemex. (2023). Cemex partnership with Silverwoods helps close the loop and upvalue nearly 130,000 tonnes of By-Pass Dust for agricultural purposes. [link]

[66] DESNZ. (2023). Unlocking Resource Efficiency - Phase 1 Cement and Concrete Report. [online]

[67] Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). Review of successful IS methods and systems for the cement industry. EPOS. [online]

[68] Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). Review of successful IS methods and systems for the cement industry. EPOS. [online]. District cooling is a centralized system that provides chilled water from a central plant to cool multiple buildings, offering energy efficiency and cost savings compared to individual cooling systems.

Table 3.2: By-products that can be sent from the cement industry

Sending Material	Sending Sector
By-pass dust	Agriculture, chemical, and ceramic and brick manufacturing
CO_2	Agriculture
Excess heat	Electricity generation and heating grid
Cold water	District cooling

Source: Europe Economics analysis.

3.3 Glass

This section summarises the opportunities for industrial symbiosis in the glass manufacturing sector. The sector mostly receives by-products from other industries.

3.3.1 Glass manufacturing as a receiving sector

The literature and stakeholder interviews highlighted **Calumite** – derived from the steel industry – as a key by-product used by the glass manufacturing sector. Calumite is a glassy calcium-alumino-silicate, produced from granulated blast furnace slag, which acts as a substitute for carbonate raw materials. The proportion of Calumite usage varies across manufacturers and depends on factors such as glass colour, glass composition and local raw materials.[69,70]

- In float glass production, Calumite is typically incorporated at a rate of four to eight per cent of the dry sand weight.
- For fiberglass, the typical inclusion level is around 11 per cent of the dry sand weight, and four per cent for glass bulbs and tubes.
- In container glass manufacturing, the quantity of Calumite used varies based on the desired glass colour, ranging from four per cent for clear glass to 30 per cent for amber glass, relative to the dry sand weight, with one stakeholder reporting that it used between 0.6 and 2.8 per cent of Calumite in its production process.

Calumite contains large amounts of calcium, silica, and alumina, which are highly desirable in glass manufacturing, reducing the need for additional carbonates.[71] Furthermore, the melting and refining characteristics of Calumite provide glassmakers with the opportunity to simultaneously enhance glass quality and decrease energy consumption as well as lower CO_2 and NO_x emissions.

A glass manufacturer we interviewed commented that they are considering opportunities to further **increase the use of Calumite**. This will depend on the technical and financial feasibility

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[69] Calumite. What is Calumite? [online]

[70] Calumite. How Calumite is used. [online]

[71] Calumite. Production. [online]

of using more Calumite, such as its impacts on the colour of the glass. The decision to explore the use of more Calumite was driven by the goal of reducing CO_2 emissions.

Box 3.3: Use of cullet in glass manufacturing

Although not directly considered industrial symbiosis, **cullet** (recycled glass) is also used by glass manufacturers as a key input in glass production.

One of the key benefits of using cullet (compared to other inputs) is that no additional energy is required to drive chemical reactions, and thus the replacement of carbonates (such as soda ash, limestone, and dolomite) with cullet leads to a reduction in processed CO_2 emissions.

Cullet represents an opportunity which, although currently under-utilised, could have a significant impact on the future of the glass manufacturing sector and the relevance of other industrial symbiosis. The substantial CO_2 savings potential from cullet in glass manufacturing suggests that using alternative by-products through industrial symbiosis may not offer comparable environmental benefits for the sector. In particular, due to its capacity to replace a higher share of core raw materials compared with alternative by-products, cullet is an effective solution for reducing carbon emissions in glass manufacturing.

However, using cullet in glass production presents minor risks, particularly with secondary cullet, which can lead to contamination and quality issues for specific types of glass. Internal cullet, derived from production waste, is lower risk but is limited in availability.

Source: Europe Economics analysis.

The glass industry is **exploring further opportunities to incorporate additional by-products from other sectors** in the glass manufacturing process, such as alternative fuels. The nature of glass furnaces means that fuel quality is less critical to product quality compared with sectors such as transport or domestic heating. This further enhances the opportunities for the glass sector to receive lower-grade, lower-cost fuels, which could represent economically viable alternatives to natural gas. By-products such as animal waste, agricultural crop residues, forestry waste, and landfill materials such as wood, paper, cardboard, and food have been identified as potential alternative and sustainable fuels for glass production in the UK.[72]

Evidence from our fieldwork on the use of alternate fuels is mixed. Some stakeholders agree that alternate, lower-grade fuels can be used successfully. One stakeholder we interviewed has successfully conducted trials using biomethane, resulting from anaerobic digestion, as an alternative fuel for glass manufacturing furnaces. On the other hand, another glass manufacturing noted the importance of fuel quality in furnace performance, highlighting the need for careful selection of the mix of alternative fuels to avoid any interruption in the furnace which could halt production. The manufacturer highlighted that glass furnaces require a very consistent fuel mix, and that **deviations in the fuel mix used could lead to quality issues**.

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[72] BEIS. (2022). Renewable Waste-Derived Fuels for Glass and Ceramics Manufacturing: Feasibility Study. [online]

Ongoing research is exploring alternative raw materials, such as mineral slags and waste incineration ashes, to replace carbonate raw materials and lower the glass melting temperature, consequently reducing energy requirements.[73]

Another stakeholder indicated that the sector is considering using **biomass ash** (or bio ash) as an alternative raw material, replacing calcium carbonate and potassium in the glass manufacturing process, which could reduce emissions. Currently, the use of bio ash is still being researched by the industry and it is not yet used in production at scale.

The table below summarises by-products that can be received by the glass manufacturing sector from other sectors.

Table 3.3: By-products that can be received from other sectors

Replacement Material	Input Replaced	Sending Sector	Status
Calumite	Dolomite, limestone and silica sand	Steel industry	Ongoing
Cullet*	Dolomite, limestone and silica sand	Glass recycling	Ongoing
Biomass ash	Soda ash	Powerplant	Potential
Mineral slag	Silica sand, soda ash, and limestone	Mining	Potential
Waste incineration ashes	Silica sand, soda ash, and limestone	Waste treatment	Potential
Cattle manure and crop waste	Fuel	Agriculture	Potential
Forestry waste wood	Fuel	Forestry	Potential
Biomethane and low-grade liquid biofuels	Fuel	Waste-to-energy/ anaerobic digestors; agriculture	Potential
Landfill waste	Fuel	Recycling centre and landfill	Potential

* As noted above, the use of cullet in glass production does not directly contribute to industrial symbiosis.
Source: Europe Economics analysis.

3.3.2 Glass manufacturing as a sending sector

In addition to its role as a receiving sector, there are some opportunities for the glass manufacturing sector to send by-products to other sectors.

The glass manufacturing sector has the potential to help achieve **energy savings** by sending waste heat to other sectors. The literature suggests that the **heat generated during the glass manufacturing process** could be redirected to industries with low and medium heating

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[73] British Glass. Glass sector Net zero strategy 2050. [link]

requirements, or used for district heating/cooling.[74] For example, in the US glass manufacturing industry, it is estimated that 30 per cent of the energy used for the glass melting furnace can be lost through flue gas exiting the stack. This means that there is approximately 2.1-2.9 GJ/tonne of potential energy available.[75]

A stakeholder noted that **(waste) heat could be used for electricity production**. However, it was unsure whether any further investment in infrastructure related to the re-use of heat would be economically worthwhile,[76] especially given a potential move to electric furnaces which would mean that no waste heat would be generated.

Furthermore, **low-quality cullet** that is too poor for re-melt (i.e. containing too much of certain non-glass materials) can still be used for a range of secondary applications, such as aggregate, an additive in building materials (including eco-cements and concretes), water filtration and blast cleaning.[77]

One stakeholder is also exploring opportunities to combine **Electrostatic Precipitator Dust** (EP Dust), resulting from the manufacturing process, with digestate from an anaerobic digester to produce biochar. The use of additives like EP dust can improve the efficiency with which the digestate is processed in the digester and improve the quality of the biochar, which aside from its use in agriculture, can also be employed in concrete manufacturing.

Table 3.4: By-products that can be sent to other sectors

Waste By-Product	Receiving Sector	Status
Low-quality cullet*	Aggregates, eco-cements and concretes, water filtration and blast cleaning	Ongoing
Heat	Industries with low and medium heating requirements, or district heating/cooling	Potential
EP dust	Agriculture and concrete	Potential

* As noted above, the use of cullet in glass production does not directly contribute to industrial symbiosis.
Source: Europe Economics analysis.

3.4 Mining

This section summarises the opportunities for industrial symbiosis in the mining sector. **The mining sector is mainly a sending sector**.

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[74] INTERREG – Central Europe. (2019). Waste heat recovery in the glass industry. [online]

[75] Nosrat, A. H., Jeswiet, J., & Pearce, J. M. (2009). Cleaner production via industrial symbiosis in glass and largescale solar photovoltaic manufacturing. In 2009 IEEE Toronto International Conference Science and Technology for Humanity, 967-970. [link]

[76] This is in addition to investment in regenerative furnaces which recover some heat from the exhaust gas which is then re-introduced into the furnace.

[77] British Glass. Recycling. [link]

3.4.1 Mining as a sending sector

Mining by-products can serve as valuable resources for various industries as well as for green technologies. For instance, metals that are found in mining waste, such as lithium, tin, copper and lead, are valuable for modern technologies. Moreover, iron ore tailings can be repurposed in hollow blocks, bricks, paving stones, floor tiles, roller compacted concrete (RCC), cement mixtures and paint production as a filler. The blast furnace slag and fly ash produced in the mining process can be used for construction applications, in which they function as active components, such as supplementary cementitious materials (SCMs). Further, rock overburden can also be used in the construction and concrete sectors.[78] Currently, many of the metals that can be recovered from mining and manufacturing waste (including lithium, rare-earth metals, vanadium and cobalt) are currently imported into the UK.[79]

The literature also suggests that as technology advances over time, the recovery of certain valuable metals from mine solid waste (e.g. iron) could increase due to the mining of lower-grades ores.[80] The decrease in ore grades increases with the volume of mine tailings produced.[81]

At present metal mining activity in the UK is limited to the exploration phase, as there are no active metal mines in operation.[82] Nevertheless, there are thousands of abandoned metal mines across the country (e.g. base metal mines in Scotland, gold and copper mines in Wales and tin mines in Cornwall) containing large amounts of legacy mineral waste.[83] Projects are ongoing to explore the feasibility of metal extraction from mine waste.[84]

According to the British Geological Survey, there are no official figures for the amount of mineral waste (including tailings, fines, oversize, slimes, dust, etc.) produced in the UK. Nevertheless, based on information on mineral production, it estimates that in 2018 the amount of mineral waste produced in the UK amounted to 75 million tonnes.[85]

Efforts are ongoing to open new mines which would also affect the amount of mining by-products available within the UK. For example, a joint venture between a china clay company and British Lithium announced plans to operate a lithium hub within the next five years in Cornwall.[86] One stakeholder we interviewed with plans to open a lithium mine commented that silica sand is expected to be the most voluminous by-product of their mining operations, with plans to extract over 100,000 tonnes annually. Silica sand is primarily used as aggregate, but

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[78] de Freitas, S. M. A. C., Sousa, L. N., Diniz, P., Martins, M. E., & Assis, P. S. (2018). Steel slag and iron ore tailings to produce solid brick. Clean Technologies and Environmental Policy, 20, 1087-1095. [link]

[79] Resource Recovery from Waste. (2018). Making the most of industrial wastes: strengthening resource security of valuable metals for clean growth in the UK. [link]

[80] Makhathini, T. P., Bwapwa, J. K., & Mtsweni, S. (2023). Various options for mining and metallurgical waste in the circular economy: a review. Sustainability, 15(3), 2518. [link]

[81] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [link]

[82] Palumbo-Roe, B., & Colman, T. (2010). The nature of waste associated with closed mines in England and Wales. [link]

[83] Bowell, R. The United Kingdom Has Thousands of Abandoned Metal Mines. SRK News. [link]

[84] For example, see: Royal Town Planning Institute. Potential for metal recovery from mining wastes. [link]

[85] British Geological Survey. Mine waste in the UK. [link]

[86] Gladwell, A., & Dixon, D. (2023). UK lithium mining announced in Cornwall. BBC. [link]

the company is exploring alternative uses, including its use as ballast for offshore wind projects. Another potential application being explored for silica sand is the production of soils.

The same stakeholder highlighted that sulphate of potash (SOP) is also expected to be a crucial "by-product" in their operations due to its chemical-grade quality and established market. Lithium and potash are often found in the same deposits and thus mined together.[87] The UK consumes 16,000 tonnes annually, representing a sizable market opportunity. Buyers of SOP include agriculture or fertilizer companies, potentially through brokers.

Gypsum, primarily used in plasterboard and construction, has also been recognised as a by-product of lithium mining by the same stakeholder. It expects its main customers to be British Gypsum and other European entities. With the decrease in coal-powered fire stations, there will be a security of supply issue for the by-product.

The stakeholder has also recognised other by-products that could be of potential use:

- Amorphous silica – This by-product is not of high purity. It has not been fully characterised yet and will be produced in very small amounts.
- Rubidium, caesium, and aluminium sulphate – Caesium is a metal of high value, but the ratio of caesium to rubidium in the by-products is unfavourable. There is a significant amount of rubidium, which is only used in small quantities by research labs.

The table below summarises by-products that can be sent from the mining sector.

Table 3.5: By-products that can be sent from the mining sector

Mining by-product	By-product of	Receiving Sector	Status
Mine tailings (containing lithium, tin, copper and lead)	Metal mining	EV battery, home energy storage, personal electronics	Ongoing
Iron, tungsten and copper ore tailings	Industrial and metal mining	Concrete, bricks, ceramics, cement and road construction	Ongoing
Rock overburden	Mining (general)	Construction and concrete	Ongoing
Blast furnace slag and fly ash	Mining (general)	Concrete – SCMs	Ongoing
Silica sand	Mining (general)	Aggregates	Ongoing
Sulphate of potassium	Metal mining	Agriculture	Potential
Gypsum	Mining (general)	Plasterboard and construction	Potential

Source: Europe Economics analysis.

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[87] Jamasmie, C. (2018). Lithium boom unlikely to disrupt potash market — analyst. Mining. [link]

3.4.2 Mining as a receiving sector

We did not find any evidence in the literature or from our stakeholders relating to opportunities for the mining sector to receive by-products.

3.5 Chemicals

This section summarises current and potential opportunities for industrial symbiosis in the chemicals sector. The sector is both a sender and receiver of waste and by-products.

Industrial symbiosis has long been integral to the chemicals industry, especially in regional clusters where plants share utilities and trade by-products and feedstocks.[88,89] Stakeholders we interviewed confirmed the importance of symbiotic exchanges, particularly in base chemical manufacturing, where margins are thin and cost and resource efficiency are an important consideration. Industrial symbiosis was particularly prevalent in the UK within large integrated companies (exemplified by Imperial Chemical Industries), but subsequent industry fragmentation has made sustaining this level of symbiosis challenging, as discussed in the barriers section.

3.5.1 Chemicals sector as a receiving sector

Literature indicates that the chemicals sector has potential as a **key receiver of waste and by-products**, particularly from energy-intensive industries, primarily utilizing waste energy from electricity, industrial gas (e.g. gas produced from steel-making), steam, and air conditioning sectors.[90] Stakeholders highlighted the potential for sourcing energy from waste-to-energy plants or biofuels (e.g. sugar cane). Stakeholders noted the chemicals sector can **receive by-product soda ash from steel plants** to assist in the electrolysis of brine as part of the chlorine manufacturing process. The literature also cites the potential to receive slag from the steel sector (although this synergy is not yet fully explored), which could bring about **CO_2 emissions reductions of 0.3 to 0.6 tonnes** for each tonne of slag that substitutes for virgin materials.[91] Additionally**, solvent recycling** was mentioned by stakeholders as an example of industrial symbiosis within the chemicals sector.

Box 3.5: Flue2Chem – Carbon Capture and Utilisation

The £5.4 million Flue2Chem project aims to use waste carbon for manufacturing surfactants in consumer products. Funded by UKRI, the project involves a consortium of businesses, universities, and NGOs. It establishes a four-step supply chain, starting with capturing waste CO2, converting it into surfactant components, and using this to

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[88] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[89] Mendez-Alva, F., Cervo, H., Krese, G., & Eetvelde, G.V. (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. Journal of Cleaner Production, 314,128031. [link]

[90] Mendez-Alva, F., Cervo, H., Krese, G., & Eetvelde, G.V. (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. Journal of Cleaner Production, 314,128031. [link]

[91] Mendez-Alva, F., Cervo, H., Krese, G., & Eetvelde, G.V. (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. Journal of Cleaner Production, 314,128031. [link]

manufacture cleaning products and coatings. This two-year program evaluates the viability of using industrial waste gases for affordable feedstocks, potentially saving 15 to 20 million tonnes of CO2 emissions annually. It exemplifies how industrial symbiosis can potentially create sustainable supply chains through collaborative efforts.

Source**:** Society of Chemical Industry. (2023). Flue2Chem: SCI, Unilever and 13 partners launch £5.4m net zero collaboration project. [link]

The literature and several stakeholders also reported the potential for the chemical industry **to receive CO_2 from foundation industries** through carbon capture (as noted above), which they consider has the potential at a technical level to replace fossil carbon altogether. Carbon capture and utilisation is already under development, but stakeholders note the process of capturing carbon and transforming it into a feedstock that the chemicals industry can use (e.g. ethylene) is not yet ready to be scaled up. A key factor is that transforming CO_2 into ethylene requires a significant amount of (renewable) energy and hydrogen, which is currently not available at the required scale. Other barriers include the costs of the process and gaps in the UK supply chain.

In addition to waste flue gases, the chemical sector can use other waste- and by-products as alternate feedstocks, such as pyrolysis oil derived from recycled tyres, or recycled plastics.[92] [93]

It was also mentioned by a stakeholder that chemical plants can **receive spent catalysts from the automotive industry**, process them and send the components to companies to refine and distribute precious metals to other industries. For example, ferrovanadium (a high-strength low-alloy steel alternative to carbon-based steel recovered from spent catalyst processing) enables a reduction in traditional steel use of 20 to 40 per cent, which can significantly reduce resource use and CO_2 emissions through creating lighter-weight structures.[94]

The chemical industry can also use chemicals and substances obtained from lithium-ion battery recycling – which include lithium, cobalt and nickel – to manufacture new batteries, produce catalysts, create specialty alloys and magnets, and synthesise various chemical compounds.[95]

The table below summarises by-products that can be received by the chemicals sector from other sectors in the UK.

Table 3.6: By-products that can be received from other sectors

Replacement Material	Input Replaced	Sending Sector	Status
Flue-gas CO_2	Fossil CO2	Steel, cement and other large foundation industries	Potential
Sugar cane	Fuel, natural gas	Food manufacturing	Ongoing

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[92] DESNZ (2024) “Unlocking resource efficiency: Phase 2 Chemicals” [link]
[93] The Royal Society (2024) “Catalysing change: Defossilising the chemical industry” [link]
[94] Shell-Amg (n.d) “Spent Catalyst Recycling” [link]

Soda ash	Raw soda ash	Steel manufacturing	Ongoing and potential
Heat/energy	Fuel, natural gas	Electricity, gas, steam and air conditioning	Ongoing and potential
Slag*	Fossil CO2, fuel	Steel manufacturing	Potential
Steel mill Gas	Hydrogen, carbon monoxide	Steel manufacturing	Ongoing and potential

* Slag can be used for thermal heat storage and mineral sequestration of CO_2, which can be used by the chemical industry as feedstock, although this use is still under research.
Source: Europe Economics analysis.

A stakeholder stated that artificial intelligence is a key factor that will affect industrial symbiosis in the sector in the future. In its view, artificial intelligence can identify useful options for chemicals that could be made from by-products, and these options can then be tested and further developed. Advances in biological engineering will also further enable bio-based feedstocks to replace fossil fuels.

3.5.2 Chemicals sector as a sending sector

The literature shows that the chemicals sector can send by-products such as CO_2, hydrogen and sludge to other industries. Alumina refineries have used carbon dioxide produced by the chemicals industry to produce lime, and CO_2 is also supplied by the chemicals sector to the mineral, steel and cement sectors in Europe.[96] The literature suggests that the chemicals industry also has the potential to participate in synergies involving industrial steam networks or district heating networks. Recovering waste heat in the chemical sector could reduce energy consumption by **five to ten** per cent for participating companies, and alternative fuels could save around **20 to 22 GJ** per tonne of waste fuel. An example is the Kalundborg eco-industrial park in Denmark, where a chemicals refinery provides heat to the city. [97]

Greenhouses can also receive waste heat and CO_2 from the chemicals industry. For example, a partnership within the UK's NISP involved a nitrogen producer, Terra Nitrogen, sending CO_2 to a small-scale vegetable grower.[98] Furthermore, stakeholders mentioned the potential for waste gas streams from chemicals plants such as methane to be converted through bioconversion methods into proteins which can then be used as feed for livestock.

The literature considers the potential for the cement sector within a cluster to substitute a primary fuel in a cement kiln with liquid waste fuels (composed of both acid and organic chemicals) from the chemicals industry. In doing so, the cluster would decrease its dependence on non-renewable energy sources, leading to a **projected reduction of**

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[96] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]
[97] Mendez-Alva, F., Cervo, H., Krese, G., & Eetvelde, G.V. (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. Journal of Cleaner Production, 314,128031. [link]
[98] IEMA. (2012). NISP – the symbiotic network. [link]

greenhouse gas emissions of four kilotons of CO_2 equivalent every year, and a reduction in non-renewable energy consumption by 135,000 GJ per year. [99]

Stakeholders confirmed that the chemical sector can sell by-products like spent sulfuric acid, but **stable market demand** is essential for profitability. Due to unreliable or fluctuating waste streams, particularly from large batch processing, companies often find it easier to reuse waste and by-products onsite rather than sell them. [100]

Gypsum, a non-hazardous by-product of titanium oxide manufacturing, is used in industrial soil, construction aggregates, and fertilisers by Venator in Italy. [101] However, the classification of gypsum as waste along with distribution challenges have hindered its re-use. Venator's Malaysian site also produces **copperas**, another titanium oxide co-product, used in animal feed, chromium reduction in cement, and various industrial applications in construction, wastewater treatment, and mining.

The table below summarises by-products that can be sent by the chemicals sector to other sectors.

Table 3.7: By-products that can be sent to other sectors

Waste By-Product	Receiving Sector	Status
CO_2	Aggregates, minerals, steel, greenhouses	Ongoing
Heat	Electricity generation, greenhouses	Ongoing
Liquid waste fuel	Aggregates (and other large foundation industries)	Potential
Methane	Agriculture	Ongoing
Spent sulphuric acid	Steel manufacturing	Ongoing
Gypsum	Aggregates, agriculture	Ongoing and Potential
Copperas	Agriculture, aggregates, wastewater treatment and mining	Ongoing and Potential

Source: Europe Economics analysis.

3.6 Food and Drink

This section summarises opportunities for industrial symbiosis in the food and drinks sector, which is predominantly a sending sector.

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[99] Cervo, H., Ogé, S., Maqbool, A.S., Alva, F.M., Lessard, L., Bredimas, A., Ferrasse, J., & Eetvelde, G.V. (2019). A Case Study of Industrial Symbiosis in the Humber Region Using the EPOS Methodology. *Sustainability*, 11(24): 6940. [link]

[100] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[101] Venator. (2022). Sustainability Report. [link]

3.6.1 Food and drink sector as a sending sector

Evidence from stakeholders and the literature suggests that many opportunities for symbiosis relate to sending organic waste and packaging to other industries, either for composting, for anaerobic digestion for biogas production, or as raw materials for biofuels and biochemicals. For instance, waste bread and bakery residues can be converted into waste-based ethanol for transport biofuels.[102]

Anaerobic digestion for treating food waste and by-products has become well-established in the UK, capable of handling large volumes from the food and drink sector, households, and other industries. WRAP data shows that in 2019, anaerobic digester plants in England had a food waste capacity of 3.2 million tonnes (out of 9.6 million tonnes of total capacity).[103] There is at least 500,000 tonnes of spare capacity at commercial sites and 450,000 tonnes at farm sites.[104]

A key benefit of food industry waste is its biogenic nature (when not in plastic packaging), making it suitable for green energy production, and nutrient-dense fertilisers. One stakeholder we interviewed cited a particular process that cleans biomass generated from food and packaging waste (using steam) and creates a fibrous product which is suitable for a wider range of uses and which generates greater benefits than non-steamed biomass. Potential uses of this product are:

- **Fuel for energy from waste** companies that are currently burning household waste and which will burn the biomass fibre instead (with improvements in energy production).
- **Biochar** from burning the biomass fibre, which can be used by the construction industry as a carbon sink.

The food and drink sector’s high-load wastewater, containing five times the energy needed for its treatment, can also be treated using anaerobic digestion to generate biogas.[105] Industrial waste from milk, coffee, beer, and energy drink production also has significant potential for biogas production.[106]

The **sending of animal waste and by-products** to other sectors has significant potential to generate a range of valuable alternative inputs including biofuel, inputs to fertilisers and energy. However, dealing with the hazardous waste produced can still remain a challenge.[107] Stakeholders confirmed the opportunities associated with meat rendering, which takes animal by-products and turns them into a number of different products. Products can include oils

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[102] Impoco, G., Arodudu, O., & Brennan G. (2021). Industrial Symbiosis: guide for policy making. SymbioBeer. [link]

[103] WRAP. (2020). AD and Composting Industry Market Survey Report 2020 Final Version. [link]

[104] WRAP. (2020). AD and Composting Industry Market Survey Report 2020 Final Version. [link]

[105] Fluence. (2022). How Much Energy Exists in Wastewater? [link]

[106] Wiwatwongwana, F., Suihirun, R., & Vivanpatarakij, S. (2020). Biogas Production from Beverage Industry Wastes by Co-Digestion, AIDIC, 80. [link]

[107] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

extracted from the waste by heating, and used in biodiesel refining, plastics or for wax on cars; liquid fertilisers; and pet food.

An Eco-park in Poland utilises 300,000 tonnes of **meat waste** and transforms it into 110,000 tonnes of meat-bone meal (MBM) **biofuel** per year. Additionally, it generates 460,000 GJ of energy per year from the combustion of MBM biofuel.[108] Stakeholders thought that (in the UK) all eligible meat by-products are currently sent to meat renderers and processors rather than being disposed of as waste.

Box 3.6: Examples from sugar production

The sugar industry produces various by-products such as aggregate, topsoil, and bioethanol, which can be used in construction, plant nutrition, and transport fuels. **Sugar beet pulp**, a key by-product, can be used for anaerobic digestion to produce energy, as animal feed, or as fuel to generate electricity in Combined Heat and Power plants. LimeX, a calcium carbonate-based by-product from sugar beet processing, serves as a high-alkaline fertilizer, suitable for concrete manufacturing and flue gas scrubbing.

Source: British Sugar. Our co-products. [link]

The sugar industry generates a variety of waste and by-products that can be utilised in other sectors. **Press mud** from the carbonation process and molasses from alcohol factories can be reprocessed into fertilisers.[109] Additionally, **bagasse**, a core by-product remaining after sugarcane juice extraction, can be used as an alternative to plastic packaging, as a supplementary material in cement to enhance its durability and mechanical properties, and in animal feed. [110] Stakeholders suggest that while sugar beet waste has high market demand, other by-products require further research and development to expand their use.

Box 3.7: Industrial Symbiosis in Beer Production

In beer production, the most common use for by-products such as spent grain is **livestock feed**, with 70 per cent of producers sharing it with animal breeders, eliminating disposal costs. **Wastewater and spent** grain are produced at large scales. For instance, it was stated that a 64 kWe biogas reactor could be installed within a typical microbrewery, which would then be able to process 48 wet tonnes of spent grain and 15,000 litres of wastewater per week and generate enough energy to power approximately 45 homes.

Spent grain can also be used in high-fibre baked products, and yeast sludge can be sold as animal feed after deactivation. Brewery wastewater can be used to produce algae for biofuels and animal feedstock.

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[108] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

[109] International Labour Organisation. (2023). Employment effects of industrial symbiosis in the Tanzanian sugar sector. [link]

[110] BioPak. (2020). What is Bagasse. [link]

Source: Haller, H., Fagerholm, A-S., Carlsson, P., Skoglund, W., van den Brink, P., Danielski, I., … Englund, O. (2022). Towards a Resilient and Resource-Efficient Local Food System Based on Industrial Symbiosis in Härnösand: A Swedish Case Study. Sustainability, 14(4), 2197. [link]

Additionally, the large amount of heat and CO_2 produced by the food and drink industry could be sent to other industries. For example, a global supplier system for the food industry has more than 120 CO_2 recovery plants installed in 35 countries. The plants have the capacity **to capture 100 to 8,000 kilograms of CO_2 per hour**, and are suitable for breweries producing between **200,000 and 16 million hectolitres** of beer per year. The process lowers overall production costs, and it is estimated that some of the plants have the ability to pay for themselves within three years of installation.[111]

Table 3.8: By-products that can be sent to other sectors

Material	Input replaced	Receiving sectors	Status
Organic waste and packaging	Fuel, fertilisers, animal feed	Chemicals, waste-to-energy, fuel refiners, agriculture	Ongoing
Wastewater (sludge)	Fuel, fertiliser inputs	Chemicals, waste-to-energy, fuel refiners	Ongoing
Animal by-products	Fuel, fertiliser inputs, animal feed	Chemicals, waste-to-energy, fuel refiners, agriculture	Ongoing and Potential
Sugar beet pulp (bagasse)	Fuel, fertiliser inputs, animal feed, binder for cement, plastic	Chemicals, waste-to-energy, fuel refiners, agriculture	Ongoing and Potential

Source: Europe Economics analysis.

Stakeholders noted that whilst the use of by-products is currently high, different uses could be made of the same products – for example, oils could be used in aviation fuel. These uses may generate higher revenues for the food and drink sector and may have greater environmental impacts that current uses. However, technological and regulatory barriers mean that many alternative uses are not fully developed yet.

3.6.2 Food and drink sector as a receiver

By-products received from other sectors can include bio-based chemical products from the chemicals industry or ammonium sulphate, waste heat and lactic acid.[112] A study based in Ireland demonstrated that high-value polyphenols (which act as an antioxidant in food and drink products as well as pharmaceutical and cosmetic applications) can be extracted from brewery by-products such as spent grains and distilleries' pot ale. This symbiosis opportunity has significant potential in Ireland, which produced over nine million hectolitres of beer in 2018.[113]

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[111] GEA. (2023). GEA plans CO2 recovery solution for small and medium-sized breweries. [link]

[112] Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. Bioresource technology, 295, 122223. [link]

[113] Impoco, G., Arodudu, O., & Brennan G. (2021). Industrial Symbiosis: guide for policy making. SymbioBeer. [link]

The drinks sector currently obtains the CO_2 that it uses in fizzy beverages from industrial symbiosis, for example CO_2 captured as a by-product of ammonia synthesis or as a by-product of the fermentation process in breweries.[114]

Table 3.9: By-products that can be received from other sectors

Replacement Material	Input Replaced	Sending Sector	Status
Waste CO_2	Virgin CO_2	Chemical industry, breweries	Ongoing
Waste heat	Fuel	Chemical industry	Ongoing
High-value polyphenols	Antioxidants	Breweries	Potential

Source: Europe Economics analysis.

3.7 Agriculture

This section summarises the opportunities for industrial symbiosis in the agriculture sector, which is both a sending and receiving sector.

3.7.1 Agriculture as a sending sector

Evidence from the literature and stakeholders highlighted that agricultural by-products like **crop residues and animal manure** can be used to produce renewable energy, such as biogas, and to replace conventional fuels (e.g. using methane to replace natural gas, or crop residue to create biofuel). For example, Kalundborg developed a full-scale biogas plant in 2017 and produces approximately 60m^3 of biogas per tonne of biomass, and **a total of 18 million m^3 of biogas annually.**[115] British Sugar has an anaerobic digestion plant which converts pressed sugar beet pulp into biomethane, exporting **38GWh** of electricity to the National Grid. Also, CO_2 from the bioethanol process can be sent to other parts of the sector – for example, to enrich greenhouse atmospheres and boost salad yields. Bioethanol is also used in disinfectants, personal care products and beverages, and as feedstocks for the chemical and pharmaceutical industries.[116] Greenville Energy in Ireland also converts farm waste and grass into methane for electricity generation and supplies power locally, resulting in cost savings, increased sales and new jobs.[117] A stakeholder noted that in the UK, **10 million tonnes** of wheat straw are used as livestock bedding, and in straw-fired power stations.

Box 3.8: Anaerobic digestion and Dyson Farming

Dyson Farming's anaerobic digestion facilities process **agricultural and food waste** to produce **biogas**, used in combined heat and power (CHP) units for electricity and heat.

The electricity powers farm operations, with surplus supplied to the national grid, while recovered heat supports agricultural processes, including potential greenhouse heating.

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[114] Business Research Company. (2021). The beverage industry is the largest user of carbon Dioxide. [link]

[115] Danfoss. (2019). Full-scale biogas plant in Kalundborg ensures the return of all nutrients back to nature. [link]

[116] DEFRA R&D Report. (2023). Foresight study to compare the relative gains, costs, feasibility and scalability of current and future 'industrial horticulture' models. [link]

[117] Invest Northern Ireland. Industrial Symbiosis: improving productivity through efficient resource management. [link]

The anaerobic digesters produce enough electricity annually to power the equivalent of 10,000 homes.[118]

Agricultural **slurry and sludge** are used for material production or energy generation.[119] Stakeholders noted that slurry is a valuable source of crop nutrients and is a supplement to fertilisers; however, it is challenging to measure out and spread compared to pellet-like or liquid fertilisers. New technologies aim to make slurry and manure more usable, although the extent to which these can be scaled up remains uncertain.

Box 3.9: Insect proteins to feed livestock

A stakeholder highlighted the emerging potential of using insect proteins, specifically soldier fly larvae raised on organic waste like wheat straw, sugar beet pulp, or dairy manure, to feed livestock such as pigs and poultry. This could reduce reliance on long supply chains for fish and soya feed. Currently, fly larvae are only used to feed fish, but there is growing interest in expanding their use. Government approval and licensing are needed for feeding larvae to livestock, making this at present only a potential opportunity for industrial symbiosis in agriculture.

The table below summarises by-products that can be sent by the agriculture sector to other sectors.

Table 3.10: By-products that can be sent to other sectors

Waste By-Product	Input Replaced	Receiving Sector	Status
Agricultural slurry and sludge	Fossil fuels; fertilizers	Large industrial emitters and electricity generators, biofuels, agriculture	Ongoing
Wheat straw	Fossil fuels, construction aggregates (e.g. concrete insulation)	Agriculture, chemicals, steel, cement and other large foundation industries, power stations	Ongoing
Sugar beet pulp	Fossil fuels, animal feed	Aggregates (and other large foundation industries), food for insect farms	Potential

Source: Europe Economics analysis.

3.7.2 Agriculture as a receiving sector

The agriculture sector can utilise by-products from various industries for applications like soil enrichment and fertilisers. For example, in Kwinana, the sector receives **sludge from wastewater treatment** for use as a soil conditioner, a fuel for energy generation, or

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[118] Dyson Farming. Our journey towards sustainability. [link]

[119] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]

compost.[120] **Bypass dust** from clinker manufacturing in the cement industry, which is rich in potassium and lime, can serve as a sustainable substitute for traditional fertilisers and lime. A cement manufacturing firm has repurposed bypass dust from a cement kiln for agricultural use since 2015, reclaiming nearly **130,000 tonnes** to date.[121]

Integration with **aquaculture** is another symbiotic trade, in which greenhouses can utilise nutrient-rich water from fish farming, which helps to optimise water and nutrient use.[122] Recent research has also investigated the use of microbes to convert methane gas into a high-protein food for livestock.[123]

Box 3.10: Industrial Symbiosis in mushroom farming

A study identified several uses for **Spent Mushroom Compost (SMC)** from mushroom production. SMC enhances soil and crop yield, can be supplemented with food industry waste to produce **biogas**, and has nutritional qualities that could make it a good animal feedstock, although the technology for this last application is still under development.124

The literature and stakeholders highlighted opportunities for CEH greenhouses to use **waste heat and CO_2** provided by anaerobic digestor plants, energy-from-waste plants, or industrial emitters.[125,126] Waste heat can be piped directly to greenhouses' heat stores to heat water for distribution. Waste CO_2 can be captured, purified to near-food quality, liquefied, and sent to greenhouses for storage and use.

Stakeholders suggested that the use of waste CO_2 in greenhouses may increase in the future if CCS and purification costs decrease, potentially supported by government funding and higher carbon prices which would encourage more emitters to capture and sell CO_2 to reduce their UK ETS liabilities.

New materials that can be spread on land as fertilisers include enhanced weathering minerals, such as **quarrying waste products.**[127] **Biochar**, another option, can enhance nutrient

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[120] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]

[121] Cemex. (2023). Cemex partnership with Silverwoods helps close the loop and upvalue nearly 130,000 tonnes of By-Pass Dust for agricultural purposes. [link]

[122] Janes, H., Cavazzoni, J., Alagappan, G., Specca, D., & Willis, J. (2005). Landfill gas to energy: a demonstration-controlled environment agriculture system. HortScience, 40(2), 279-282. [link]

[123] Shahzad, H. M. A., Almomani, F., Shahzad, A., Mahmoud, K. A., & Rasool, K. (2024). Challenges and opportunities in biogas conversion to microbial protein: a pathway for sustainable resource recovery from organic waste. Process Safety and Environmental Protection, 185, 644-659. [link]

[124] Haller, H., Fagerholm, A-S., Carlsson, P., Skoglund, W., van den Brink, P., Danielski, I., … Englund, O. (2022). Towards a Resilient and Resource-Efficient Local Food System Based on Industrial Symbiosis in Härnösand: A Swedish Case Study. Sustainability, 14(4), 2197. [link]

[125] Cecconet, D., Raček, J., Callegari, A., & Hlavínek, P. (2019). Energy recovery from wastewater: A study on heating and cooling of a multipurpose building with sewage-reclaimed heat energy. Sustainability, 12(1), 116. [link]

[126] Pesch, H., & Louw, L. (2023). Exploring the Industrial Symbiosis Potential of Plant Factories during the Initial Establishment Phase. Sustainability, 15(2), 1240. [link]

[127] For example, UNDO in Scotland spread 100,000 tonnes of quarry waste on crops, which reacts with soil nitrogen to fix biogenic carbon.

absorption and act as a carbon sink, thus earning carbon credits; however, its use in agriculture is not yet widespread.

The table below summarises by-products that can be received by the agriculture sector from other sectors.

Table 3.11: By-products that can be received from other sectors

Replacement Material	Input Replaced	Sending Sector	Status
Sludge, slurry	Traditional fertilizers	Wastewater treatment companies; other agriculture	Ongoing and Potential
Bypass dust	Traditional fertilizers	Cement	Ongoing and Potential
CO_2	Fossil CO_2	Steel, cement, glass and other large industrial emitters	Ongoing and potential
Heat/energy	Fuel, natural gas	Steel, cement, glass and other large industrial emitters; waste-to-energy	Ongoing and potential
Quarry waste	Traditional fertilisers	Quarry and mining companies	Potential
Biochar	Traditional fertilisers	Agriculture, forestry	Ongoing and potential
Spent Mushroom Compost	Traditional fertilisers	Food manufacturing	Potential

Source: Europe Economics analysis.

3.8 Future trends

There are a number of future trends that may affect the potential for industrial symbiosis in the UK.

3.8.1 Decarbonisation

Stakeholders considered the **decarbonisation agenda** as a key driving force for industrial symbiosis going forward. As government policies focus on decarbonisation (e.g. through targets and regulations, including reporting on scope 3 emissions), companies will increasingly be looking for ways to reduce their carbon footprint, with industrial symbiosis being increasingly explored as a means of doing so.

Related to this, potential future increases in **carbon prices** may lead to an increase in industrial symbiosis by incentivising companies to explore ways of reducing their carbon footprint. Carbon prices could increase as a result of policy (e.g. changes to the number of carbon allowances issued under the EU and UK ETS) or as a result of market forces.

Decarbonisation may also increasingly drive companies’ behaviour if it is beneficial in attracting consumers and investors. Indeed, stakeholders from the chemicals sector have noted that consumers will need to be willing to pay a ‘green premium’ for many products containing chemicals if de-fossilisation of the sector through industrial symbiosis is to reach its potential.

3.8.2 Circular economy

Similar to decarbonisation, stakeholders thought that the circular economy agenda which is gaining traction in Europe and the UK will also drive companies’ behaviour as they seek to ‘close the loop’ on resource usage to minimise the amount of resources that become waste.

3.8.3 Digitisation and artificial intelligence

Given the importance of information and knowledge dissemination in enabling industrial symbiosis, technology that increases the ability of firms to identify potential by-product materials to either send or receive, as well as potential partners to trade with, will increase the potential for industrial symbiosis. Stakeholders have noted that artificial intelligence applications capable of learning from synergies and able to identify new synergies will increase the opportunities for industrial symbiosis and reduce the costs.

3.8.4 Changes in production techniques

Changes in production techniques and the growth or decline of certain sectors will also affect the volumes of by-products available for industrial symbiosis, and the capacity of sectors to use by-products. For example, the availability of GBBS and fly ash as alternative materials for the cement sector is declining with the phasing out of blast furnace steel production and coal generation; and the potential transition to electric furnaces will reduce the ability of the glass sector to take waste fuels. However, new opportunities may equally emerge, such as developments in the creation of cement clinker using electric arc furnaces in the steel sector. [128]

3.8.5 Advances in renewable energy

The costs of green electricity may fall over time due to technology development, policy changes and consumer acceptance, which may mean that a range of new industrial symbiotic synergies become viable, such as the replacement of fossil carbon with waste carbon in the chemicals sector.

However, cheaper electricity may lead to a change (or accelerate the change) in some industries towards the use of electricity as an energy source instead of the combustion of fuels, including for cement kilns and for glass and steel furnaces. This will reduce the opportunities

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[128] Institute of Materials. Minerals and Mining. [link]

for some synergies, such as the burning of fuels that are by-products from other industries, or the use of steel blast furnace slag.

3.9 Summary

The literature and our stakeholder engagement shows that there are numerous opportunities for industrial symbiosis. The literature concerning the UK is relatively limited, with a greater number of sources relating to examples from other countries. However, there is some literature evidence of industrial symbiosis in the UK and non-UK examples are also valuable in highlighting the breadth of potential in general and in our six chosen sectors. Our research shows there is a relative lack of comprehensive evidence that quantifies the potential scale and value of industrial symbiosis across Europe and certainly within the UK.

Our stakeholder engagement has been valuable in highlighting examples of industrial symbiosis in the UK, both in terms of current and widespread practices, and in terms of opportunities that are either undertaken in a limited way or are still being researched and explored. The evidence also highlights different forms of industrial symbiosis, namely:

- Relatively **ad hoc exchanges** between companies across sectors, often (but by no means always) facilitated in some way by a third party. For example, crop farmers spreading livestock slurry on their fields; the cement sector using waste-derived fuels; a chemical plant receiving soda ash from a steel foundry; or a glasshouse locating next to an energy-from-waste plant to receive waste heat.
- Individual companies within a sector seeking to **market their by-products** in a more formalised way and break into existing supply chains (rather than seeking out specific partners), such as polyphenols being extracted from brewery by-products and sent to the food and cosmetics sectors; or sugar beet bagasse being transformed into a lime product and marketed as a fertiliser.
- By-products being sent through an **established supply chain** and widely used across a sector, often with intermediary processing companies, such as Calumite in the glass sector; GGBS and fly ash in cement production; CO_2 from manufacturing emissions sent to the drinks sector; and food and meat waste sent to energy-from-waste plants.
- **Sector-wide process transformations** that are seeking to fundamentally change production techniques across a sector in conjunction with establishing new supply chains for by-products, such as using waste carbon emissions to replace fossil carbon in the production of surfactants in the chemicals industry; or reactivating recycled concrete in electric arc furnaces used to make steel.

UK government policy can affect the potential for industrial symbiosis going forwards, such as through increases to the landfill tax or through policy changes that increase the carbon price under the UK ETS.

There are a number of **future trends** that may affect the potential for industrial symbiosis in the UK, both positively and negatively. An increasing focus on decarbonisation and the circular economy is likely to raise the profile of industrial symbiosis as a way of increasing resource efficiency and reducing carbon emissions and energy use. At the same time, the decarbonisation agenda may speed up a transition away from manufacturing approaches that currently play a large role in industrial symbiosis (such as the use of blast furnaces to produce steel, which creates blast furnace slag as a by-product). Advances in digital technology, including artificial intelligence, may improve the facilitation of symbiotic networks and synergies. Advances in renewable energy may enable a range of new symbiotic technologies that are currently too energy-intensive to be used at scale. However, such advances in renewable energy may also incentivise some production processes to transition to using green electricity, thus ending the existing use of fuels that are by-products from other industries.

4 Drivers and Enablers

In this section we present evidence on the drivers and enablers of industrial symbiosis, drawing on our **literature review** and our **stakeholder interviews**.

The literature often interchangeably uses the term ‘enablers’ and ‘drivers’, but does draw out differences between them. Enablers are factors or conditions that facilitate the establishment, development, or success of collaborative relationships between industries aimed at resource exchange and waste reduction. Enablers play a crucial role in creating an environment conducive to industrial symbiosis initiatives. Drivers on the other hand are compelling forces or motivations that push industries towards engaging in industrial symbiosis initiatives, such as regulatory pressures to comply with environmental standards, market demands for sustainable products and practices or concerns about resource scarcity and rising costs.

Based on the literature, we distinguish between the following six categories for drivers and enablers:

- technological;
- technical knowledge and other information;
- organisational and cultural;
- geographical;
- economic and financial; and
- regulatory and policy-related.

Below, we discuss in turn each of these categories of drivers/enablers. In each case, we first discuss evidence from the general literature and our stakeholder interviews, and then present evidence relating specifically to our six chosen sectors.

This section of the report finishes by analysing the relative importance of these different drivers and enablers, and then summarising our conclusions in this area.

4.1 Technological

4.1.1 Evidence from the general literature and stakeholder interviews

Materials technology

The development of industrial symbiosis is **closely linked to the development of circular economy (CE) related technologies**. This encourages industrial symbiosis by **providing efficient tools for resource recovery and reuse**. These technologies include waste treatment, advanced recycling technologies, and resource optimisation technologies emphasise the importance of operations facilities (equipment and treatment plants) and control facilities (laboratories) to the technological viability of synergies. [129][130]

Stakeholders contributing to this study also noted that technological enablers play an important role in facilitating industrial symbiosis. Technological research and development is often needed to explore the potential to re-use materials, especially when the potential for industrial symbiosis is less well-known and obvious to potential collaborators. Stakeholders view many of these enablers as being closely linked to the technical knowledge and other information-related enablers discussed below.

Digital technology

Technologies that promote industrial networks also play a significant role in advancing industrial symbiosis. This may include technologies that support the process of matching, and digitisation technologies which enhance control over production processes, data availability, waste and resources.[131] Examples include Multi-Layer Stream Mapping (MSM), a process that assesses efficiency and **matches 'donors' to 'receivers'** to promote symbiosis; and the SWAN platform, a digital solid waste platform in the Balkans that supports the development of industrial solid waste reuse models.[132][133] Technological capabilities in evaluating economic, environmental and efficiency performance within production systems also facilitate industrial symbiosis, as these illustrate the costs and benefits of collaborative efforts.[134] Technical data also aids in generating simulations of synergies, which can enhance confidence in a potential synergy. Simulations of the economic implications are particularly attractive to firms, as they can model the worst-case scenario and thus the highest level of risk, especially for newcomers to industrial symbiosis.[135] Furthermore, modelling using actual firm data can identify how processing facilities within clusters should be integrated to extract maximum value.[136]

Similarly, **online waste exchanges** – digital marketplaces where companies can list their available waste materials and search for potential recipients that can use these materials as resources in their own processes – have played a critical role in catalysing industrial symbiosis.[137] Examples include the United States Material Market Place, WasteIsNotWaste

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[129] Núñez, G.R., & Perez-Castillo, D. (2023). Business Models for Industrial Symbiosis: A Literature Review. Sustainability, 15(12), 9142. [link]

[130] Guo et al. (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[131] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[132] Holgado et al., (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[133] Angelis-Dimakis et al. (2021) cited in Vladimirova, D., Miller, K., & Evans, S. (2018) -- Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[134] Marchi, Zanoni, & Pasetti, (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018) -- Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[135] Karner, Theissing, & Kienberger, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[136] Hein et al. (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[137] Grant et al. (2010) cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]

(Green Future Solutions), Resource Efficient Scotland (WRAP), Minnesota Materials Exchange (iWasteNotSystems), and The Waste Exchange (Northrow).

4.1.2 Evidence from the six chosen sectors

The below summarises the key technological enablers and drivers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors. The evidence suggests that these drivers play a particularly important role in the chemical sector.

Table 4.1: Summary of technological enablers and drivers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	No specific evidence from the sector.	Research to enable the incorporation of a wider range of SCMs in production.
Glass	No specific evidence from sector.	Government funding for research initiatives.
Mining	Use of technology and digital platforms (e.g. Urban Mine Platform) to track material and waste locations, quantities, qualities and timings.[138]	New process technologies (e.g. multi-product flowsheet) to lower capital investment requirements.
Chemicals	Technology to enable the conversion of flue gases to chemical compounds.[139]	Availability of technologies (although many at the research/development stage) to transform waste products into useable feedstock.
Food and drink	No specific evidence from sector.	No specific evidence from sector.
Agriculture	New technologies to produce low carbon energy from biomass (although some issues around their economic viability).[140]	New technologies (e.g. to enable greater use of slurry as fertilisers, to manufacture fertilisers from green ammonia, to grow animal feed proteins from chemical by-products).

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[138] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [link]

[139] Cozier, M. (2023). Flue2Chem: SCI, Unilever and 13 partners launch £5.4m net zero collaboration project. Society of Chemical Industry. [link]

[140] Saleem, M. (2022). Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon, 8(2). [link]

4.2 Technical knowledge and other information

4.2.1 Evidence from the general literature and stakeholder interviews

To engage in industrial symbiosis, companies need to possess the requisite **knowledge and technical expertise**. This includes the capacity to identify sources from which by-products can be obtained or receiving companies to which waste or by-products can be sent, along with an understanding of the procedures and methodologies involved.

Networks

The **development of co-operative networks** is identified in the literature as a key enabler for industrial symbiosis.[141,142] This is supported by the European Commission, which has indicated that larger and longer-term networks are more successful and yield better synergy results, indicative of economies of scale in symbiosis facilitation.[143] Henriques et al. (2021) highlight the role of internal and external networks in prompting symbiosis, by **creating common spaces** which facilitate interactions between different actors (e.g. companies, knowledge actors, government entities). They can either be physical locations **like innovation hubs or industrial parks**, or virtual, such as online **forums or platforms.**[144]

Information

Stakeholders involved in industrial symbiosis programmes spanning multiple sectors highlighted that information and knowledge are essential enablers for industrial symbiosis, especially among SMEs. This extends beyond the initial identification of synergies to providing companies with the information required to manage the process. In particular, stakeholders noted that **facilitation**, whereby companies are assisted in identifying potential synergies and how to access them, is a key enabler, although some stakeholders believed that facilitation can be less effective if companies need to pay for it directly (rather than it being externally funded) as this could mean that companies expect a ‘guaranteed’ synergy which is not always possible.

Governmental support strategies, such as workshops facilitated by initiatives like NISP in the UK, have helped companies identify potential synergistic opportunities.[145]

Information platforms, such as networking platforms for waste exchanges, have been cited as key enablers for industrial symbiosis, and are often further supported by the involvement of Research and Development (R&D) institutions and universities to promote knowledge

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[141] Paquin and Grenville (2013) cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]

[142] van Ewijk, Park, & Chertow, (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER.

[143] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[144] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[145] Bellantuono, Carbonara, & Pontrandolfo, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

transfer.[146] This links with the development of digital technologies discussed above. For example, the EPOS Hull industrial cluster highlights that knowledge platforms encourage cross-sectoral knowledge-building to enable collaboration with other sectors; and that subscriptions to waste trading platforms can facilitate cross-sectorial matches.[147,148]

Life cycle assessment (LCA) is often used as a tool to promote collaborations, as it involves undertaking quantitative analysis to measure the impact of substituting virgin materials with waste.[149] Other evaluations, in conjunction with LCA, help to provide stronger assessments of the opportunities and potential trade-offs.[150] For example, certain literature uses LCA to evaluate environmental strategies in industrial symbiosis systems within a Swedish industry cluster.[151] They find that a substantial portion of greenhouse gas emission reductions occur off-site, and they emphasise the need to consider the entire life cycle of processes for accurate environmental impact assessments.

Stakeholders also believe that data and management tools / information platforms have an important role to play in enabling symbiotic exchanges. For example, software containing a library of symbiotic exchanges is seen as a key tool aiding the development of symbiotic networks by bringing together information about potential senders and receivers of waste/by-products.

An important enabler is the existence of appropriate **indicators and tools** which can be used to **evaluate symbiotic relationships and improve technical expertise**.

The literature cites various examples of industrial symbiosis tools and indicators:

- The Recovery Potential Indicator, a metric used in industrial ecology in the US and resource management, assesses the potential for recovering resources from waste streams or by-products.[152]

- Geographic information system technologies have been developed to help visualise regions, which in turn simplifies the identification of locations for industrial symbiosis.[153]

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[146] Guo et al. (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[147] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]

[148] Ceglia et al., (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[149] Husgafvel et al., (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[150] Dias et al., (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[151] Røyne et al. (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[152] van Ewijk, Park, & Chertow, (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER.

[153] Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019) -- Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]

- Laybourn and Morrissey discuss the Core Resource for Industrial Symbiosis Practitioners (CRISP), a tool that was employed by NISP.[154] This tool facilitated the development of industrial symbiosis by gathering data that assisted companies and practitioners in identifying synergy opportunities.

- There are databases of materials flows in the UK, such as from WRAP in Wales[155] and the UK Circular Plastics Network.[156] These databases were identified as important sources of information by stakeholders, especially in the chemicals sector.

4.2.2 Evidence from the six chosen sectors

The table below summarises the evidence from the literature and stakeholders regarding the enablers and drivers related to technical knowledge and other information for the six chosen sectors. These enablers and drivers appear to play a more important role for more fragmented sectors such as agriculture and food and drink.

Table 4.2: Summary of enablers and drivers related to technical knowledge and other information in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	• No specific evidence from sector.	• Knowledge and experience of production processes (e.g. to identify suitable fuels for operations and their impact on emissions).
Glass	• No specific evidence from sector.	• External facilitators (e.g. Glass Futures) to bring together parties along the supply chain and encourage symbiotic relationships.
Mining	• External institutions to connect stakeholders and facilitate symbiotic relationships.[157]	• International collaborations (e.g. to provide technology and/or knowledge), supported by grant funding (e.g. from Innovate UK).
Chemicals	• Facilitation reducing the resource needs for companies. • Data templates to provide information about flows of materials, energy and processes.	• Increased communication about opportunities to share resources and access to detailed information on producers and quantities of waste materials.

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[154] Laybourn and Morrissey (2009) cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology,23(5),1087-1108. [link]

[155] WRAP. Circular Materials Mapping Tool for Wales. [link]

[156] UKCPN. UK Circular Plastics Network. [link]

[157] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [link]

	• Standardised waste and by-product streams, e.g. based on quality.[158]	• Help from the Environment Agency's advisory panel on waste and by-products to understand how by-products could be used.
Food and drink	• Initiatives to encourage collaborations and reduce transaction costs (e.g. policies fostering information exchange and trust between parties).[159] • Centralised digital platforms to transfer information between stakeholders.[160]	• Having a facilitator to reduce the time and resources required to identify contacts. • Facilitation process should ensure that the exchange remains on track through effective project management.
Agriculture	• Collaborative networks and partnerships connecting farmers and other stakeholders to enhance flow of by-products and resources. • Trust between stakeholders to enable collaborations and the exchange of information.[161]	• Knowledge of potential opportunities e.g. information for greenhouses about the availability of energy and CO2 supplies, and temperatures of heat, from waste sources. • Facilitators and advisors to provide information on factors affecting the benefits of co-locating greenhouses with heat emitters (e.g. land topography, transport links, availability of labour).

4.3 Organisational, social and cultural

4.3.1 Evidence from the general literature and stakeholder interviews

Trust and collaboration are crucial in establishing networks for industrial symbiosis. They are heavily influenced by industry culture, which, in turn, shapes organisational behaviours and structures.

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[158] Mendez-Alva, F., Cervo, H., Krese, G., & Eetvelde, G.V. (2021). Industrial symbiosis profiles in energy-intensive industries: sectoral insights from open databases. Journal of Cleaner Production, 314,128031. [link]

[159] Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G.,…D'Amico, M. (2023). Industrial symbiosis in the agri-food system: themes, links and relationships. Frontiers, 6. [link]

[160] Haller, H., Fagerholm, A-S., Carlsson, P., Skoglund, W., van den Brink, P., Danielski, I., … Englund, O. (2022). Towards a Resilient and Resource-Efficient Local Food System Based on Industrial Symbiosis in Härnösand: A Swedish Case Study. Sustainability, 14(4), 2197. [link]

[161] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]

Having common social, organisational, and cultural goals within a company is cited as a key driver for the success of industrial symbiosis.[162] At a firm level, companies with a **long-term perspective and a vision for the future** are more inclined to engage in symbiotic relationships. Moreover, companies that seek to establish new partnerships, lead in innovation, and already have existing environmental policies are more likely to be motivated to participate in industrial symbiosis.[163]

The European Commission funded Community of Practice "Hubs4Circularity" investigating the key trends impacting industrial symbiosis practices across Europe also mentioned social drivers as an important factor for the development of industrial symbiosis networks. Half of the respondents from the study stated that **increasing welfare and creating new jobs** were key motivations for establishing industrial symbiosis partnerships, while one mentioned that community-building and facilitating innovation were key drivers.

Stakeholders we interviewed mentioned the value of **organisational 'buy-in' to the concept of industrial symbiosis**, and a culture of information sharing, as important drivers.

Rising environmental awareness at a company level, and concern for the **impacts of industrial activities on the environment**, is another social and cultural driver which has facilitated symbiotic synergies.[164] Environmental degradation is recognised as a significant concern that is driving industrial symbiosis in sectors such as cement and steel production, the pulp and paper industry, and oil and gas refining.[165, 166]

It was also identified that concerns for **environmental sustainability** are important, as all organisations participating in the Hubs4Circularity project cited this as a major driver for industrial symbiosis activities. In particular, it was highlighted that **energy efficiency, water efficiency, CO2 reduction and resource efficiency** were the main environmental drivers. This also overlaps with financial incentives for industrial symbiosis, as described below.

The literature also highlights that a **culture of partnership** among firms is an enabler of industrial symbiosis. Establishing **effective communication channels**, as highlighted in the literature, not only creates favourable conditions for stakeholders but also promotes green consumerism.[167] These cultural aspects increase interactions among stakeholders, strengthening collaborations and partnerships, including international ones.[168, 169] **Trust** and

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[162] Núñez, G.R., & Perez-Castillo, D. (2023). Business Models for Industrial Symbiosis: A Literature Review. Sustainability, 15(12), 9142. [link]

[163] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[164] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[165] van Ewijk, Park, & Chertow, (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER.

[166] Iacobescu, Angelopoulos, Jones, Blanpain, & Pontikes, (2016)) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[167] Yedla & Park (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[168] van Capelleveen, Amrit & Yazan, (2018) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[169] Aid, Eklund, Anderberg, & Bass (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

engagement are also highlighted as important factors for networks. The creation of enduring relationships built on trust can be accomplished by building **learning networks** and forums.[170, 171]

4.3.2 Evidence from the six chosen sectors

The table below summarises the evidence from the literature and stakeholders regarding the organisational, social and cultural enablers and drivers across the six chosen sectors. These factors have only rarely been mentioned in the sector-specific literature or by stakeholders as enablers of industrial symbiosis.

Table 4.3: Summary of organisational, social and cultural enablers and drivers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	• Culture of partnership among firms (e.g. collaboration with research institutes and industry to develop products using alternative cementitious materials).[172]	• Education and knowledge-sharing by cement firms e.g. to educate engineers and contractors about the benefits of using cement that contains by-products.
Glass	• No specific evidence from sector.	• Extensive knowledge-sharing facilitated by British Glass and Glass Futures. • Further collaboration to share new industrial symbiosis practices (although some firms may be reluctant to share information due to competitive pressures).
Mining	• Organizational and cultural attitude within the region where mining companies are headquartered, which sets industry norms and common practices.[173]	• Positive organisational attitude towards circular economy principles. • Engagement with public to understand preferences and concerns regarding mining operations.
Chemicals	• No specific evidence from sector.	• No specific evidence from sector.

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[170] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[171] Ceglia et al., (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[172] Ramsheva, Y. K., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. In 1st International Conference on Technologies & Business Models for Circular Economy, 35-54. [link]

[173] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [link]

Food and drink	- No specific evidence from sector.	- No specific evidence from sector.
Agriculture	- No specific evidence from sector.	- No specific evidence from sector.

4.4 Geographical

4.4.1 Evidence from the general literature and stakeholder interviews

There is an abundance of literature on the influence of **industrial parks** in enabling symbiosis. An eco-industrial park (EIP) is a group of businesses located on shared property, aiming to achieve a positive environmental, economic, and social impact by collaborating to address environmental and resource challenges. The provision of common services such as transport and landscaping, in addition to shared infrastructure management, can accelerate symbiotic synergies.

EIPs can lead to **administrative simplification**, inducing new players to join the network, and can also encourage symbiosis by **developing infrastructure** to facilitate resource exchange and by **establishing public-private partnerships**.[174, 175] To enhance EIP development opportunities and network connections between industrial complexes, the literature suggests that any industrial complex with the potential to scale to an EIP should be designed as the central node, with three or four minor neighbouring complexes connected, a notion endorsed by other authors.[176, 177]

More generally, **close geographic proximity** has been identified as a strong enabler of industrial symbiosis.[178, 179] Geographic proximity has also been mentioned as an important enabler for building trust.[180] The SCALER report, which analysed synergy potentials across the EU, states that industrial symbiosis is more likely to thrive in regions with a high density of industrial facilities, facilitating the identification of potential partners.[181] The availability of **logistic networks**, which can improve communication and the transport of materials, is another key enabler for firms.[182]

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[174] Freitas & Magrini, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[175] Yedla & Park (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[176] Park et al., (2016) cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]

[177] Mulrow, Derrible, Ashton, & Chopra, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[178] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[179] Velenturf & Jensen, (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[180] Hubs4Circularity Europe (2023) Community of Practice project [link]

[181] Quintana, J., Chamkhi, R., Bredimas, A. (2020). Quantified potential of industrial symbiosis in Europe. SCALER. [link]

[182] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

Stakeholders also highlighted the importance of close geographic proximity of firms as an enabler, especially for sectors such as agriculture, chemicals and mining. For example, much of the chemicals sector is clustered around fossil fuel feedstock sources, particularly the companies engaged in the manufacture of base organic chemicals which receives natural gas from ports which is considered to be an enabler of symbiosis.

That said, a number of stakeholders viewed geographic proximity as only one dimension among many when considering the value of a symbiotic trade, and cited many examples of symbiosis occurring over longer distances. A number of stakeholders highlighted that clusters or industrial parks may help in symbiosis but are by no means necessary.

The presence of **suitable physical infrastructure within a specific area** is another important factor.[183, 184] Particularly for industries involved in the production and handling of hazardous waste, physical facilities play a pivotal role in establishing symbiotic relationships. Since waste often requires storage unless it can be immediately utilised by the recipient, having appropriate storage facilities is essential for facilitating symbiosis.[185, 186]

Similarly, stakeholders saw the availability of logistic networks and suitable physical infrastructure (e.g. storage) as especially important enablers of industrial symbiosis in some sectors such as agriculture, chemicals and mining.

4.4.2 Evidence from the six chosen sectors

The table below summarises the evidence from the literature and stakeholders regarding geographic enablers and drivers across the six chosen sectors. These enablers and drivers are especially important for the transport of heavy/bulky products (or those otherwise difficult to transport), or sectors that have historically been located in clusters, such as chemicals.

Table 4.4: Summary of geographical enablers and drivers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	• Geographic proximity to other industries (e.g. Aalborg Cement in Denmark).[187] • Ease of transport for some solid waste streams (e.g. slag and fly	• No specific evidence from sector.

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[183] Liu, Z., Adams, M., Cote, R.P., Geng, Y., Ren, J., Chen, Q., Liu, W., Zhu, X. (2018). Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on energy analysis. Renewable and Sustainable Energy Reviews, 81, 1522-1529. [link]

[184] Sun, Spekkink, Cuppen, & Korevaar, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[185] Wu, Guo, Li, & Qi, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[186] Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., & Matias, J.C.O. (2019).The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. Sustainability, 11(24), 7095. [link]

[187] Ramsheva, Y. K., & Remmen, A. (2018). Industrial symbiosis in the cement industry-Exploring the linkages to circular economy. In 1st International Conference on Technologies & Business Models for Circular Economy, 35-54. [link]

	ash) due to characteristics e.g. lower hazard and risk potential.[188]	
Glass	- No specific evidence from sector.	- Geographical proximity of (glass) processing sites and/or low transportation costs.
Mining	- No specific evidence from sector.	- Clustering, also to keep transport costs to a minimum. - Access to transportation networks e.g. rail line.
Chemicals	- Spatial planning can encourage clustering and increase industrial interactions and exchanges within clusters. - Multi-modal transport networks can also promote cross-sectoral collaboration.[189]	- Geographic proximity e.g. to reprocess waste streams into aggregates for the construction industry. - Benefits from clustering e.g. around sources of oil and gas.
Food and drink	- No specific evidence from sector.	- No specific evidence from sector.
Agriculture	- No specific evidence from sector.	- Geographic proximity e.g. for waste heat piped directly from the source to the greenhouse or where CO_2 is shared as a gas and sprayed into the greenhouse directly.

4.5 Economic and financial

4.5.1 Evidence from the general literature and stakeholder interviews

Economic and financial drivers and enablers have been identified in the literature as instrumental in promoting industrial symbiosis by offering incentives and cost-saving opportunities for collaborative resource management. Economic and financial enablers include **subsidies, grants, and cost-sharing arrangements** that make collaboration economically viable. They also include financial gains from improved resource efficiency and reduced waste disposal costs. These factors were also identified as enablers by some stakeholders we interviewed, who noted that funding support from the government (e.g. for research or carbon

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[188] Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). Review of successful IS methods and systems for the cement industry. EPOS. [link]
[189] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]

capture and storage installations) was valuable and/or could further enhance symbiotic relationships.

Integration of industrial symbiosis by companies and industries in order to **develop a competitive advantage** over their competitors has been identified as a key driver in enabling industrial symbiosis development.[190][191] This competitive advantage has been achieved through reductions in operational costs and company costs related to resources such as raw materials, water or energy. In addition, savings in waste management, mainly relating to landfill tax and waste management costs, have also prompted increases in symbiotic synergies.

Cost savings arising through efficiencies such as landfill reduction, feedstock optimisation and energy reuse were cited as the second most important driver for companies specialising in industrial symbiosis practices in Europe in the Hubs4Circularity research. Additionally, strategic drivers such as increasing the companies' global competitiveness and stability and resilience were key reasons why respondents decided to develop and engage in industrial symbiosis networks. Through collaborating in industrial symbiosis activities, companies mentioned they can establish stable and resilient infrastructure, and benefit from opportunities that they would not be able to if they were working independently.[192]

New revenues arising from industrial symbiosis have prompted firms to pursue new business opportunities through the integration of new products and services that involve synergies.[193]

Energy efficiency is cited as a significant driver in energy intensive industries (e.g. iron and steel), as firms potentially recognise the benefits of shared services, utilities and knowledge.[194]

Economic and financial benefits were highlighted as the single most important driver of industrial symbiosis by the majority of stakeholders that we interviewed, who emphasised that symbiosis opportunities need to be profitable for both parties to succeed. For example, financial benefits arising from the synergies, such as reduced costs of material extraction, lower carbon and landfill taxes and other cost savings (e.g. through the use of waste-derived fuels) were all identified as key drivers.

4.5.2 Evidence from the six chosen sectors

The table below summarises the evidence from the literature and stakeholders regarding economic and financial enablers and drivers across the six chosen sectors. Both the sector-specific literature and stakeholders have highlighted these as a key driver of industrial symbiosis, especially when it comes to potential cost savings realised through symbiotic exchanges.

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[190] Núñez, G.R., & Perez-Castillo, D. (2023). Business Models for Industrial Symbiosis: A Literature Review. Sustainability, 15(12), 9142. [link]

[191] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[192] Hubs4Circularity Europe. (2023). Community of Practice project. [link]

[193] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[194] Wu, Wang, Pu & Qi, (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

Table 4.5: Summary of economic and financial enablers and drivers in the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	• No specific evidence from sector.	• Cost savings (although use of by-products also depends on the relative value of primary and alternative raw materials and/or applications). • Other financial incentives to reduce carbon expenses e.g. through the use of waste-derived fuels.
Glass	• Cost savings realised by a reduction in energy consumption and emission charges.[195]	• Cost savings through lower energy consumption and emission charges.
Mining	• Cost savings due to reduced disposal costs for mining waste products.[196]	• Cost savings through reduced (on-site) storage costs, sending less waste to landfill and additional revenues from the sale of by-products (e.g. silica sand and sulphate of potassium from lithium mining).
Chemicals	• Potential to sell by-products, creating revenue streams.[197] • Reduction in landfill costs through valorising waste/by-products.	• Reduced cost of material extraction and landfill. • End consumers willing to pay higher prices for products with lower environmental footprint.
Food and drink	• Avoidance of landfill costs.[198]	• Creating a viable product which can be sold for additional revenue.

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[195] ARUP. (2018). Re-thinking the life-cycle of architectural glass. [link]

[196] Makhathini, T. P., Bwapwa, J. K., & Mtsweni, S. (2023). Various options for mining and metallurgical waste in the circular economy: a review. Sustainability, 15(3), 2518. [link]

[197] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[198] Patricio, J., Axelsson, L., Blome, S., & Rosado, L. (2018). Enabling industrial symbiosis collaborations between SMEs from a regional perspective. Journal of Cleaner Production, 202, 1120-1130. [link]

Agriculture	• No specific evidence from sector.	• Reducing growers' costs in the CEH sector as they operate on tight margins. • Reducing energy costs (even if these do not reduce emissions), particularly where lighting is used in greenhouses. • Reducing CO_2 costs, although growers are often unable to get waste CO_2 any more cheaply than from original sources.

4.6 Regulatory and policy-related

4.6.1 Evidence from the general literature and stakeholder interviews

Regulatory and policy-related enablers facilitate industrial symbiosis by establishing **laws and incentives that incentivise collaboration** among industries. These regulations can mandate resource efficiency and waste reduction, as well as impose environmental taxes, encouraging businesses to seek partnerships for shared resource utilisation and waste management. Incentives like tax breaks or grants further motivate participation. If there are subsidies and incentives for waste diversion and alternatives to landfilling and incineration, then the opportunity for engaging in industrial symbiosis is greater.[199]

At a macroeconomic level, global factors are strongly driving national governments' activities as regards to legislation, policymaking and taxation in this field. These include the Paris Accord and United Nations Sustainable Development Goals, which have indirectly encouraged industrial symbiosis. Policy changes in the European Union relating to the Waste Framework Directive (WFD), which came in to force in 2008, widely support the efficient use of industrial waste and by-products which encourages more firms across all industries to focus on symbiotic initiatives.[200]

Existing EU regulations and policies were highlighted to significantly influence the implementation of industrial symbiosis practices in the Hubs4Circularity research. Around 50 per cent of interviewees mentioned that regulations such as the CE action plan and EU Green Deal encourage companies to find ways to reduce waste and emissions and encourage resource efficiency, which can lead to the wide scale adoption of industrial symbiosis.[201]

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[199] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]
[200] Husgafvel et al., (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]
[201] Hubs4Circularity Europe (2023) Community of Practice project [link]

At a national level, regulations can play critical roles as enablers of industrial symbiotic networks. Landfill taxes, landfill bans, CO_2 emission controls and waste management policies act as drivers of industrial symbiosis.[202, 203]

Stakeholders we interviewed agreed that carbon prices and landfill taxes provide strong incentives for companies to explore re-using waste and reducing emissions. In addition, a stakeholder highlighted that an increasing emphasis on companies' own sustainability policies is also driving decisions regarding the use of waste/by-products.

Governments can also provide support by stimulating private **sector investments related to reuse and recycling of waste**; and through subsidies for the development of waste exchange networks and projects.[204] In addition, banks and entities promoting private sector contributions through innovation projects and initiatives have also supported some firms in adopting industrial symbiosis.[205]

More streamlined waste regulations can also enable industrial symbiosis. For example, in the case of the EPOS Hull industrial cluster, a review of the current waste legislation was recommended to enable waste streams (including hazardous waste) to be reused as a resource. For example, the cement burner required a new license due to it producing hazardous waste, a procedure that took 26 weeks. Therefore, reducing the administration and lag time in this process was identified as an enabler for reuse of resources. Similarly, additional support mechanisms and incentives such as investment aid to finance joint infrastructure or reducing taxes and penalties were cited as key enablers in cases where positive environmental and social impacts are anticipated.[206]

An **industrial policy framework** is cited as an important enabler as many clusters arise from an organised effort to develop symbiotic or "sustainable" systems.[207] An example of development being stimulated by legislation and regulation is in Italy, where a law outlines a model for 'Ecologically Equipped Industrial Areas' (EEIAs) to guide local developments in achieving industrial symbiosis.[208]

The literature highlights that the development of national and state solid waste policy needs to be matched with an increase in enforcement mechanisms to support these policies. Lessons

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[202] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[203] Notarnicola et al., (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[204] Ceglia et al., (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[205] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[206] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]

[207] Boons, Chertow, Park, Spekkink, & Shi, (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[208] Taddeo (2016) cited in Vladimirova, D., Miller, K., & Evans, S. (2018) -- Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

from the Korean EIP are helpful as they reveal that there was a focus on setting up appropriate legal and regulatory systems from the beginning of the development of industrial parks.[209][210]

UK policies that may incentivise industrial symbiosis

The UK has established a framework of regulations aimed at protecting the environment which may incentivise industrial symbiosis. At the same time, a stakeholder commented that more emphasis on the UK's industrial strategy could provide more clarity as to the areas with most need or potential for industrial symbiosis. Another stakeholder thought that government policy could also help to raise awareness of industrial symbiosis.

The box below summarises the **UK policies that may incentivise industrial symbiosis**.

The **UK Emissions Trading Scheme (UK ETS)** is a carbon pricing mechanism introduced by the UK government to help achieve its carbon reduction targets. The UK ETS is a cap and trade scheme and incentivises businesses to reduce their carbon emissions. This may indirectly encourage some companies to engage in industrial symbiosis. Traded carbon values (prices) are expected to increase over time until 2050, providing a greater incentive for companies to reduce emissions and thus their costs of compliance, which may further incentivise industrial symbiosis. For example, in DESNZ's central scenario the carbon price is expected to increase from £72/tCO2e in 2024 to £87/tCO2e in 2030, and to £138/tCO2e in 2050.[211]

The **UK Climate Change Levy (CCL)** is a tax on the energy usage of businesses and organisations, designed to encourage energy efficiency and reduce carbon emissions. Businesses are charged based on the amount of energy they consume, with higher rates applied to sectors producing more carbon-intensive goods or services. By increasing the cost of energy consumption, the CCL provides a financial incentive for businesses to adopt energy-saving measures and invest in renewable energy sources, and may also increase the attractiveness of industrial symbiosis to reduce overall energy consumption.

The **landfill tax** in the UK aims to reduce the amount of waste sent to landfills while encouraging recycling, reuse, and waste reduction.[212] Under this tax, businesses and waste operators are charged a fee based on the weight of waste they dispose of in landfills, with the tax rate varying depending on the type of waste. In April 2024, the standard rate rose to £103.70 per tonne and the lower rate rose to £3.30 per tonne.[213] Further increases have been announced in the Spring Budget, with the standard rate set to rise to £126.15 per tonne and the lower rate to £4.05 per tonne in 2025-26. The landfill tax serves as a financial incentive for businesses to seek alternative waste management solutions, including through industrial symbiosis.

The **UK Aggregates Levy** is a tax imposed on the commercial exploitation of primary aggregates, such as sand, gravel, and rock, extracted from quarries or pits. This levy aims to discourage excessive extraction of natural resources, promote sustainable use of

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[209] Ceglia et al., (2017) cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]
[210] Park et al., (2016) cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019) -- Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]
[211] DESNZ. (2023). Traded carbon values used for modelling purposes, 2023. [link]
[212] HMRC Landfill Tax (2023) [link]
[213] HMRC Landfill Tax (2023) [link]

aggregates, and encourage the recycling and reuse of construction materials.[214] Certain materials are excluded from this tax. These include coal, lignite, shale, slate, clay, industrial minerals, soil, vegetable (or other organic) material, cut building stone, lime and cement. The tax was £2 per tonne and increased to £2.03 on 1 April 2024.[215] By participating in symbiotic relationships, businesses can access alternative sources of aggregates, reducing their reliance on primary materials subject to the levy.

The **Plastics Packaging Tax** in the UK is a levy introduced by the government to discourage the use of single-use plastic packaging and promote the use of recyclable materials. Under this tax, businesses are charged £210.82 per tonne of finished plastic packaging components that contain less than 30 per cent recycled plastic.[216] This initiative aims to reduce plastic waste and encourage the development of a circular economy for plastics. Through industrial symbiosis, companies can reduce their reliance on virgin plastics and minimise their tax liabilities under the Plastics Packaging Tax.

4.6.2 Evidence from the six chosen sectors

The table below summarises the evidence from the literature and stakeholders regarding regulatory and policy-related enablers and drivers across the six chosen sectors. The sector-specific literature emphasises the importance of government strategy to fund/promote decarbonisation and carbon capture and storage, as well as taxes to incentivise cost saving. At the same time, stakeholders view landfill tax and carbon costs as important incentives, and also consider government strategy and research funding key to driving sector-wide transformations involving industrial symbiosis (e.g. in chemicals and glass).

Table 4.6: Summary of regulatory and policy-related enablers and drivers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	• No specific evidence from sector.	• No specific evidence from sector.
Glass	• Long term environmental targets to reduce CO2 emissions.[217]	• Reducing CO_2 emissions to align with the industry's long-term environmental objectives.
Mining	• Regulations imposing stringent requirements around the storage of tailings (e.g. in South Africa).[218]	• Regulation, including permits/approvals for mining projects and considerations around their environmental footprint.

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[214] HMRC Aggregates Levy (2024) [link]

[215] HMRC Aggregates Levy (2024) [link]

[216] HMRC Plastics Packaging Tax (2024) [link]

[217] Calumite. An essential raw material for the glass industry. [link]

[218] Makhathini, T. P., Bwapwa, J. K., & Mtsweni, S. (2023). Various options for mining and metallurgical waste in the circular economy: a review. Sustainability, 15(3), 2518. [link]

	• Regulations and policies around sustainability and circular economy (e.g. reduced value-added tax for manufacturers using industrial by-products).[219]	• Carbon pricing to incentivise low-energy flowsheets, even though these would be more expensive.
Chemicals	• Clearer and more consistent government policy on development of alternative feedstocks (e.g.carbon capture and utilisation, chemical recycling and the bio-economy are currently separate policy ambitions). • UK government's Net Zero Investment Roadmap providing signals for investment in carbon capture and storage technologies.[220]	• Policy to drive incentives and clarify strategy, e.g. through action plans, clustering incentives and awareness-increasing actions. • Need for uniformity and consistency within industrial policy to transform the sector away from fossil feedstocks.
Food and drink	• Central strategies, policies and regulations e.g. taxation to switch from low-value applications of waste (landfill, composting) to higher-value ones.[221]	• Greater clarity from government regarding future regulations and policies (e.g. inputs permitted for anaerobic digestion plant). • Policy reforms e.g. increase in landfill tax, extension of the UK ETS to waste-to-energy plants in 2028. • Coordination between regulators needed to minimise regulatory burden and to reduce approval times for using waste products.
Agriculture	• Support schemes (e.g. Feed-in Tariffs) to secure investment for low-carbon technologies – although	• Policy and funding to support the installation of carbon capture and storage technologies (e.g. in CEH sector).

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[219] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [link]

[220] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[221] Impoco, G., Arodudu, O., & Brennan G. (2021). Industrial Symbiosis: guide for policy making. SymbioBeer. [link]

	issues about their economic viability remain. - Legislation (e.g. by the European Commission, the Malaysian government) to introduce financial support (e.g. subsidies and tax credits) for agriculture-based biomass fuel.[222]	- Regulatory certainty is needed e.g. regarding carbon credits for the use of quarry fines.

4.7 Analysis of drivers and enablers

In the preceding sections we have set out our typology of drivers and enablers for industrial symbiosis, and presented evidence on the likely effects of regulation and policy.

In this section we present our analysis of the **relative importance of the drivers and enablers**. Our assessment is based on the evidence presented above from the general and sector-specific literature, and the stakeholder interviews. In the table below, we indicate the importance of each driver/enabler using the five-point scale set out below:

- **Very low** – barely mentioned in literature or stakeholder interviews.
- **Low** – mentioned in both literature and by stakeholders, but considered to be of low importance or frequency.
- **Medium** – mentioned often in literature and/or by stakeholders, but not considered to be a key driver.
- **High** – considered to be an important driver in the literature and by stakeholders.
- **Very high** – considered to be an essential driver both in the literature and by stakeholders.

We consider whether the importance of drivers and enablers differs significantly across **sectors and firms of different sizes**. Where this is the case, we indicate this in the table with a range of importance scores.

We also assign a **conviction rating** to the scores based on the strength of the evidence underpinning our analysis, as follows:

- **Weak** – evidence only from 1-3 sources, or sources of lesser quality, and minimal stakeholder interviews.
- **Medium** – evidence found across 3-5 quality sources, and some stakeholder interviews.
- **Strong** – evidence found across multiple quality sources and stakeholder interviews.

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[222] Saleem, M. (2022). Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon, 8(2). [link]

Table 4.7: Analysis of drivers and enablers

Drivers and enablers	Importance	Conviction rating	Rationale
Economic and financial e.g. cost-saving opportunities (such as reduced waste disposal costs, energy efficiency etc.); new revenue streams from sale of by-products; subsidies or grants.	Very High	Strong	Profitability identified as key driver in the general and sector-specific literature, in particular cost savings (rather than new revenue streams). Stakeholders confirm the importance of financial drivers, in particular avoiding landfill tax, saving energy and reducing carbon costs.
Technological e.g. technology to enable waste or by-products to be used as inputs; synergy optimisation technologies to match ‘senders’ to ‘receivers’; digital platforms for collaboration among stakeholders.	Medium to Very High depending on sector.	Medium	General literature mentions importance of digital platforms for matching, and synthesis paper mentions importance of technology to ensure viability of synergies. Sector literature scarcely mentions as driver/enabler. Stakeholders agree that some degree of technology can be necessary to enable synergies (e.g. matching platforms and technology that enables the use of by-products). Considered Very high for the chemicals sector. Much more widely noted as a barrier.
Information and knowledge e.g. awareness of industrial symbiosis opportunities; tools for evaluating potential symbiotic relationships; technical expertise for implementing industrial symbiosis; external facilitation and management of synergies.	Medium to High depending on sector and size/sophistication of firms.	Strong	General and sector-specific literature fairly extensive on the importance of information and knowledge in identifying and establishing symbiotic synergies, including the value of facilitators. Also supported by stakeholders as an important enabler, particularly the value of facilitation among SMEs. Appears relatively more important for more fragmented sectors such as agriculture and food and drink. However, a number of individual stakeholders are undertaking IS without facilitation and do not consider information / technical knowledge as the most important driver of IS.

Regulatory and policy-related e.g. to mandate resource efficiency or influence financial incentives for businesses such as taxes; environmental regulations and targets; industrial funding and strategies.	Medium to High depending on sector	Strong	General literature mentions role of funding and policies to support IS, wider waste and emissions goals and industrial policy; mentioned in some papers as critical. Sector-specific literature covers the importance of government strategy to fund/promote relevant activities such as decarbonisation and carbon capture and storage, and taxes to incentivise cost saving. Stakeholders view landfill tax and carbon costs as important incentives, and also consider government strategy and research funding key to driving sector-wide transformations involving industrial symbiosis (e.g. alternative feedstocks in chemicals and glass). In addition, some viewed companies' internal environmental and decarbonisation strategies – influenced by policy – as relevant drivers.
Geographical e.g. industrial/eco-industrial parks/clusters; close geographic proximity; the availability of logistic networks and shared, suitable physical infrastructure (e.g. storage).	Low to High depending on value/bulk of by-product concerned and difficulty of transportation.	Medium	The general literature discusses the importance of clusters and industrial parks for IS, but there are many examples of successful IS without close geographic links or EIPs. Sector-specific literature mentions importance of geography in relation to heavy/bulky or difficult to transport by products, or sectors that have historically been located in clusters, like chemicals. Stakeholders note that geography (and associated costs) tends to be considered along with other factors in determining the value of a potential synergy. However, it is considered an essential enabler for CEH, and important for chemicals.

Organisational, social and cultural e.g. trust between firms, common goals, collaboration and environmental awareness	Low	Weak	The general literature discusses the importance of environmental awareness and a positive culture towards industrial symbiosis. Very rarely mentioned in the sector-specific literature or by stakeholders as an enabler.

4.8 Summary

Evidence from the literature and stakeholders points to a range of drivers and enablers of industrial symbiosis.

Among the six categories that we have analysed, **financial drivers and enablers are considered the most important**, scoring ‘very high’ in our ranking. Essentially, companies will only consider industrial symbiosis if the benefits (in terms of various savings and revenue creation) justify the costs. Financial drivers are linked to other drivers in that many of these will have a cost element, for example geographic proximity is an enabler as it reduces the costs of transporting materials; and regulatory and policy-related factors can reduce or subsidise the costs of industrial symbiosis for firms, or drive them to pursue symbiotic networks as a way of reducing costs and taxes.

Some drivers and enablers **vary in their importance depending on the sector or nature of firms**. This is particularly the case with geographic proximity which is key in sectors where materials are difficult or costly to transport; technological enablers where the sector requires innovative production methods to expand the use of by-products (such as chemicals and cement); and knowledge and informational enablers for smaller or less sophisticated firms and for sectors that are more diverse. Policy-related drivers are considered particularly important in encouraging industrial symbiosis in sectors where this is linked with sector-wide transformation of production processes to make use of by-products, for example research funding and strategic policies in the chemicals and glass sectors.

5 Barriers to Industrial Symbiosis

In this section we present evidence from the literature and stakeholder interviews on the barriers to industrial symbiosis, both in general and for our six chosen sectors. This is followed by our **analysis** of which barriers are market and regulatory failures and our assessment of the relative importance of different barriers to industrial symbiosis.

We have placed barriers into six categories, namely:

- technological;
- technical knowledge and other information;
- organisational and cultural;
- geographical;
- economic and financial; and
- regulatory and policy-related.

Our typology of barriers of industrial symbiosis is intended to assist in review, albeit acknowledging the overlaps between categories.

5.1 Technological

5.1.1 Evidence from the general literature and stakeholder interviews

Shortfalls in technologies can pose a barrier to sustainable by-product exchanges.[223] Even where technology may already be in place to develop synergies, it may not be commercially available or scalable, or may be too costly to adopt.[224] Companies may also not prioritise investment in the necessary technologies – for example, if there is a lack of appetite to engage in industrial symbiosis or there are competing demands on resources. In addition**, insufficient technology for waste stream management** can also impede industrial symbiosis. Waste and by-products often consist of chemical mixtures, presenting significant challenges in terms of clean-up or separation processes before they can be reused or recycled.[225] Effective transformation of waste often demands intricate and specialised technological solutions.

Around half of the stakeholders that we interviewed noted the **significant research, development and testing required** before particular waste/by-products can be used in production processes. This means that companies often require some 'proof of concept' before technologies are rolled out at industry scale, which poses a barrier to the adoption of symbiotic exchanges. Stakeholders also saw the **high costs associated with many new technologies**

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[223] Bacudio et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[224] Henriques, J., Ferrão, P., Castro, R., and Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[225] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

and processes (e.g. carbon capture and storage; developing alternative feedstocks for chemicals; infrastructure to adapt to alternative fuels in cement and glass sectors) as a key barrier. A number of stakeholders highlighted that funding and support was needed for both researchers and industries to ensure that the required infrastructure is available at industry scale.

One stakeholder highlighted the **lack of suitable processes to incorporate synthetic waste gypsum** in the cement manufacturing process. This is because the system used to incorporate gypsum at the stakeholder's cement manufacturing facility is tailored for processing rocky gypsum, while plasterboard yields a finer material, which is incompatible with the system. As a result, the manufacturer can only use about 5-10 per cent of the waste/recycled gypsum it receives in its production.

However, some stakeholders were of the view that technological barriers are not very relevant for the majority of companies, citing examples of synergies already taking place enabled by the necessary technology which is already available.

Stakeholders thought that technological barriers were greatest in sectors in which industrial symbiosis is part of a sector-wide change involving the replacement of inputs with by-products, as this requires fundamental changes to production technologies. Examples would be moving towards alternative feedstocks in chemicals, or using waste-derived fuels in the glass and cement sectors.

In general, stakeholders did not think that barriers related to the availability of suitable technologies and processes varied noticeably by firm size. Some noted that **smaller companies can be more agile** in terms of developing new uses for by-products and waste, **but often need to partner with bigger companies** or access funding in order to scale up their research.

Research and innovation

The **absence of adequate research** can pose a barrier to exploring opportunities to exchange materials, with certain materials posing considerable technological challenges. Stainless steel slags, for example, contain components that could serve as valuable feedstocks in cement production; however, due to the lack of research in this area, a feasible symbiotic network has not yet been identified.[226]

While innovation frequently enables symbiotic exchanges to bring (net) benefits to a sector as a whole, individual firms may be reluctant to explore and participate in these exchanges if there is a chance that they **would not capture a large enough proportion of the benefits** individually to justify this expense. This relates to the concept of innovation spillovers, in which innovation by one organisation creates benefits for other organisations which copy or build on the innovation. A stakeholder noted that intellectual property is often raised as an issue in expanding industrial symbiosis. For example, start-ups working with universities can be

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[226] Iacobescu et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

hesitant to engage in industrial symbiosis discussions and/or to share results because they want to protect intellectual property related to their research or products.

A few stakeholders noted that, in order to cut costs, some industries have reduced their in-house capacity to carry out research into how materials can be replaced with by-products. In turn, this reduces the ability of these companies to explore the use of new materials and by-products and to develop business cases for investing in industrial symbiosis processes.

For example, a stakeholder we interviewed mentioned that many companies (including theirs) have reduced their innovation efforts to cut costs and rely on external research partners to find ways of using co-products. This can be a lengthy process as it requires more negotiating and collaboration time compared to in-house research.

5.1.2 Evidence from the six chosen sectors

The table below summarises the key technological barriers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.1: Summary of technological barriers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	• Lack of research and relevant technology.[227] • Technical feasibility of using alternative secondary cementitious materials.[228]	• Cost and availability of technology: • Additional investment required to handle and use waste-derived fuels. • Lack of suitable processes to incorporate synthetic waste gypsum.
Glass	• Lack of accommodative technology enabling the use of alternative raw materials. • Technical feasibility of using waste-derived fuels (e.g. impacts on furnaces and products).[229]	• New technical solutions required to enable the use of waste-derived fuels. • Significant further investment in infrastructure to enable the use of alternative raw materials and fuels.
Mining	• No technological barriers identified.	• No technological barriers identified.

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[227] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [online]

[228] Sourmelis, S., Pontikes, Y., Myers, R. J., & Tennant, M. (2024). Business models for symbiosis between the alumina and cement industries. Resources, Conservation and Recycling, 205, 107560. [online]

[229] British Glass. Glass sector Net zero strategy 2050. [link]

Chemicals	- High cost of equipment required to process alternative feedstocks. [230] - Shortage of cheap, low-carbon energy to enable the shift from fossil-fuel derived chemicals to green alternatives. - Lack of commercially viable techniques. [231]	- Some technology not yet proven and still very expensive. - Significant investment required in new equipment and infrastructure to enable new forms of industrial symbiosis. - Lack of funding for research to provide 'proof of concept' and scalability for new technologies.
Food and drink	- No technological barriers identified.	- Lack of willingness to commit resources to innovation projects unless directly beneficial to company. - Collaborating with external research partners to research uses for co-products costly and time-consuming.
Agriculture	- Expensive technology for CO_2 capture and storage for the CEH sector.[232]	- Expensive technology for CO_2 capture and storage for the CEH sector. - Technologies that could enable other forms of industrial symbiosis in agriculture are not yet fully developed or scalable.

5.2 Technical knowledge and other information

5.2.1 Evidence from the general literature and stakeholder interviews

A barrier to realising industrial symbiosis arises when stakeholders **lack awareness of industrial symbiosis concepts** or do not possess sufficient expertise in industrial symbiosis terminologies. This was reported as key a barrier by about half of the stakeholders interviewed for our study. They noted that low levels of awareness about industrial symbiosis and the general **lack of information about potential uses of waste streams, opportunities for collaboration and potential partners** are all key barriers to establishing such relationships.

Similarly, the literature notes that barriers can also arise when companies are aware of potential exchanges but **lack the necessary knowledge to engage in symbiotic practices**

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[230] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[231] Henriques, J., Ferrão, P., Castro, R., and Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[232] DEFRA R&D Report. (2023). Foresight study to compare the relative gains, costs, feasibility and scalability of current and future 'industrial horticulture' models. [link]

— specifically, they may struggle to identify counterparties for the purchase or sale of waste by-products, or they may lack the necessary technical expertise, such as understanding the procedures and methodologies involved. A lack of information concerning potential processes and materials could further exacerbate these challenges.[233, 234] Some companies may not have the requisite knowledge of how specific waste streams perform when used as inputs and may lack knowledge of industrial sustainability, whether at the corporate, occupational or community level.[235]

The Hubs4Circularity (2023) Community of Practice project highlighted that companies lack knowledge about other companies with whom they could form partnerships.[236] This is related to the issue that **companies may not consider their by-products to be viable inputs for other sectors**, and buyers are unaware of these sources of materials due to a lack of marketing activities for waste streams.

Furthermore, **a lack of information sharing** and conflicts arising from differing stakeholder objectives can impede resource exchange, including the dissemination of critical information.[237]

In addition to resource availability, stakeholders also noted the **potentially significant costs involved in exploring these exchanges** due to the cross-sectoral nature of exchanges, which require firms to understand processes in industries that are less familiar to them. Stakeholders noted that even when these opportunities are identified there is a significant uncertainty around securing a contract. For example, one project brought together around 100 sites and identified over 400 potential links between them involving the re-use of materials, but after negotiations around four have resulted in contracts to send and re-use materials, with an additional two agreements to produce new materials by combining co-products.

Stakeholders suggested that company size could further exacerbate these issues, as **SMEs may be more likely to lack the knowledge, time and resources** to explore and establish potential symbiotic relationships. However, difficulties faced by larger companies were also mentioned.

It can also be difficult to entice participants to engage in symbiotic relationships due **to insufficient or low-quality data** on the types, quantity, and location of waste streams, and **uncertainty about the continuity of waste flows in sufficient quantities and quality**.[238, 239,]

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[233] Low et al., 2018, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[234] Henriques, J., Ferrão, P., Castro, R., and Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[235] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[236] Hubs4Circularity Europe. (2023). Community of Practice project. [link]

[237] Bacudio et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018) -- Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[238] Song et al, 2017, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[239] Felicio et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[240] These difficulties can also pose challenges to cost-effectively collecting and processing significant amounts of information.[241, 242]

Stakeholders expressed similar concerns regarding the quality of waste/by-products, noting that the scarcity of an input, or competition for these products from other sectors, could further exacerbate uncertainties around their availability. This was mainly an issue in the cement and glass sectors, although it was also mentioned as an issue for controlled environment horticulture (in relation to stable supplies of waste heat). These uncertainties may also **affect firms' decisions about whether to invest in (new) technology** that would enable them to use these streams as replacement inputs in their production processes.

Uncertainties about the quality of waste/by-products were noted by stakeholders as a particular concern in cases where the chemical consistency of the input(s) could affect the quality of the final products (e.g. glass, cement). Nevertheless, some stakeholders noted that this was less of a hard barrier and more of a cost/burden, as additional research has to be carried out to test the impacts of different materials.

Companies also expressed concern over a lack of information about the economic sustainability of industrial symbiosis. Industrial symbiosis practices are perceived as costly and risky for the reasons given above, and companies reported that they are hesitant to adopt industrial symbiosis business models, and are most inclined to focus on end-of-life products.[243]

5.2.2 Evidence from the six chosen sectors

The table below summarises the key barriers related to technical knowledge and other information highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.2: Summary of technical knowledge and other information related barriers in the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	• Lack of awareness and/or knowledge of waste streams. • Uncertainty about quality of alternative raw materials and waste-derived fuels which can	• Lack of awareness and/or knowledge of waste streams – a more systematic approach is needed to connect waste producers with potential users. • Uncertainty about quality of alternative raw materials and

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[240] Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., & Matias, J.C.O. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. Sustainability, 11(24), 7095. [link]

[241] Holgado, M., Benedetti, M., Evans, S., Baptista, A.J., Lourenço, E.J.. (2018) Industrial Symbiosis Implementation by Leveraging on Process Efficiency Methodologies, Procedia CIRP, 69. [link]

[242] Song et al, 2017, cited in Vladimirova, D., Miller, K., & Evans, S. (2018) -- Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. [link]

[243] Hubs4Circularity Europe. (2023). Community of Practice project. [link]

	affect quality of final product.[244] • Uncertainty around the supply of specific waste streams (fly ash, GGBS).[245]	waste-derived fuels which can affect quality of final product. • Lack of secure and substantial supply of waste products which can disrupt operations.
Glass	• Varying quality and consistency of lower grade fuels.[246] • Lack of confidence in future fuel availability affects willingness to invest in alternative fuel technologies.[247]	• Uncertainty about the supply of waste-derived fuels which can disrupt operations. • Uncertainty about the supply as well as quality of alternative raw materials (by-products) can disrupt operations and/or affect the quality of final product.
Mining	• Lack of information sharing, driven by data protection rules and commercial sensitivity.[248]	• Lack of information sharing. • Lack of awareness and knowledge. • Uncertainty about the quality of by-products as variability in quality of mine tailings can have knock-on impacts on processes
Chemicals	• Lack of information sharing.[249]	• Challenges in understanding which waste/by-products can be re-used and how, especially in the downstream production of chemicals. • Lack of information on sources of emissions in waste materials to identify opportunities for exchanges.

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[244] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [online]

[245] Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). Review of successful IS methods and systems for the cement industry. EPOS. [online]

[246] British Glass. Glass sector Net zero strategy 2050. [link]

[247] BEIS. (2022). Renewable Waste-Derived Fuels for Glass and Ceramics Manufacturing: Feasibility Study. [online]

[248] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [online]

[249] Cervo, H., Ogé, S., Maqbool, A.S., Alva, F.M., Lessard, L., Bredimas, A., Ferrasse, J., & Eetvelde, G.V. (2019). A Case Study of Industrial Symbiosis in the Humber Region Using the EPOS Methodology. *Sustainability*, 11(24): 6940. [link]

		- Uncertainty around security of supply, exacerbated by competition from other industries.
Food and drink	- Limited resources available to identify opportunities. - Lack of collaboration and information exchange among companies.[250]	- Lack of awareness and information about industrial symbiosis. - Lack of knowledge, meaning that by-products are classified as waste. - Reluctance to invest time/resources into developing new products and technologies to process waste and by-products due to limited information about benefits. - Uncertainty about the security of supply and/or quality of waste/by-products, especially in the case of smaller sending companies.
Agriculture	- Uncertainty about reliable, consistent fuel supply from bioenergy.[251] - Lack of documented cases and detailed descriptions of how organic matter is used, hindering the scaling up of these initiatives.[252]	- General lack of incentives to find out about opportunities or industrial clusters. - Significant time required to arrange symbiotic exchanges. - Uncertainty about the supply and quality of waste/by-products. - Conservative nature of sector means that stakeholders are less willing to take on risk.

5.3 Organisational, social and cultural

5.3.1 Evidence from the general literature and stakeholder interviews

An important barrier inhibiting industrial symbiosis can be **low levels of trust between potential stakeholders**.[253, 254] This could be particularly problematic for organisations that are

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[250] Patricio, J., Axelsson, L., Blome, S., & Rosado, L. (2018). Enabling industrial symbiosis collaborations between SMEs from a regional perspective. Journal of Cleaner Production, 202, 1120-1130. [link]

[251] Bioenergy Association. Overview of the drivers for bioenergy solutions – a market analysis. [link]

[252] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]

[253] Aid et al. 2017, cited in Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]

[254] Low et al., 2018, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

competing with each other.[255] It can be difficult for companies to have a relationship that is strong and trusting enough to form a symbiotic network.[256]

Furthermore, **the lack of prior cooperation with other companies can reinforce the lack of trust** that exists between potential partners for industrial symbiosis. As seen in the literature, all respondents mentioned that a lack of trust (to share data on energy usage, materials flows quantity etc.) was among the most important challenges in the adoption of industrial symbiosis practices.[257]

A **lack of top management support**, which is essential for the success of industrial symbiosis, represents another significant obstacle that can hinder the development of a symbiotic network. The implementation of industrial symbiosis initiatives could be further impeded by **inadequate leadership and management practices**, which hinder effective training programmes for industrial symbiosis implementation.[258]

Moreover, a **lack of communication** and dialogue between the companies involved and the **absence of a robust network**, including policy actors, industries and knowledge agents, further hampers the development of industrial symbiosis.[259]

Stakeholders to whom we spoke considered that the key barrier is the **costs and difficulties involved in changing company culture**. One stakeholder mentioned that a lack of a collaborative culture, and especially a mindset among firms of thinking only about their own sector, posed a barrier to industrial symbiosis. Collaborative efforts can depend on companies' location too, as some regions or clusters were considered to have a stronger collaborative culture than others.

Some stakeholders noted that large companies' attitudes to smaller firms can also be a potential barrier. For example, it can be challenging for a small firm interested in a symbiotic synergy to effectively communicate with a large firm (e.g. a steel foundry), as the large firm may not think that it is worthwhile to engage with the smaller one.

In other cases, even where opportunities for information and knowledge exchange could be established, companies or parties involved in research projects may be **hesitant or slow to share results with other firms or potential collaborators** due to competition concerns. Fragmentation within a sector (e.g. in the case of chemicals) can also make communication and collaboration more costly and difficult.

The tendency of businesses to **concentrate on their core activities** was also seen as a barrier which further hinders their willingness to explore and engage in symbiotic exchanges. A

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[255] Taddeo, 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]
[256] Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087-1108. [link]
[257] Hubs4Circularity Europe. (2023). Community of Practice project. [link]
[258] Bacudio et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]
[259] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

few stakeholders, particularly from the food and drink, agriculture and cement sectors, were of the view that their sectors are typically conservative in relation to new sources of inputs (as well as restricted by tight margins), especially if there is a perceived risk, as is the case with industrial symbiosis.

Another barrier highlighted in the literature is that **firms with established and stable supply chains may be hesitant to alter their existing practices.**[260] The WMCA report highlights organisational barriers in the WMIS program due to the self-organised/unfacilitated approach of the current material exchange system in operation in the region.[261]

The literature suggests that a **lack of government funding** and awareness to promote industrial symbiosis and the dissemination of information can also act as a barrier in some cases.[262] In cases in which markets are immature, the market might also not be prepared for the incorporation of industrial.[263]

5.3.2 Evidence from the six chosen sectors

The table below summarises the key organisational, social and cultural barriers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.3: Summary of organisational, social and cultural barriers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	No organisational, social and cultural barriers identified.	No organisational, social and cultural barriers identified.
Glass	No organisational, social and cultural barriers identified.	No organisational, social and cultural barriers identified.
Mining	No organisational, social and cultural barriers identified.	• Existing supply chains may not accommodate new suppliers, especially if the technical properties of waste/by-products are different.
Chemicals	• Lack of intermediaries promoting communication between parties.[264]	• Lack of open communication and collaboration to share waste/by-products.

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[260] Taddeo, 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[261] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Case for Investment.

[262] Bacudio et al., 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[263] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[264] Henriques, J., Ferrão, P., Castro, R., and Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

	- Lack of commitment to sustainable development.[265]	
Food and drink	No organisational, social and cultural barriers identified.	- Cultural issues within firms and a focus on core activities could exacerbate firms' reluctance to invest time and resources into developing new products and technologies to process waste/by-products.
Agriculture	No organisational, social and cultural barriers identified.	- Lack of forward planning and joined-up thinking could hamper industrial symbiosis, especially in relation to the location of new industrial sites.

5.4 Geographical

5.4.1 Evidence from the general literature and stakeholder interviews

The geographical scope of industrial symbiosis projects may be limited by several factors. Firstly, **technological feasibility becomes a concern when transporting certain types of resources over long distances**, like steam or heat. Secondly, the **cost-to-value ratio of transportation** becomes significant, particularly for resources with high volume and low value (e.g. sludge), and this can also act as an economic barrier. Long distances, especially, are highlighted as the most critical geographical barrier.[266]

While not necessarily a key barrier, stakeholders highlighted **transportation costs** as an important factor in companies' decisions about the use of waste/by-products in their production processes. In particular, around a third of the stakeholders that we interviewed stated that they faced high costs transporting these products, often over significant distances. By contrast, a minority of stakeholders were of the view that transportation costs were not a barrier to using waste/by-products. Moreover, some stakeholders noted the **lack of infrastructure or a logistical network** to transport resources between companies further exacerbates the problem.

The **environmental impacts of transporting waste materials** over extended distances can also affect project feasibility. Some stakeholders in the cement and mining sectors also stated that, in their case, the use of waste/by-products (e.g. waste-derived fuels) required a model shift from rail to road transport, which also contributes to higher emissions.

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[265] Cervo, H., Ogé, S., Maqbool, A.S., Alva, F.M., Lessard, L., Bredimas, A., Ferrasse, J., & Eetvelde, G.V. (2019). A Case Study of Industrial Symbiosis in the Humber Region Using the EPOS Methodology. *Sustainability*, 11(24): 6940. [link]

[266] Henriques, J., Ferrão, P., Castro, R., and Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

One stakeholder mentioned **planning controls or other regulations that prevent relevant firms from locating together** as a barrier to industrial symbiosis – this was in the chemicals sector and related to the administrative burden of co-locating a chemicals site with a foundation industry site.

5.4.2 Evidence from the six chosen sectors

The table below summarises the key geographical barriers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.4: Summary of geographical barriers in the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	• High costs of transportation of SCMs.[267]	• High costs of transportation. • Modal shift to road transport leading to increased costs and reduced CO_2 savings.
Glass	No geographic barriers identified.	No geographic barriers identified.
Mining	No geographic barriers identified.	• High costs of transportation. • Mode of transport may also limit the volume of waste/by-products that can be transported.
Chemicals	No geographic barriers identified.	• Different parts of supply chain located far away from each other. • Regulations about co-location of firms, especially where waste/by-products are difficult to transport. • High costs of transporting bulky chemicals.
Food and drink	• Challenges around co-location of food and drink and other industries due to perishable nature of waste.[268]	No geographic barriers identified.
Agriculture	• Challenges of co-locating CEH with suitable waste heat sources due to zoning restrictions and geographical	• High costs of transportation (e.g. for wheat straw).

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[267] Hashimoto, S., Fujita, T., Geng, Y., & Nagasawa, E. (2010). Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. Resources, Conservation and Recycling, 54(10), 704-710. [online]

[268] Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G.,D'Amico, M. (2023). Industrial symbiosis in the agri-food system: themes, links and relationships. Frontiers, 6. [link]

	distribution of industrial sites.[269]	- Low cost-to-value ratio of transportation (e.g. for poultry manure).

5.5 Economic and financial

5.5.1 Evidence from the general literature and stakeholder interviews

Economic and financial barriers can be linked to a number of other barriers that have been discussed, as many of these have a financial element. However, in this section we focus on additional barriers that are economic and financial in nature.

The literature notes that industrial symbiosis can entail **high set-up costs** compared with other forms of waste disposal including landfill, the costs of which remain relatively low in the EU. Additionally, there may be financial barriers such as credit constraints, which may **prevent investment** in these projects.[270] Stakeholders we interviewed expressed similar concerns and stated that high fixed costs in many sectors also mean that firms need to pay off investments by **continuing to use the same production processes** rather than switching to ones using alternative fuels or raw materials (e.g. in the case of cement).

A company in the chemical industry mentioned that investment in an oil cracker plant (a type of petrochemical facility that processes crude oil to produce smaller, more useful molecules e.g. naphtha) could be around £2 billion. This highlights the scale of opportunity cost in transforming the industry away from fossil-based feedstocks towards alternatives such as flue gases or plastics.

The West Midlands Combined Authority (2020) cites financial barriers – primarily the cost of access to an information and communication technology (ICT) platform – as an impediment to gaining access to the information required for industrial symbiosis.[271]

The report by Hubs4Circularity (2023) highlighted that the **lack of funds available to support the high initial costs of infrastructure** is a key barrier.[272] For the establishment of industrial symbiosis networks that require infrastructure for heat exchange, the initial costs of the infrastructure tend to be very high. Indeed, the European Commission report finds that the majority of the industrial symbiosis networks in Europe are funded by the government, and are not self-sustaining.[273]

Linked to uncertainties about the return on investment, some stakeholders thought that companies needed **assistance to access the innovation required** to e.g. enable a waste

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[269] DEFRA R&D Report. (2023). Foresight study to compare the relative gains, costs, feasibility and scalability of current and future ‘industrial horticulture’ models. [link]

[270] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

[271] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Case for Investment.

[272] Hubs4Circularity Europe. (2023). Community of Practice project. [link]

[273] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

product to be effectively used as an input. In addition, stakeholders highlighted the time and effort involved in going from the initial identification of potential synergies through to an actual contracted agreement.

Many **businesses often do not see waste as a valuable commodity** but instead as material to be disposed of as quickly and cheaply as possible.[274] It may also not be cost-effective to engage in waste-to-resource exchanges, for example due to costs related to collection, sorting and recycling.[275] Some managers or owners may **focus solely on what they consider to be the core business** and may view industrial symbiosis as a distraction. As a result, there might be a hesitancy to divert resources, both human and financial, from current business processes.[248] This links with the cultural and organisation barriers to industrial symbiosis discussed earlier.

While in general stakeholders did not view **low carbon prices** as a key barrier to industrial symbiosis, some noted their importance in terms of the types of waste/by-products used (e.g. in the case of the glass and chemicals sectors, see below).

5.5.2 Evidence from the six chosen sectors

The table below summarises the key economic and financial barriers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.5: Summary of economic and financial barriers in the six chosen sectors

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	No economic and financial barriers identified.	• Not commercially viable to send/sell by-products (e.g. kiln bypass dust) to other sectors.
Glass	• High operational costs for biofuels which may rise further in future.[276] • Costs of processing glass waste compared with sending to landfill. [277]	• High cost of processing by-products to send/sell waste glass to other sectors (compared with landfill costs).
Mining	No economic and financial barriers identified.	• Lack of funding opportunities, linked to general negative reputation of sector.

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[274] Notarnicola, Tassielli, & Renzulli, 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[275] Low et al., 2018, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[276] British Glass. Glass sector Net zero strategy 2050. [link]

[277] Interdisciplinary Circular Economy Centre for Mineral-Based Construction Materials (2023) “Policy Brief – Landfill Tax, Construction and Demolition Waste and the Circular Economy”

Chemicals	No economic and financial barriers identified.	- Lack of commercial incentives to move away from fossil carbon to alternative feedstocks due to the costs involved.
Food and drink	- Lack of commercial incentive to take financial risks with industrial symbiosis due to low margins in the sectors.[278]	- Difficulties in making a viable product out of waste that can be sold in a market.
Agriculture	- Lack of funding to make an agriculture biomass-derived fuel feasible and competitive with conventional fuels.[279]	- High cost of carbon capture and storage facilities, particularly for smaller emitters not able to capture/sell a sufficient volume of CO_2 to make investments worthwhile.

5.6 Regulatory and policy-related barriers

5.6.1 Evidence from the general literature and stakeholder interviews

Both a lack of regulation or overly rigid economic regulations can limit symbiotic relationships.[280][281]

In the UK, the **Waste Framework Directive** sets out definitions related to waste management, including definitions of waste, by-products and end of waste. In order for a by-product to be eligible for re-use, it must either never have been classified as waste and meet a ‘by-product’ test or ‘reuse’ requirements; or it must be declared ‘end of waste’. Materials that have been discarded are defined as waste and cannot be re-used without being subject to waste regulations. In order to determine whether a by-product is not waste, or to obtain end of waste status, producers must fulfil a number of tests and procedures which can take significant time and resources, and involve interactions with a number of regulatory bodies. These can act as a deterrent or barrier to undertaking industrial symbiosis.[282]

The literature also found that **complex, often bureaucratic procedures and the high costs incurred by businesses** to acquire the permits required to re-use waste/by-products in production processes can deter industries from adopting industrial symbiosis. Exchanges of waste materials can be especially complicated as in some cases these cannot legally be

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[278] Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G.,D’Amico, M. (2023). Industrial symbiosis in the agri-food system: themes, links and relationships. Frontiers, 6. [link]

[279] Saleem, M. (2022). Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon, 8(2). [link]

[280] Mulrow, Derrible, Ashton, & Chopra, 2017, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[281] Low et al., 2018, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[282] GOV.UK. (2024). Check if your material is waste. [link]

exchanged. Negotiations with regulatory authorities are needed to overcome this (provided safety requirements are met), and such discussions may be brokered by intermediaries.[283]

Over half of the stakeholders we interviewed mentioned similar issues around **waste regulations** hindering the re-use of waste in production processes. In their view, this barrier is especially relevant for sectors in which it is more complex to demonstrate that waste and by-products meet the conditions for end of waste status. One stakeholder noted that end of waste regulations are also a source of many legal cases (as companies go to court to prove that a material can be safely considered 'end of waste'), which can deter companies from seeking end of waste status as not many of them have the expertise and resources to go through the relevant case law to make their case. In addition, some stakeholders noted that a hazardous label on waste could also significantly hinder re-use of these materials, which will likely end up in landfill. However, this would only be a barrier in cases in which by-products could be safely re-used (e.g. after some processing); in cases in which materials should not be used due to safety considerations, then the regulations are appropriate. Given these complexities, stakeholders also commented that there needs to be an incentive to find a purpose for waste/by-products before these are classified as waste (although they considered that demonstrating that a material is not waste is also burdensome).

Stakeholders also mentioned that the time taken by the Environment Agency to reach a decision on whether specific waste materials meet the conditions for end of waste status can be significant and can further deter investment. Some stakeholders considered that greater capacity within regulators to apply the relevant regulations was needed. Moreover, the **uncertainty** related to whether the Environment Agency will decide that a material meets the conditions for end-of-waste status can also deter investment in industrial symbiosis.

Another stakeholder reported it took the Environment Agency 10 months to provide it with a decision on the waste status of one of its products, during which time the company was unable to market or invest further in the product. Additionally, the firm invested approximately £22,000 in legal advice regarding the waste status of their product, which was a considerable expense for them as a small business.

Uncertainty about future policy or regulations, including in relation to the environment, waste management, and industrial ecology, has been raised as another key barrier in the literature.[284] According to a survey conducted by the European Commission, the risk and uncertainty related to regulatory compliance is among the biggest barriers to industrial symbiosis.[285]

For example, in the WMIS Programme, the restrictive regulatory framework for waste disposal is considered to be a primary obstacle to the implementation of industrial symbiosis. These

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[283] Taddeo, 2016, cited in Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

[284] Henriques, J., Ferrão, P., Castro, R., & Azevedo, J. (2021). Industrial Symbiosis: A Sectoral Analysis on Enablers and Barriers. Sustainability,13(4), 1-22. [link]

[285] European Commission. (2018). Cooperation Fostering Industrial Symbiosis. [link]

regulations obstruct the transfer of waste materials between various sectors and businesses. This constraint often stems from the definition of waste within this framework.[286]

According to stakeholders **unexpected changes in rules and regulations** can also create significant risks for businesses, which could affect decisions about whether to use waste/by-products as inputs. Unintended consequences from government policy can further exacerbate such risks. For example, a stakeholder in the cement sector stated that it lost access to animal meal due to the Renewable Heat Incentive (RHI), which meant that it became more financially advantageous for animal meal suppliers either to produce biomethane or to combust animal meal themselves to generate power. In the stakeholder's view, the incentive was introduced despite evidence that the use of animal meal for energy generation is far less energy-efficient (achieving around 20-25 per cent efficiency) than using it in cement kilns where efficiency reaches 100 per cent.

The **lack of effective funding frameworks** has been cited in the literature as a reason why companies find it challenging to access sufficient funding to invest in the infrastructure for industrial symbiosis. For example, government funding in Europe tends to go to technology with low readiness levels (which is not yet suitable for use by companies in industrial symbiosis) rather than to mature technology.[287] Our stakeholder evidence suggests that there is substantial funding in the UK for industrial symbiosis research programmes, but that a number are still at a low readiness level, meaning that there is uncertainty as to how much these programmes will contribute to industrial symbiosis in reality.

Furthermore, the application process for grants can be a significant burden (combined with intense competition for the available funds), which can make companies hesitant to apply. A report suggested that while the available funds cover capital expenditure, operating expenditures also tend to be high, which can limit companies' ability to take projects forward as a significant proportion of costs are not covered by funding frameworks.[266]

5.6.2 Evidence from the six chosen sectors

The table below summarises the key regulatory and policy-related barriers highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 5.6: Summary of regulatory and policy-related barriers in the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	• Adherence to existing industry standards can limit the use of SCMs.[288]	• Adherence to existing industry standards can limit the use of SCMs. • Time and cost involved in updating standards can delay products that

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[286] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Case for Investment.

[287] Hubs4Circularity Europe. (2023). Community of Practice project. [link]

[288] Sourmelis, S., Pontikes, Y., Myers, R. J., & Tennant, M. (2024). Business models for symbiosis between the alumina and cement industries. Resources, Conservation and Recycling, 205, 107560. [online]

	• Narrowly defined regulations can hinder symbiotic exchanges.[289]	use alternative raw materials being brought to the market. • Variation in permit required for both the trial and use of new alternative raw materials. • Regulations may result in unintended consequences e.g. diverting waste/by-products to other sectors. • Waste regulations can limit the waste/by-products used. • Planning permission can be required to extract certain waste/by-products (e.g. landfill ash).
Glass	• Shifts in government policy can affect the availability and supply of waste/by-products e.g. biofuels.[290]	• No regulatory and policy-related barriers identified.
Mining	• Regulatory and policy environment (e.g. exemption from landfill taxes).[291] • Lack of appropriate regulatory frameworks. • Lack of research into circular supply chains for industrial symbiosis.[292]	• Waste regulations can limit the re-use of waste/by-products (e.g. processing is limited to certain processes such that the waste/by-product is not available in a usable form). • Compliance with regulatory requirements (e.g. Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) for sulphate of potassium).[293]
Chemicals	• Lack of clarity and guidance on the de-fossilisation technologies to focus on.[294]	• Lack of clarity and guidance on the de-fossilisation technologies to focus on (e.g. plastics, biomass or flue gases).

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[289] Hashimoto, S., Fujita, T., Geng, Y., & Nagasawa, E. (2010). Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. Resources, Conservation and Recycling, 54(10), 704-710. [online]

[290] British Glass. Glass sector Net zero strategy 2050. [link]

[291] Kinnunen, P., Karhu, M., Yli-Rantala, E., Kivikytö-Reponen, P., & Mäkinen, J. (2022). A review of circular economy strategies for mine tailings. Cleaner Engineering and Technology, 8, 100499. [online]

[292] Resource Recovery from Waste. (2018). Making the most of industrial wastes: strengthening resource security of valuable metals for clean growth in the UK. [online]

[293] A stakeholder noted that sulphate of potassium (SOP), a by-product of the mining industry, can be used in the agricultural sector. However, it faces regulatory barriers as it must comply with the REACH regulations in both the UK and the EU.

[294] Innovate UK. (2019). Unlocking the UK's biomass resources as a feedstock for Chemical Manufacturing. [link]

		• Uncertainty or sudden changes in regulation. • Regulations around carbon capture and storage. • Carbon policies can hinder the development of emitted carbon as an alternative feedstock.
Food and drink	• Challenges associated with obtaining the necessary approvals for the use of waste/by-products.[295]	• Complex and restrictive end-of-waste regulations, both to classify certain products as 'waste' and to obtain 'end-of-waste' status. • Difficulties in identifying new market for by-products due to changes in legislation.
Agriculture	• No regulatory and policy-related barriers identified.	• Restrictive end-of-waste regulations and classification of waste as hazardous. • Government policy related to carbon capture and storage funding can hinder symbiotic relationships between CEH and energy from waste plants.

5.8 Analysis of the barriers

In this section we present our analysis of the **relative importance of the barriers** to industrial symbiosis. Our assessment is based on the evidence presented above from the general and sector-specific literature and the stakeholder interviews.

We have disaggregated the six categories of barriers covered earlier in this section into sub-categories in order to indicate those likely due to market or regulatory failures, and those that are intrinsic to industrial symbiosis.

In the table below, we indicate the importance of each barrier using the following five-point scale:

- **Very low** – barely mentioned in literature or stakeholder interviews.
- **Low** – mentioned in both literature and by stakeholders, but considered to be of low importance or frequency.

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[295] Impoco, G., Arodudu, O., & Brennan G. (2021). Industrial Symbiosis: guide for policy making. SymbioBeer. [link]

- **Medium** – mentioned often in literature and/or by stakeholders, but not considered to be a key barrier.
- **High** – considered to be an important barrier in the literature and by stakeholders.
- **Very high** – considered to be a crucial barrier both in the literature and by stakeholders.

We consider whether the importance of barriers differs significantly across **sectors and firms of different sizes**. Where this is the case, we indicate this in the table with a range for the importance score. We highlight those barriers that we consider to be **market or regulatory failures** using shading.

We also assign a **conviction rating** to the scores based on the strength of the evidence underpinning our analysis, as follows:

- **Weak** – evidence only from 1-3 sources, or sources of lesser quality, and minimal evidence from stakeholder interviews.
- **Medium** – evidence found across 3-5 quality sources, and in some stakeholder interviews.
- **Strong** – evidence found across multiple quality sources and stakeholder interviews.

Table 5.8: Relative importance of barriers

Barrier	Importance score	Conviction rating	Rationale
Other costs of industrial symbiosis	High	Strong	Financial barriers identified in the literature include high set-up costs, credit constraints, and the cost of access to an ICT platform. High costs related to (regulatory) permits are also identified as a barrier. Sector-specific literature notes that operational and purchase costs of alternative inputs can be greater than primary materials (e.g. for glass and CEH). Stakeholders note that investment costs to accommodate alternative inputs can be high (glass, cement). Time costs also cited as relevant across many firms.
Lack of information/awareness	High	Strong	There is extensive general and sector-specific literature on the lack of awareness and information as a barrier to industrial symbiosis. Stakeholder feedback also suggests that this is a crucial barrier, most noticeably in food and drink, agriculture and chemicals, but also in other sectors.
Suitable technology/process not available, unproven or too expensive	Medium – Very high (depending on how much processing / production adjustment a by-product requires)	Strong	General and sector-specific literature mentions the lack of commercial availability of many material recovery technologies and high acquisition prices; and certain materials pose considerable technological challenges. Stakeholders agree, particularly in the chemicals sector, and also in the glass and cement sectors. Many new synergies require research which then takes time and funding to scale up – even in the other sectors considered. This is hampered by costs of research and innovation and a lack of in-house expertise to develop business cases for new synergies. However, there are many synergies for which the technology already exists.

Waste regulation inappropriately hinders re-use of waste	Medium	Medium	The literature on this issue is not extensive – restrictive regulatory frameworks for waste disposal are mentioned as a barrier in the general literature, and the sector-specific literature covers the burden of food safety regulations in re-using by-products in the food and drink sector, and limitations to what waste products can be burned in cement kilns. Stakeholder evidence is extensive on the time and cost burden of waste regulations, either relating to restrictions on what waste can be used or the burden of proving the conditions for end of waste are met or demonstrating that a material is not waste in the first place. Uncertainty about what view will be taken by the Environment Agency and delays in receiving an opinion can disincentivise investment.
Regulatory uncertainty deters investment in industrial symbiosis	Low – Medium (depending on sector)	Medium	The general literature highlights uncertainty about future policy, including in relation to the environment, waste management, and industrial ecology, as a barrier to industrial symbiosis. Evidence from sector-specific literature mainly relates to uncertainty around government policy for the use of biofuels. Stakeholder feedback is more extensive – government promotion of some by-products in certain sectors can affect the supply to other sectors; unstable or inconsistent industrial strategy deterring investment in costly industrial symbiosis techniques; uneven funding for CCS across emitters creating uncertainty in the availability of waste CO2 as a by-product. Product standards in the cement industry are seen as a key barrier to industrial symbiosis.
High costs / infeasibility of transporting waste/by-product given distance	Low – Medium depending on sector	Weak-Medium (depending on sector)	The general literature cites a high ratio of transportation cost to value and a lack of infrastructure/ logistical networks as barriers; the issue is not widely covered in the sector-specific literature but is mentioned for cement, food and drink and

			CEH. Stakeholders viewed transport costs as one of many costs factored into an assessment of the viability of a synergy. The issue is seen as hard barrier in CEH where waste heat is only viable if greenhouses are co-located with the supplier.
Uncertainty about quality of waste product/by-product	Very low - Medium (depending on sector)	Weak-medium (depending on sector)	The general literature notes uncertainty about the quality of by-products as a barrier; however, this is not covered in the sector-specific literature that we reviewed. Some stakeholders noted this was relevant where the quality of the by-products had direct implications for the end-product, such as with glass and cement. Quality issues sometimes seen more as a cost/burden than a barrier to industrial symbiosis, e.g. where additional research is needed to be carried out to test the impacts of different materials.
Uncertainty as to whether stable demand for / supply of waste/by-product will be available over long term	Very low – Medium (depending on sector)	Medium	The general literature identifies uncertainty about the continuity of waste flows in sufficient quantities as a barrier. Relevant sector-specific literature mentioned this issue for the cement and glass sectors. Similarly, stakeholders view this as important mainly in the cement and glass sectors, although it has some relevance to CEH (stable supply of waste heat).
Individual firms cannot capture a sufficiently large share of the benefits of research	Low	Weak	Literature from the EU suggests most industrial symbiosis involves some government funding, pointing to externalities. However, innovation spillovers are not directly mentioned in general or sector-specific literature. Some stakeholders agreed that firms (particularly innovators/start-ups) may be reluctant to share decarbonisation ideas that would be relevant to industrial symbiosis due to a fear of losing their competitive advantage. A reluctance to share information and

			data (see company culture below) could also be linked to this barrier.
Difficulty/costs of changing company culture	Low	Medium	Low levels of trust between potential stakeholders, firms with established supply chains hesitant to alter existing practices, poor communications and inadequate management and leadership have all been cited as barriers in the general literature. Sector-specific literature mentions organisations' reluctance to share information and data relevant to potential industrial symbiosis and the lack of a collaborative culture as barriers. Stakeholders consider company inertia, a focus on core business practices and a lack of collaborative culture as barriers to exploring the use of new materials through industrial symbiosis. Some sectors are considered conservative and less likely to adopt new materials (cement, agriculture). However, other stakeholders maintain that company culture is much less relevant than the economic viability of synergies.
Planning controls or other regulation prevent relevant firms locating together	Low	Weak	Not widely covered in the literature (and not for the UK). Stakeholders mentioned this barrier in the context of the chemicals sector.
Limited revenues from selling waste/by-product	Low	Weak	A small number of literature sources mention that many businesses often do not see waste as a valuable resource. This was not covered in the sector-specific literature nor by stakeholders in any depth. It is likely to be an implicit barrier (i.e. synergies may simply not be considered if they are not economically viable).
Market price of saved energy / carbon does not reflect	Low	Weak	The role of low carbon prices as a barrier to industrial symbiosis is not directly addressed in the literature nor by many stakeholders (indeed, carbon prices are seen more as

environmental impact of emissions			a driver). The exception is stakeholders in the chemicals sector who consider that the move away from fossil feedstocks in inhibited by a carbon price that is too low. At the same time, an increase in the carbon price may reduce some opportunities for industrial symbiosis e.g. by leading to the use of electric glass furnaces that are incapable of taking waste fuels. Government policy was mentioned as relevant in the chemicals sector (e.g. the coverage of the UK ETS was seen as insufficient to incentivise the use of alternate feedstocks).
Market price of saved water does not reflect environmental impact of water abstraction for some materials	Low	Weak	Very little evidence is available on water savings through industrial symbiosis in the UK.
Landfill tax does not fully capture environmental impact of landfill (e.g. harmful leachates) for some materials	Low	Weak	Landfill tax is cited largely as a strong driver of industrial symbiosis rather than as a barrier. It is likely that the landfill tax covers the full environmental impacts for many materials, although there could be a residual externality for some materials.

5.9 Summary

The literature shows that barriers to industrial symbiosis are present in the same categories as for drivers and enablers – indeed, in many cases the absence of a driver or enabler manifests as a barrier. Hence, key barriers are related to technology, knowledge and information, organisation and cultural, geography, financial impacts, and regulation / policy.

Within these categories, we have developed a more disaggregated set of barriers to capture the full range of barriers that exist and also to separate out those barriers likely to be the result of market or regulatory failures and those likely to be intrinsic to industrial symbiosis (or indeed relevant to any business and not specific to industrial symbiosis).

The evidence from the literature and stakeholders shows that the **most important barriers** are a lack of knowledge of industrial symbiosis in general and a lack of awareness of specific symbiotic opportunities in particular; suitable technologies or processes being unavailable, unproven or too expensive; and other general costs of industrial symbiosis such as set-up and capital investment costs, time, transportation costs, regulatory costs and the costs of purchasing the by-products themselves.

That said, stakeholders involved in facilitating industrial symbiotic networks have noted that often a number of **barriers act together** to disincentivise industrial symbiosis, and that many can be simultaneously important. This points to the potential value of having a coordinated industrial symbiosis strategy or facilitation that seeks to address multiple barriers together.

Some barriers **vary in their importance** across sector or firm type. For example, stakeholders consider that regulatory uncertainty particularly limits investment in large-scale production transformation where the availability of a by-product, or the market for a by-product, depends in part on government strategy and policy. The costs of transporting by-products over long distances is also a barrier that is more relevant to sectors in which the by-products are bulky or difficult to transport, or where suitable markets are far apart. Uncertainty about the quality or long-term supply of by-products also varies by sector. This factor is most relevant in sectors such as cement and glass in which the use of by-products requires substantial investment in new production techniques and where it is infeasible or very costly to switch between inputs in response to supply shortages.

6 Risks

In this section we address the risks of industrial symbiosis. In particular, we discuss:

- Findings from the **general literature** and **stakeholder views** across all our interviews.
- Evidence from sector-specific literature and stakeholders in the **six chosen sectors**.
- Our **analysis** of the risks.

6.1 General literature and stakeholder views

There is relatively little literature available on the risks of industrial symbiosis. Stakeholders interviewed for this research identified a number of risks, including both risks faced by companies and some broader risks to society of symbiotic exchanges.

6.1.1 Changes in the quantity and quality of by-products available

Since industrial symbiosis exchanges generally depend on the demand and supply of waste, which are subject to fluctuations, there is an increased dependency and vulnerability, as changes in the quantity and quality of output and waste can lead to supply chain crises. In an analysis conducted by Turken et al. (2020),[296] they concluded that frequent resource exchange and complex resource flows may ultimately reduce the stability of the network. This is further exacerbated by frequent replacement of symbiotic partners, which both undermines the stability of the network and increases the costs to the firm.

This was also identified as a key risk by many stakeholders we interviewed. Fluctuations in quantity and quality of by-products may lead to supply chain disruptions and could also affect the quality of final products. For example, the critical role of fuel quality has been emphasised in the glass sector where ensuring the correct fuel mixture is essential for furnaces, as any deviation poses risks to glass quality and the overall production process. By contrast, a stakeholder argued that the risk of uncertain material flows as a barrier to symbiotic trade is overstated as once a symbiotic opportunity is identified, the ongoing risk can be very low. Nevertheless, the stakeholder noted that the risk associated with finding such opportunities could be significant which reinforces the benefits of external facilitators.

6.1.2 Agglomeration diseconomies

Industrial clusters which engage in symbiotic exchanges can also lead to agglomeration dis-economies.[297] In the case of the pharmaceutical cluster in Barceloneta, the abundant water supply initially encouraged the spontaneous co-location of companies in the area. However, in

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[296] Turken, N., Geda, A. (2020). Supply chain implications of industrial symbiosis: A review and avenues for future research. Resources, Conservation & Recycling 55(10), 3118-3123. [link]
[297] Chertow M.R., Ashton, W.S., & Espinosa, J.C. (2008). Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. Regional Studies, 42(10), 1299-1312. [link]

recent years, the reservoir has suffered from high extraction rates and areas of contamination because of this.

Stakeholders in our research did not identify this as a relevant risk, with one participant noting that negative impacts of agglomeration would be due to poor resource management within the cluster.

6.1.3 Risks around the suitability or quality of by-products and exchanges

Investing time and resources to investigate symbiotic relationships was seen as a risk by some stakeholders. In addition, **investing in new equipment and/or processes** either to process or accommodate by-products given fluctuating demand was also seen as a risk. For example, a manufacturer in the food and drink sector noted that investments in the range of £100m may be needed to enter markets, which require a certain element of certainty to be attached to them. **Company size** can impact companies' exposure to investment risks. For example, a stakeholder from the food and drink sector noted that it lost the investment resources it had put into the production of a by-product following the withdrawal of its much larger partner from the contract.

Stakeholders also noted risks around the environmental quality of by-products. For example, anaerobic digestion of animal waste creates risks due to the high nitrogen level of the residues, which has prompted governments to introduce rules and regulations around the use of anaerobic digestion plants.

6.1.4 Unintended consequences of policy

Stakeholders noted that **unintended consequences** of regulations and policy changes could exacerbate risks around investment decisions by affecting the viability of symbiotic trades. For example, a cement manufacturer noted that despite a significant investment in a new waste fuel system that enabled it to use sewage sludge in cement production, the system was only in operation for six months due to a policy change that incentivised other sectors to use sewage sludge and thus reduced the available supply.

A stakeholder also argued that the absence of government support for symbiotic exchanges could put **the UK at a disadvantage** given the focus on industrial symbiosis in other countries. In particular, it could lead to companies deciding to locate in other countries, which would ultimately affect the potential for industrial symbiosis in the UK.

6.1.5 A disproportionate focus on waste as fuel

A potential risk of industrial symbiosis is a disproportionate focus on using waste as a fuel. A number of examples of industrial symbiosis in our research related to the burning of waste products instead of fossil fuels (e.g. in the cement and glass sectors), or the use of heat and energy produced by energy-from-waste plants (e.g. by greenhouses). On the one hand, this can be beneficial if the only alternative for the waste is landfill (as it can prevent methane emissions) or incineration without energy recovery. Similarly, where industries need to burn fuel (for example, the cement and glass sectors), burning waste can be preferable to burning fossil fuels as it reduces carbon emissions and resource extraction.[298, 299] However, using waste as fuel can emit pollutants such as carbon dioxide, sulphur dioxide and nitrogen dioxide, and result in the loss of embedded energy and resources.[300] It may also divert resources and funding away from recycling and reuse efforts. Therefore, it should be a last resort after reuse and recycling (for example, as seen in the DEFRA waste hierarchy).[301] Improvements in technology can mitigate some of the risks from energy-from-waste. For example, anaerobic digestion, pyrolysis and gasification can convert waste into products like biofuels, chemicals and fertilizers and result in lower carbon emissions and energy loss compared with traditional incineration.[302]

6.2 Evidence across the chosen sectors

6.2.1 Cement

The literature notes the importance of establishing **joint ventures** between alumina and integrated cement plants to alleviate risk. For instance, interviewees from the Sourmelis et al. (2024) study stated that the cement industry is unlikely to install manufacturing processes for treating bauxite residue, a SCM intended to replace clinker volumes, due to the costs involved, and that this treatment cost would be borne by alumina producers (which generate the bauxite by-product). The study suggests that the cement industry may need to purchase the material at what it calls a “fair price” and may need to establish long-term contracts to alleviate the cost risks borne by alumina producers.[303]

Stakeholders highlighted the cost risk (and in particular the risk associated with the cost of investment) inherent in companies transitioning their production processes to use waste products. This means that companies often require a degree of assurance regarding the **security of supply of the waste materials used**. This risk has been further exacerbated by the increase in waste exports out of the UK.

Similarly, any **uncertainty around the chemical consistency of alternative raw materials** can pose a significant risk, as this could affect the quality of the final product.

Moreover, sudden or unexpected **changes in policies** can also pose a risk. For example, a policy change incentivising other industries to adopt waste materials that could also be used by the cement (and concrete) sector may inadvertently disrupt existing supply chains and/or mean

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[298] Nageler-Petritz (2023). Waste-to-Energy in a Circular Economy: Friend or Foe?. Waste Management World, [link]

[299] University of Birmingham Hub (2023). The future of waste-to-energy – is it as good as we are led to believe? [link]

[300] IEA Bioenergy (2022). Material and Energy Valorisation of Waste in a Circular Economy. [link]

[301] Defra (2011). Guidance on Applying the Waste Hierarchy. [link]

[302] Freer, Martin, et al (2020). Energy from Waste and the Circular Economy: Net-Zero and Resource Efficient by 2050. The Birmingham Policy Commission, University of Birmingham. [link]

[303] Sourmelis, S., Pontikes, Y., Myers, R. J., & Tennant, M. (2024). Business models for symbiosis between the alumina and cement industries. Resources, Conservation and Recycling, 205, 107560. [link]

that companies are hesitant to invest in specialised equipment needed to use specific by-products in their production processes.

6.2.2 Glass

Stakeholders highlighted as a key risk the **uncertainty about the quality and supply of alternative fuel sources** and the associated **risks of investing in equipment** to utilise a certain fuel type which may subsequently become unavailable or too expensive.

They highlighted the importance **of maintaining chemical consistency in raw materials, including fuel**. Given the continuous operation of furnaces around the clock, any inconsistency in the chemical composition of fuel (e.g. due to a shortage of a certain fuel type) can halt production or lead to faulty, unwanted products. Therefore, a continuous supply of the same fuel types is very important. The **scarcity of adequate raw materials** further exacerbates this risk. The risks associated with the chemical consistency of raw materials can also make companies averse to exploring new opportunities. For example, while government funding would be available for additional research, glass manufacturers have in the past exercised caution in using the funding for trials to explore the use of alternative raw materials.

6.2.3 Mining

Stakeholders perceive variability in waste quality as a risk, as quality cannot be assumed to be consistent. This variability can have knock-on impacts on processes, potentially leading to high costs.

Another risk identified by a stakeholder is the necessity of establishing **the economic feasibility of extracting minerals from waste**. Without a compelling economic case, companies may not be willing to pursue such endeavours.

The stakeholder also believed that **future developments within the UK and in other jurisdictions** can pose a risk to industrial symbiosis, as other countries are investing heavily in circular economy initiatives. This provides companies with stronger incentives to (re)locate elsewhere, which could affect the UK's competitiveness.

6.2.4 Chemicals

Driving investments and scaling up alternative feedstocks

While alternative feedstocks have the potential to replace the majority of fossil-fuel derived feedstocks, there is a risk associated with their **not-yet-understood impacts** on the environment. This includes impacts of increasing the use of biomass, as increased biomass production can in fact lead to increased emissions due to indirect land use change.[304] This lack of certainty may deter investments in high-cost technology and equipment if the impacts remain poorly understood. For example, the risks and trade-offs of using biomass, green hydrogen and captured carbon are not yet outlined within the government's Biomass Strategy.

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[304] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

Therefore, clearer direction and transparency from government may encourage the adoption of greener technology. Additionally, while hydrogen has had significant investment, there are still risks associated with the use of it.[305] One stakeholder stated that it is dangerous to store and transport. This therefore prevents the widespread use of hydrogen as an alternative feedstock.

A further risk with the use of biomass to generate alternative sources of feedstock highlighted by stakeholders is **instability in volume and inconsistency of waste**, as the composition of municipal waste changes over time which will affect the nature of the biomass that can be produced from it.

Industrial clusters: safety issues

There are various **safety issues** linked to industrial symbiosis in the chemical industry.[306] Chemical industrial parks are key to establishing effective links between companies; however, they have been considered to be a cause of dangerous environmental pollution accidents. In addition to this, the areas surrounding industrial parks are also at risk from chemical accidents. For example, the explosion caused by Tianjin Port Chemical Industry Park in China resulted in significant casualties and economic losses in the surrounding areas.[307]

Stakeholders also expressed the concern that the **hazardous nature** of many chemical waste streams and the specialisation required to handle them creates risks when engaging in industrial symbiosis.

Additionally, another stakeholder highlighted that **impurities in chemicals wastewater** are a safety and environmental concern, particularly where wastewater is processed as an alternative source of acid. This is because there is often uncertainty around the levels and concentration of chemicals and impurities in chemicals wastewater. This is supported by the literature, which for example finds that hazardous chemicals in waste streams hamper current re-use and recycling initiatives, and that legal frameworks for chemical risk management (for example, the use of tailored risk assessments) do not yet fully facilitate a circular economy.[308]

6.2.5 Food and Drink

There are several risks particularly for the processing of meat waste, which is why there are stringent rules and regulations that have to be met in order to use animal waste and by-products. Anaerobic digestion of animal waste creates risks due to the **high nitrogen level of the residues**. In Europe, the utilisation of anaerobic digestion plants is restricted by the Animal By-product Regulation 1069/2009/EC to account for these risks.[309]

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[305] Department for Energy Security and Net Zero. (2024). Unlocking Resource Efficiency – Phase 2 Chemicals, 49. [link]

[306] Cui, H., & Liu, C. (2017). Applying industrial symbiosis to chemical industry: a literature review. [link]

[307] Cui, H., & Liu, C. (2017). Applying industrial symbiosis to chemical industry: a literature review. [link]

[308] Bodar, C., Spijker, J., Lijzen, J., Waaijers-van der Loop, S., Luit R., Heugens, E., …Traas, T. (2018). Risk management of hazardous substances in a circular economy. Journal of Environmental Management, 212. [link]

[309] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

A small company processing waste in the food and drink sector mentioned that other companies perceive its product as risky, due to **uncertainty about the stability of supply** over the long-run. Many larger companies have established supply chains and their budgets are fixed for the year ahead, which can reduce the ability of smaller firms selling alternative waste or by-products to enter these markets.

6.2.6 Agriculture

Literature indicates that reliance on certain types of biomass can lead to **supply chain vulnerabilities** if the supply fluctuates due to agricultural variability or market conditions.[310] Additionally, while biofuels can contribute to a reduction in carbon emissions, a study highlighted some adverse effects associated with its production. For instance, the utilisation of crops for biofuel production may put pressure on limited arable land, promote deforestation, and create a loss in biodiversity as well as potential excessive water use.[311]

In the case of CEH, there are risks associated with it being dependent on systems for using waste heat and water. Dependence on technology can be a risk, as even short-term technical issues may significantly affect crops and output.[312] Stakeholders we interviewed considered that whilst supply interruptions can also occur with traditional heat sources, the risk was greater when dealing with individual waste heat suppliers. This risk also depends on whether the greenhouse, and is located close to alternative sources of heat (such as gas from industrial emitters).

A stakeholder we interviewed considered that emitters do not find it worthwhile to invest in CCS infrastructure to send waste CO_2 to the CEH sector due to the risk of unstable demand from growers.

6.3 Analysis of risks

In this section we present our typology and analysis of risks, drawing on the literature and stakeholder evidence. We separate risks into those risks directly affecting companies engaging in industrial symbiosis, and those risks that have a wider impact on society.

Risks to companies are:

- **Risks of by-products being unsuitable or environmentally damaging**. Unknown impacts of waste or by-products can pose risks to companies, for example wasted investment if the product proves to be unusable, or costs incurred in dealing with problems that materialise with the by-product.
- **Fluctuations in supply and demand of waste**. Changes in the quantity and quality of waste and by-products can pose risks to companies' investments where investment is

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[310] Bijon, N., Wassenaar, T., Junqua, G., & Dechesne, M. (2022). Towards a sustainable bioeconomy through industrial symbiosis: Current situation and perspectives. Sustainability, 14(3), 1605. [link]
[311] Awogbemi, O., & Kallon, D.V.V. (2022). Valorization of agricultural wastes for biofuel applications [link]
[312] Food north-west. (2022). Barriers & Opportunities for Controlled Environment Agriculture in North-West Europe. [link]

needed to use/send a by-product. This is particularly relevant where a by-product is replacing a primary product (rather than just being used alongside it as an additional source) in a way which requires production processes to change. Changes in the quantity and quality of waste and by-products supplied and demanded can also create supply chain risks, whereby disruptions to one part of the supply chain engaged in industrial symbiosis can affect the rest of the chain.

- **Viability of symbiotic trades changing due to unforeseen changes in policy**. Policy changes can pose risks to firms if they result in the costs of a trade exceeding the benefits, for example by making the by-products more expensive, increasing administration or other regulatory burdens associated with using the material, preventing the use of certain materials, or reducing the scope to establish a market for the products.
- **Unintended consequences of promoting industrial symbiosis in different sectors.** This is a more specific sub-set of the above risk, in which government promotion of industrial symbiosis in one sector – such as funding the use of a certain by-product – can negatively affect another sector (e.g. by artificially increasing the price of the by-product in question even if its use in the first sector was more valuable).

Risks to wider society may consist of:

- **Agglomeration dis-economies**, whereby the clustering of industries to encourage industrial symbiosis can degrade resources and the surrounding environment, for example through excessive water abstraction or pollution.
- **Reduced incentives for carbon-intensive industries to decarbonise**, if carbon emitters are able to valorise their carbon through industrial symbiosis. This is a theoretical risk for which we have found no evidence.
- **A disproportionate focus on waste as fuel,** where waste is used as alternate fuel or in energy-from-waste plants when it could rather be reused or recycled.
- **Supply chain risks associated with fluctuations in the supply of waste or the demand for waste** are also relevant to wider society if they affect the supply of products to consumers.

The table below presents our analysis of these risks based on the evidence from the literature and stakeholders. We indicate the likely impact of each risk and its likelihood of materialising using a three-point scale – Low, Medium and High. We also consider potential ways in which risks can be mitigated.

Table 6.1: Risk Analysis

Risk	Impact	Likelihood	Conviction rating	Rationale	Mitigation
Fluctuations in supply of waste and demand for waste (quantity and quality)	Low-High, depending on sector	Medium	Medium	There is some evidence in the general literature that industrial symbiosis can create vulnerabilities in supply chains. Agriculture is the only sector where the literature we reviewed noted supply risks (given production fluctuations). Stakeholders noted a range of risks related to the quantity and quality of waste, particularly the risk that costly investments to adapt to a new input are made redundant if supply fails (glass, cement, chemicals). Smaller companies producing by-products can be viewed as risky in terms of supply. Supply risks include by-products being exported.	Diversification of inputs by companies where possible. Smaller companies could form joint venture partnerships to reduce perceived risk of lack of supply.
Waste/by-products are unsuitable for use or environmentally detrimental	Low-Medium, depending on sector	Medium	Weak (cited more as a barrier to engaging with symbiosis in the first place).	Stakeholders in the chemicals sector noted risks associated with hazardous waste being used in industrial symbiosis. Cement and glass stakeholders cited risks that waste inputs affect the quality of the end-product.	Research into the impacts and suitability of by-products. Sharing of results between companies and/or dissemination by industry bodies.
Viability of exchanges changes due to	Low	Low-Medium	Weak	The literature does not cover this risk with the exception of changes in regulation posing a risk in the mining sector (not from	Regular communication between industry and

unforeseen policy changes				the UK). Stakeholders mentioned that policy changes affecting the commercial viability of biofuels may have an impact on industrial symbiosis in agriculture and food. The chemicals sector is considered particularly influenced by government policy around carbon capture, biomass usage and green hydrogen.	government on upcoming changes to policy.
Unintended consequences of promoting industrial symbiosis in different sectors	Low	Low-Medium	Medium	A number of stakeholders mentioned the risk that government promotion or subsidisation of industrial symbiosis in one area can increase the price of a particular by-product such that it is too costly for more valuable use in another sector.	Research and impact assessment of government policy to avoid these unintended consequences.
Disproportionate use of waste as fuel	Medium	Low	Weak	The literature highlights the potential risks of using waste as fuel rather than reusing or recycling it. There are a number of examples in our research of waste being used as alternatives to fossil fuels, and energy-from-waste plants sending by-products like heat to other sectors. However, there is little evidence in the literature (and none from stakeholders) that there is a material risk of inappropriate use of waste as fuel.	Technology advances to reduce the negative impacts of using waste to generate energy.
Agglomeration dis-economies	Low	Low	Weak (no evidence)	Only mentioned in a couple of literature sources (not from the UK), and not by stakeholders.	Sufficient cluster management.

Reduced incentives for carbon-intensive industries to decarbonise	Low	Low	Weak (no evidence)	Not mentioned in the literature or by stakeholders. Some stakeholders did note that this is a theoretical risk but one that could be offset by wider carbon reduction policies.	Ensure adequate policy incentives for decarbonisation.

6.4 Summary

Risks of industrial symbiosis include both risks to companies and risks to wider society. There is **relatively little evidence of risks** in the literature compared with the evidence available on drivers, barriers and impacts of industrial symbiosis. Stakeholders highlighted a number of risks, although in some cases these overlap with barriers to industrial symbiosis. For example, risks around the quality or environmental impact of waste can also act as a barrier to undertaking industrial symbiosis in the first place.

The most **important risks** highlighted in our research in terms of impact or likelihood are fluctuations in the demand for or supply of by-products, particularly where this undermines investment or disrupts supply chains; and the risk that the by-products turn out to be unsuitable or environmentally damaging. Stakeholders also mentioned risks associated with government policy, for example where the viability of a symbiotic trade changes due to unforeseen changes in policy, and where the promotion of industrial symbiosis in one sector creates unintended consequences in another sector.

Risks of industrial symbiosis to wider society were much less evident in the literature and stakeholder input. In particular, agglomeration dis-economies and reduced incentives for carbon-intense industries to decarbonise were not seen to be relevant by stakeholders, and there was only very limited literature evidence around agglomeration impacts.

7 Benefits of Industrial Symbiosis

In this section we present the benefits of industrial symbiosis from the **general literature** as well as an **overview of stakeholder** views from across all our interviews. We also set out the evidence from sector-specific literature and stakeholders in the **six chosen sectors**.

In the sections which follow, we first discuss environmental benefits **environmental benefits** and then **economic benefits**.

7.1 Environmental benefits

Through the exchange of waste materials, by-products and energy between different industrial processes, industrial symbiosis can lead to a reduction in overall resource consumption and waste generation. As such, industrial symbiosis practices can minimise a firm's environmental impact, enhance resource efficiency and mitigate the carbon footprint associated with production.

7.1.1 Energy savings

Stakeholders we interviewed highlighted that the use of by-products could lead to reductions in energy consumption and energy costs, in cases in which by-products require less energy to be used in the production process. Energy savings were mentioned by several stakeholders, although another stakeholder noted that achieving goals around circularity and re-use of materials could result in significant energy costs.

Evidence from the six chosen sectors

The table below summarises the key benefits in terms of energy savings highlighted in the sector-specific literature and by stakeholders we interviewed in the six chosen sectors.

Table 7.1 Summary of energy savings across the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	Use of GGBS reduces energy consumption by 3,500 MJ, (a reduction of approximately 70 per cent) as compared with Portland cement.[313]	No specific evidence from sector.
Glass	As a **receiving sector**, the use of alternative materials can reduce energy use due to lower melting temperatures: Every 10 per cent of Calumite used leads to energy savings of 2.5 to 2.6 per cent.[314] Every 10 per cent of cullet (recycled glass) uses three per cent less energy,[315] equating to 300 kWh of energy saved for every one tonne of cullet used.[316] Biomass ash also lowers energy demand by the same mechanism.[317] As a **sending sector**, 30 per cent of the energy used in glass melting furnaces can be lost through flue gas released from the stack, equating to approximately 2.1-2.9 GJ/tonne of energy available for other uses (e.g. heating greenhouses).[318]	No specific evidence from sector.
Mining	No specific evidence from sector.	No specific evidence from sector.

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[313] Heidelberg Materials. Regen GGBS - Cement Substitute. [link]

[314] Calumite. An essential raw material for the glass industry. [link]

[315] European Container Glass Federation. (2016). Recycling: Why glass always has a happy CO_2 ending. [link]

[316] The UK Green Building Council. (2018). Building glass into the circular economy: How to guide. [link]

[317] Sheffield Hallam University. (2019). Biomass Ash: A Past and Future Raw Material for Glass-Making? [link]

[318] Nosrat, A. H., Jeswiet, J., & Pearce, J. M. (2009). Cleaner production via industrial symbiosis in glass and largescale solar photovoltaic manufacturing. In 2009 IEEE Toronto International Conference Science and Technology for Humanity, 967-970. [link]

Chemicals	Industrial symbiosis in the chemical industry can lead to decreased energy consumption.[319]	No specific evidence from sector.
Food and drink	As a **receiving sector**, a 1MWe CHP plant enabled one of Europe's largest bakery plants to save £400,000 per year from reduced energy costs through transforming exhaust gases into electricity and heat, allowing significant amounts of energy to be produced on-site and improving supply resilience.[320] A coffee producer receiving energy from a nearby biorefinery led to energy efficiency gains of 384GJ per year (6 per cent), equating to an economic gain of $511,000 per year.[321] As a **sending sector**, the sales of products (e.g. MBM production from animal waste and generation of energy from combustion of biofuel) can decrease consumption of energy from fossil fuels.[322]	No specific evidence from sector.
Agriculture	No specific evidence from sector.	Heat generated from energy-from-waste plants can be sent to greenhouses directly, providing them with all the heat they need and thus saving energy.

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[319] Cui, H., & Liu, C. (2017). Applying industrial symbiosis to chemical industry: a literature review. [link]

[320] Centrica Business Solutions. (2018). Distributed Energy Powering Yorkshire and Humberside's Economic Future. [link]

[321] Sheppard, P., Garcia-Garcia, G., Angelis-Dimakis, A., Campbell, G.M., & Rahimifard, S. (2019). Synergies in the co-location of food manufacturing and biorefining. Food and Bioproducts Processing, 117, 340-359. [link]

[322] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

7.1.2 Emissions reduction

Evidence from the general literature and stakeholder interviews

CO_2 emissions

Industrial symbiosis can lead to a reduction in **CO_2 emissions** as the additional emissions associated with the re-use of waste or by-products can be significantly lower than the emissions associated with the production of virgin materials. This is because the emissions generated in the production of the waste- or by-product would have been generated anyway in the production of the primary product of that industry (although there are likely to be emissions and energy requirements in reprocessing by-products). In addition, where industrial symbiosis networks entail shared infrastructure and energy systems, this can lead to improved energy efficiency, further reducing emissions.

There are multiple examples of emissions reductions in the literature. For example, in an analysis of the synergies facilitated by the UK's NISP during its first five years, a study found that median CO_2e[323] savings per synergy (such as the reuse of a company's waste as a raw material by another) were 51 tonnes and mean CO_2e savings per synergy were 3,508 tonnes.[324]

In the case of John Pointon & Sons, meat and bone meal was produced as a by-product of its animal rendering services and was traditionally landfilled.[325] Since meat and bone meal is highly calorific, Pointon provided 150,000 tonnes per year of meat and bone meal waste to cement kilns as fuel. This resulted in a reduction of 277,000 tonnes per year in CO_2e emissions compared with the use of traditional fuels.[326]

Another study modelled the effects of linking China's three key industries (steel, cement, and power) in a symbiotic loop based on historical data and scenarios for 2015-50.[327] One scenario led to carbon emissions falling to 3,767 megatonnes by 2050, compared with a rise in carbon emissions to 6,600 megatonnes by 2040 in the case of no action.

On the other hand, one study found that the global emission reduction potential from exploiting industrial symbiosis opportunities in the bulk material production of steel, cement, paper, and

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[323] CO_2e refers to "carbon dioxide equivalent", and is a measure of the total greenhouse gases emitted expressed in terms of the amount of carbon dioxide that would have an equivalent global warming effect.

[324] Jensen, P. D., Basson, L., Hellawell, E. E., Bailey, M. R., & Leach, M. (2011). Quantifying 'geographic proximity': experiences from the United Kingdom's national industrial symbiosis programme. Resources, Conservation and Recycling, 55(7), 703-712. [link]

[325] Paquin, R. L., Busch, T., & Tilleman, S. G. (2015). Creating economic and environmental value through industrial symbiosis. Pacific Economic Cooperation Council. [link]

[326] Laybourn, P., & Morrissey, M. (2009). The Pathway To A Low Carbon Sustainable Economy. NISP. [link]

[327] Zhang, Q., Xiang, T., Zhang, W., Wang, H., An, J., Li, X., Xue, B. (2022). Co-benefits analysis of industrial symbiosis in China's key industries: Case of steel, cement, and power industries. Journal of Industrial Ecology, 26, 1714-1727. [link]

aluminium is relatively low, at around seven per cent of the total bulk material system emissions, even with major changes to by-product utilization in cement production.[328]

Stakeholders stated that a key benefit associated with industrial symbiosis is the often significant reductions in CO_2 and other GHG emissions as the replacement by-products used tend to generate lower emissions in production processes. In particular, CO_2 emissions savings were identified as a benefit by around half of the stakeholders interviewed, providing both a benefit to society and cost savings to firms.

Other emissions

In Guayama, a town in Puerto Rico, a coal-fired power plant uses cooling water from the local wastewater treatment plant and also sells steam to the oil refinery. The refinery then circulates its condensate back to the power plant. The environmental benefits of these symbiotic exchanges were found to be substantial, with a 99.5 per cent reduction in sulphur dioxide (SO2) emissions, an 84 per cent reduction in nitrous oxide (NOx) emissions, and a 95 per cent reduction of particulate matter smaller than 10 microns (PM10).[329]

In the case of DETDZ in China, major advances were made from 2006 to 2011 through the use of eco-industrial development strategies.[330] As a result, total Chemical Oxygen Demand decreased by 51 per cent between 2011 and 2012, while sulphur dioxide emissions dropped by 41 per cent.

Another study highlighted that using industrial symbiosis to reduce the solid waste associated with the traditional approach to producing paper and fertilizer would reduce the contamination of underground water and/or land from the leaching of phosphogypsum constituents.[331]

The box below illustrates the benefits at an industrial park in Japan.

Box 7.1: Benefits generated through industrial symbiosis at an industrial park in Japan

A case study of cement production within the Kawasaki eco-town, explored various scenarios to assess the impact of industrial symbiosis on CO2 emissions:

- Under current practices, where clay substitutes all virgin clay material (approx. 260,000 tonnes per year), the cement firm within the Kawasaki eco-town saved approximately 41,000 tonnes of CO2 emissions annually, representing five per cent of original emissions.

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[328] Gast, L., Serrenho, A.C., & Allwood, J.M. (2022). What Contribution Could Industrial Symbiosis Make to Mitigating Industrial Greenhouse Gas (GHG) Emissions in Bulk Material Production? Environmental Science & Technology, 56(14), 10269-10278. [link]

[329] Chertow M.R., Ashton, W.S., & Espinosa, J.C. (2008). Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. Regional Studies, 42(10), 1299-1312. [link]

[330] Liu, Z., Adams, M., Cote, R.P., Geng, Y., Ren, J., Chen, Q., Liu, W., Zhu, X. (2018). Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on energy analysis. Renewable and Sustainable Energy Reviews, 81, 1522-1529. [link]

[331] Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., & Matias, J.C.O. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. Sustainability, 11(24), 7095. [link]

- Under a scenario in which alternative raw materials from locally occurring by-products are used, the emissions of the cement manufacturer could be reduced by about 43,100 tonnes per year, equating to 5.2 per cent of original emissions. Under this scenario, industrial plastic replaced seven per cent of the coal typically used as fuel in cement production.

- In another scenario in which municipal solid waste (MSW) is also used to replace coal as a fuel, MSW could replace 14 per cent of the coal typically used, resulting in CO2 reductions of approximately 125,000 tonnes per year, equating to 15 per cent of original emissions.

In addition, the Kawasaki eco-town project generates a range of financial benefits. These benefits include increased revenues from the sale of wastes, increased sales due to "green" and niche marketing, and the adoption of more competitive production methods. (Increased sales due to 'green' and niche marketing stem from promoting environmentally friendly products and targeting specific consumer segments who prioritise sustainability.)

Source: Hashimoto et al (2010) Realizing CO_2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki [link]

Evidence from the six chosen sectors

The table below summarises the key benefits in terms of emissions reductions highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

Table 7.2: Summary of emissions reductions across the six chosen sectors

	Evidence from literature	Evidence from stakeholder interviews
Cement	Reducing clinker content through the use of SCMs decreases GHG emissions. Globally, achieving an average clinker-to-cement mass ratio of 14 per cent (compared to the current ratio of 75 percent) represents a maximum potential reduction of 61 percentage points. In particular, global GHG emissions from cement production could be reduced by up to approximately 44 per cent (1.3 Gt CO_2-equivalent) by maximizing the amounts of SCMs utilised to substitute clinker, equivalent to reducing global anthropogenic GHG emissions by approximately 2.8 per cent. • For the UK, GHG emissions could be reduced by approximately 85 per cent, equivalent to reducing national GHG emissions by approximately 1.5 per cent.[332] • The European cement industry's emission targets for 2030 could yield reductions of up to 39kg (80kg if	Use of alternative raw materials and fuels results in significant CO_2 savings. For example, the use of landfilled fly ash has the potential to reduce carbon emissions, and the use of GGBS leads to lower carbon emissions than the use of clinker. Carbon sequestration could also lead to reductions in a product's CO_2 footprint, e.g. SCMs can have very low or even negative CO_2 emissions due to carbon sequestration. However, there can be **trade-offs between different objectives,** e.g. increasing the circularity of material flows and carbon reduction. For example, using recycled aggregates in concrete can lead to a higher carbon footprint as it requires more cement for binding even though it reduces wastage of aggregates.

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[332] Shah, I. H., Miller, S. A., Jiang, D., & Myers, R. J. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature communications, 13(1), 5758. [link]

	biogenic carbon is disregarded) of CO_2 per tonne of cement.[333] The sector's goal to source 70 per cent of its thermal input from waste biomass is projected to reduce emissions by 16 per cent compared with 2018, representing a decrease in CO_2 emissions of 1.3 million metric tons per year in the UK.[334] For **concrete**, using one tonne of Regen GGBS reduces the embodied CO_2 by around 900kg (a reduction of approximately 92 per cent) compared with using one tonne of Portland Cement, while also increasing its durability.[335]	
Glass	Each tonne of Calumite used reduces overall CO_2 emissions by 600-700kg.[336] Biomass ash as an input can also reduce CO_2 emissions.[337] Wide-scale uptake of biofuels across the sector could reduce UK CO_2 emissions by at least 1.07 MtCO2e/year.[338] Each tonne of glass cullet leads to approximately 200kg CO_2 saved in production/process emissions and 580kg CO_2 saved throughout the supply chain. [339] Moreover, a 10	A biodiesel trial using animal tallow converted into oil in a manufacturer's furnaces resulted in an 89 per cent reduction in CO_2 emissions.

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[333] Capucha, F., Henriques, J., Ferrão, P., Iten, M., & Margarido, F. (2023). Analysing industrial symbiosis implementation in European cement industry: an applied life cycle assessment perspective. The International Journal of Life Cycle Assessment, 28(5), 516-535. [link]

[334] Mineral Product Association. (2023). Delivering Net Zero UK Cement. [CONFIDENTIAL – SENT BY DESNZ]

[335] Heidelberg Materials. Regen GGBS - Cement Substitute. [link]

[336] Calumite. An essential raw material for the glass industry. [link]

[337] Sheffield Hallam University. (2019). Biomass Ash: A Past and Future Raw Material for Glass-Making? [link]

[338] BEIS. (2022). Alternative Fuel Switching Technologies for the Glass Sector: Phase 3. [link]

[339] British Glass. Glass sector Net zero strategy 2050. [link]

	per cent increase in cullet usage in the furnace reduces CO_2 emissions by five per cent.[340]	
Mining	No specific evidence from sector.	No specific evidence from sector.
Chemicals	The Flue2Chem initiative aims to cut carbon emissions by 15 to 20 million tonnes annually by capturing waste flue gases from large foundation industries.[341]	There is potential to reduce the sector's reliance on fossil carbon sources by transforming carbon already present in industrial emissions (as well as in plastics and biomass).
Food and drink	As a **sending sector**, a biofuel MBM bio combustion project at Eco-park in Poland produced 75,000 tonnes of ash containing hydroxyapatite and 460,000 GJ of steam per year, enabling a coal-fired heating plant to close and eliminate the consumption of over 25,000 tonnes of coal per year. Overall, the Eco-park eliminates 92,000 tonnes of CO_2 annually.[342] As a **receiving sector**, a 1MWe CHP plant has enabled one of Europe's largest bakery plants to reduce CO_2 emissions by 1000 tonnes.[343]	Biomass produced using food waste in waste-to-energy incinerators could reduce carbon emissions by 90 per cent. Biochar can act as a carbon sink in the construction industry, with each kilogram of biochar capable of absorbing two kilograms of carbon dioxide.
Agriculture	An energy-intensive factory located in Italy sent waste CO_2 emissions to a nearby greenhouse, enabling the capture of up to 21 per cent of the overall CO_2 emissions produced by the industrial process.[344] A study found that the symbiotic reuse of organic residues within a relatively small geographic region (94 per cent of	Using waste heat generates carbon savings through not having to use a gas boiler.

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[340] European Container Glass Federation. (2016). Recycling: Why glass always has a happy CO_2 ending. [link]

[341] Unilever. (2024). Flue2Chem: Putting carbon waste to work for net zero. [link]

[342] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

[343] Centrica Business Solutions. (2018). Distributed Energy Powering Yorkshire and Humberside's Economic Future. [link]

[344] Marchi, B., Zanoni, S., & Pasetti, M. (2018). Industrial symbiosis for greener horticulture practices: the CO_2 enrichment from energy intensive industrial processes. Procedia CIRP, 69, 562-567. [link]

	materials within 20 km) can reduce transportation-related emissions.[345]	

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[345] Bain, A., Shenoy, M., Ashton, W., & Chertow, M. (2010). Industrial Symbiosis and Waste Recovery in an Indian Industrial Area. Resources, Conservation and Recycling, 54(12), 1278-1287. [link]

7.1.3 Decrease in waste sent to landfill

Evidence from the general literature and stakeholder interviews

Industrial symbiosis can also decrease the amount of waste sent to landfills, as by-products and waste flows can be reused. Diverting waste from landfills can achieve environmental benefits, including a reduction of harmful emissions such as methane generated during landfill decomposition, and a reduction in the risk of toxins leaching into the soil and contaminating groundwater. The reduction in waste being sent to landfills also reduces the need to develop new landfill sites, as existing ones have a longer lifespan; and can save firms money by reducing landfill tax payments.

An estimated 7 million tonnes of waste were diverted from landfills in the first five years of the NISP programme, including 0.363 tonnes of hazardous waste.[346] Similarly, the implementation proposal for the West Midlands Industrial Symbiosis Programme (WMIS) estimates that between 17,000 and 44,000 tonnes of waste will be diverted annually from landfills as a result of the programme.[347] Types of waste that can be diverted are wide ranging — an example would be commercial food waste being reused as an input for pharmaceutical/chemical processes.

Stakeholders we interviewed also highlighted the decrease in waste sent to landfill and associated cost savings (including landfill tax) as a key benefit of industrial symbiosis.

Evidence from the six chosen sectors

While the benefits associated with not sending waste sent to landfill are not explored in the sector-specific literature and interviews to the same extent as reductions in emissions or energy savings, these are seen as particularly important for some of the chosen sectors:

- In the **cement** sector, stakeholders noted that the use of alternative raw materials, such as landfilled fly ash into cement and concrete production, has led to a decrease in waste materials sent to landfills by other sectors.
- In the **mining** sector, reprocessing mine tailings can reduce the amount of waste leading to better waste and water management, and can also reduce the environmental hazards associated with mines (e.g. acid mine drainage, heavy metal contamination, impacts on the soil and water quality, etc.). Despite these benefits, there are environmental risks associated with reopening and processing old mining heaps.[348]
- In the **agriculture** sector, rerouting organic by-products from waste streams to productive uses such as material manufacture or energy production can reduce landfill

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[346] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report.

[347] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Case for Investment.

[348] Kinnunen, P. H. M., & Kaksonen, A. H. (2019). Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production, 228, 153-160. [link]

usage. For example, in the case of Cemex, the reuse of cement bypass dust in agricultural applications has eliminated the landfilling of a process by-product.[349]

The box below illustrates some of the expected benefits from a mining project in the UK.

Box 7.2: Expected benefits from use of process materials at Hemerdon Mine

Tungsten West aims to restart production of tungsten and tin at the Hemerdon Mine (formally Drakelands Mine) in Devon. When production restarts, Tungsten West plans to maximise the use of process materials (formally defined as waste) as high-quality aggregates for a local market. The anticipated benefits from this approach include: lower transportation costs as well as reduced onsite road haulage activities and transport emissions; reduced 'wet' tailings disposal and lower disposal costs; reduced direct emissions; conserving primary virgin material resources; and protecting ecosystems and maintaining biodiversity.

Source: Critical Minerals Association. A Blueprint for Responsible Sourcing of Critical Minerals. [online].

7.1.4 Other environmental benefits

Virgin materials saved

The implementation of symbiotic relationships between firms can reduce the use of virgin materials through increased efficiencies or changes to more sustainable, renewable materials. This can have benefits in terms of reducing environmental degradation and emissions.

For example, at the Shenyang Economic and Technological Development Zone (SETDZ), the gypsum extracted from the desulfurization process of cogeneration power plants is used for gypsum board production and can replace 21,300 tonnes of virginal gypsum per year.[350] Separately, the evaluation of the UK's NISP estimated that over 9.7 million tonnes of virgin material were saved over the first five years of the programme.[351]

Stakeholders we interviewed highlighted the benefits of reducing the use of primary materials, including reduced environmental degradation and reduced energy use and emissions resulting from extraction and/or processing of raw materials. In particular:

- In the **glass** sector, it is estimated that for each tonne of cullet used in the manufacture of float glass, 1.2 tonnes of raw material are saved, reducing requirements for quarrying and associated processing and transportation.[352]
- Similarly, in the **mining** sector, resource recovery and the use of by-products also reduce the need for primary raw materials.[353]

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[349] Cemex. (2023). Cemex partnership with Silverwoods helps close the loop and upvalue nearly 130,000 tonnes of By-Pass Dust for agricultural purposes. [link]

[350] Geng, Y., Liu, Z., Xue, B., Dong, H., Fujita, T., & Chiu, A. (2014). Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone. Environ Sci Pollut Res, 21, 13572–13587. [link]

[351] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report.

[352] The UK Green Building Council. (2018). Building glass into the circular economy: How to guide. [link]

[353] Resource Recovery from Waste. (2018). Making the most of industrial wastes: strengthening resource security of valuable metals for clean growth in the UK. [link]

Water savings

Through the collaborative approach offered by industrial symbiosis, companies can identify synergies in water management, such as sharing water treatment facilities, recycling wastewater, or implementing more efficient water usage systems in order to reduce their water consumption. This not only reduces environmental impacts but also generates economic benefits by cutting costs associated with water consumption and treatment.

A study estimated that a total of 9.5 million tonnes of water were saved in the first five years of the UK's NISP programme.[354] The two core synergies responsible were improved water efficiency through knowledge transfer, and the matching of companies to allow the re-use of water.

In the case of DETDZ, industrial symbiosis strategies led to an increase of 16 to 40 per cent in the reutilization ratio of regenerated water to fresh water. Additionally, water consumption relative to DETDZ's GDP decreased by 24.2 per cent.[355]

Water savings or re-using water in the production process was not noted as a benefit by stakeholders or in the sector-specific literature. This could be due either to the relatively low cost of water, or to the fact that the common types of symbiosis in these sectors did not involve material water synergies.

7.2 Economic benefits

Industrial symbiosis can generate a number of financial and economic benefits. Linked to the above benefits, industrial symbiosis can lead to cost savings as businesses can utilise each other's waste materials, reducing the need for virgin resources and cutting down on disposal costs. Industrial symbiosis can also encourage innovation and technological advances as companies collaborate to find creative ways to repurpose materials. This collaborative environment can lead to the development of new products and processes, enhancing efficiency. Additionally, by optimising resource use and minimising waste, industrial symbiosis can contribute to a more resilient and robust economy, reducing the environmental impact of industrial activities and supporting long-term economic sustainability.

7.2.1 Cost reductions and revenue generation

Evidence from the general literature and stakeholder interviews

As highlighted above, firms are able to reduce costs associated with waste disposal and/or resource use. In addition, financial benefits can also arise from additional sales and revenues stream, such as the selling of waste or by-products. For example:

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[354] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report.

[355] Liu, Z., Adams, M., Cote, R.P., Geng, Y., Ren, J., Chen, Q., Liu, W., Zhu, X. (2018). Co-benefits accounting for the implementation of eco-industrial development strategies in the scale of industrial park based on energy analysis. Renewable and Sustainable Energy Reviews, 81, 1522-1529. [link]

- The net impact of NISP activities was assessed based on an assessment of attribution (of 60 per cent) and persistence (of five years). The study estimated that there was an increase in net sales for firms participating in the programme of between £317 million and £528 million, and net cost savings of between £281 million and £468 million.[356]
- In the case of the EPOS Hull cluster in the chemicals sector, the business case for symbiosis between INEOS and CEMEX identifies potential annual benefits for INEOS of £576,000 from an initial investment of £820,000 (implying a two-year payback time for the initial investment).[357]

A stakeholder also mentioned the additional revenues generated from selling waste as a benefit of industrial symbiosis.

The economic benefits generated through symbiotic exchanges may not be distributed equally across senders and receivers. For example, in the case of quarry fines, farmers often agree to spread the waste on their land whilst the sending sector benefits from the carbon credits.

Evidence from the six chosen sectors

The table below summarises the key benefits in terms of cost reductions and revenue generation highlighted in the sector-specific literature and by stakeholders in the six chosen sectors.

	Evidence from literature	**Evidence from stakeholder interviews**
Cement	No specific evidence from sector.	No specific evidence from sector.
Glass	No specific evidence from sector.	No specific evidence from sector.
Mining	No specific evidence from sector.	Economic benefits stem primarily from the avoidance of landfill and storage costs, as well as from increased sales of waste/by-products.
Chemicals	A Chemical Industrial Park in China involving exchanges such as the transfer of carbide slag from a cement plant to a chemical plant generated more than ¥380 million of financial benefits by reducing 5.86 million tons of resource consumption and waste emissions such as fresh water, coal gangue, carbide slag and fly ashes.[358]	Reducing emissions translates to reduced spending on carbon credits for companies, offering a competitive advantage. Energy from an energy-from-waste plant can lower the price of electricity to less than the price on the open market. The price paid for soda ash from a steel plant is lower than the open-market price.

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[356] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report.
[357] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]
[358] Cui, H., & Liu, C. (2017). Applying industrial symbiosis to chemical industry: a literature review. [link]

	The EPOS Hull cluster identified potential annual benefits for INEOS from a partnership with CEMEX of £576,000 from an initial investment of £820,000.[359]	Exchanges between companies located nearby under a long-term contract can also lower transport costs.
Food and drink	At an eco-park in Poland, MBM production from animal waste and the generation of energy from the combustion of biofuel can generate revenues of over €520 million, with gross profits of over €100 million annually. The more productive utilisation of material flows as well as decreased material and energy consumption also leads to lower operating costs.[360]	Selling by-products could reduce costs associated with landfill, incineration and CO_2 permits, especially when a significant amount of waste is involved. For example, a stakeholder avoids sending around 900,000 tonnes of material to landfill each year by selling by-products.
Agriculture	The exchange of waste CO_2 from a factory to a greenhouse can result in economic benefits of €0.68 to €1.6 million per year due to increased crop production from using recovered CO_2 for plant enrichment, reduced costs related to CO_2 emissions and lower utilisation of natural gas for CO_2 production for greenhouses.[361] Transforming organic by-products into higher-value products such as fertilizers, animal feed, and biofuels generates further revenue for agricultural operations.[362]	Cost savings can be realised from using cheaper fertilisers from agriculture waste. Subject to materials meeting quality standards, farmers can also obtain waste products for free to spread on land e.g. quarry fines or wastewater sludge.

7.2.2 Increased efficiency and innovation

Industrial symbiosis can drive efficiency by enabling industries to share resources, waste, and expertise to optimise overall production processes. By tapping into shared infrastructure, such

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[359] EPOS Insights. (2019). Industrial symbiosis in the Humber Region. [link]

[360] Kowalski, Z., Kulczycka, J., Makara, A., Mondello, G., & Salomone, R. (2023). Industrial Symbiosis for Sustainable Management of Meat Waste: The Case of Smiłowo Eco-Industrial Park, Poland. International Journal of Environmental Research and Public Health, 20(6), 5162. [link]

[361] Marchi, B., Zanoni, S., & Pasetti, M. (2018). Industrial symbiosis for greener horticulture practices: the CO_2 enrichment from energy intensive industrial processes. Procedia CIRP, 69, 562-567. [link]

[362] DEFRA R&D Report. (2023). Foresight study to compare the relative gains, costs, feasibility and scalability of current and future ‘industrial horticulture’ models. [link]

as a shared energy or water system, industries can also benefit from economies of scale and enhanced operational efficiency. Additionally, the exchange of knowledge and best practices within an industrial symbiosis network encourages innovation and the adoption of more efficient technologies. For example, a University of Birmingham and C-Tech Engineering study of 125 NISP case studies found that innovation was a key component for over 70 per cent of all facilitated synergies. Additionally, the study showed that 56 per cent of synergies used the best available technologies, while 19 per cent involved significant amounts of new technology development or pure research.[363]

One stakeholder noted that innovation spillovers in which the technology enabling a synergy is used by other companies or sectors could be substantial.

Increased efficiency and innovation spillovers were not identified as specific benefits for any of our chosen sectors.

7.2.3 Job creation and business opportunities

By engaging in symbiotic relationships, businesses experience potential commercial benefits which contribute directly to their growth as well as to the economic growth of the wider region. As industries collaborate to streamline their processes and share resources, this can lead to the creation of new jobs and the opening of new business ventures, thus contributing to sustainable economic growth. The literature cites a number of examples:

- Terra Nitrogen was looking for opportunities to reuse its excess CO_2 and steam heat from its ammonia production. A nearby vegetable grower was looking to expand operations, and by exchanging resources was able to build a new 38-acre greenhouse which was heated with Terra's excess steam heat and which used 12.5K tons/year of Terra's excess CO_2 for plant growth. This made expansion cost-effective for the greenhouse, resulting in eighty new jobs.[364]
- In a review of NISP's activity in the first five years, Scott Wilson Business Consultancy (2016) found that the increase in sales and cost savings led to over 8,770 jobs being safeguarded and created.[365]
- In its net annual benefits model, the West Midlands Combined Authority estimated that its proposed Industrial Symbiosis Programme (WMIS) will create a minimum of 50 jobs.[366]
- In the case of John Pointon, the diversion of meat and bone meal from landfills supported job creation and new opportunities as companies generated sales and achieved significant cost savings.[367]

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[363] Laybourn, P., & Lombardi, D.R. (2007). The role of audited benefits in Industrial Symbiosis: The UK National Industrial Symbiosis Programme. Measurement and Control, 48(8), 244-247. [link]

[364] Paquin, R.L., Busch, T., Tilleman, S.G. (2015). Creating Economic and Environmental Value through Industrial Symbiosis. Long Range Planning, 48(2), 95-107. [link]

[365] Scott Wilson Business Consultancy. (2009). NISP Economic Evaluation Report.

[366] West Midlands Combined Authority. (2020). West Midlands Industrial Symbiosis Programme Case for Investment.

[367] Laybourn, P., & Morrissey, M. (2009). The Pathway To A Low Carbon Sustainable Economy. NISP. [link]

A stakeholder noted that the revenues generated from selling waste could also increase companies' resilience, which in turn can accelerate growth plans, leading to more jobs, output and GVA. Some stakeholders also highlighted a reduction in transportation costs and associated emission costs as a benefit of industrial symbiosis.

Job creation and business opportunities (beyond the possibility of generating additional revenue) were not identified as specific benefits for any of our chosen sectors.

7.3 Summary of benefits

The literature and stakeholder evidence indicate a wide range of benefits from industrial symbiosis.

- **Reduction in the use of primary materials**, reducing environmental degradation and emissions/energy resulting from extraction and/or processing of those materials.
- **Reduction in CO_2 and other GHG emissions**, when replacement by-products generate fewer emissions in production processes.
- **Energy and water savings**, in cases where by-products require less energy or water in the production process or where water is re-used.
- **Avoided landfill**, and associated disposal costs, landfill tax payments and pollution.
- **Reduction in transportation costs**, and associated emissions.
- **Revenues generated** (for sending firms) and **cost savings** (for receiving firms).
- **Economic growth and job creation (or safeguarding).**
- **Innovation spillovers**, where technology enabling a synergy is used elsewhere.

Some of these types of impact may be either benefits or costs, depending on the specific context. For example, while transportation costs or energy usage may decrease in some examples of industrial symbiosis, in other examples they may increase.

Some of these benefits are particularly relevant to certain of our chosen sectors, as mentioned by stakeholders:

- **Energy savings** stemming from lower temperatures being needed in glass furnaces when using by-products (e.g. Calumite) or from a decrease in the production of high-energy Portland cement when SCMs are used were seen as key benefits for these sectors. In addition, the re-use of waste heat from production processes was also highlighted as important.
- Benefits associated with reducing/eliminating the amount of **waste ending up in landfill** were seen as particularly significant for the mining, cement, and food and drink sectors.
- **Carbon and emissions savings** were highlighted as a key benefit across all the sectors examined.

8 Costs of Industrial Symbiosis

In this section we present the evidence on the costs of industrial symbiosis from the **general literature** as well as an **overview of stakeholder** views from across all our interviews. We also set out the evidence from sector-specific literature and stakeholders in **the six chosen sectors**.

8.1 Evidence from the general literature and stakeholder interviews

In general there is less literature available on the costs of industrial symbiosis, and these are not typically quantified to the extent that benefits are.

The time and resources required to investigate opportunities for symbiotic exchanges and to subsequently secure contracts with suppliers/receivers of by-products was reported as a key cost by stakeholders. The implementation of industrial symbiosis can require **significant investment of both time and financial resources**, making potential participants view it as an unappealing and complex process.[368]

Stakeholders also mentioned that **investment in new equipment and/or processes to accommodate by-products** (e.g. new storage facilities, and upgrades or changes to existing machinery / production processes so that the by-products can be used) can represent a significant expense for companies.

In addition, some stakeholders stated that firms may also incur **costs associated with processing or transforming by-products** into suitable forms. While the use of by-products can lead to a range of benefits in terms of lower emissions and reductions in water and energy usage, a few stakeholders noted that in some cases **energy, water and/or carbon costs** may be incurred in processing or using by-products. Furthermore, companies may also face substantial **costs associated with technology or research and development (R&D)** before by-products may be used in production processing.

The **costs of applying for regulatory permits and approvals** that allow companies to use specific streams of waste products were also highlighted as a major cost by stakeholders, including in terms of the time and resources spent understanding and navigating the application process.

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[368] Vladimirova, D., Miller, K., & Evans, S. (2018). Lessons learnt & best practices for enhancing industrial symbiosis in the process industry. SCALER. [link]

Similarly, while the potential benefits of industrial symbiosis include cost reductions, for materials with few opportunities for reuse or little residual economic value, the **costs of long-distance transportation** might pose a problem. In such cases, it might be a more attractive option to incur the fees of landfilling than the logistical and financial costs of transportation.[369]

Higher transportation costs — for example, because the by-products are located further away than the raw material(s) replaced or because by-products require different transportation links — were also reported as an important cost by stakeholders. In addition, transport-related emissions associated with the use of by-products could be higher than those associated with the use of original inputs. A stakeholder noted that these trade-offs between higher emissions stemming from transporting by-products by road and/or over longer distances and lower carbon and GHG emissions from using these by-products in production processes should be carefully considered.

Since industrial symbiosis exchanges generally depend on the demand and supply of waste, which are subject to fluctuations, there is an increased dependency and vulnerability, as **changes in the quantity and quality of output and waste** can lead to supply chain crises. A study found that frequent resource exchange and complex resource flows may ultimately reduce the stability of the network. This is further exacerbated by frequent replacement of symbiotic partners, which both undermines the stability of the network and increases the costs to the firm.[370]

However, not all stakeholders view these costs as additional to what would otherwise be incurred. In particular, a stakeholder commented that with two exceptions[371] most costs represent “business as usual” costs, and that failing to take this into account could lead to the costs directly attributable to industrial symbiosis being overstated.

8.2 Evidence across the chosen sectors

There appears to be little literature and quantitative evidence available on the costs associated with industrial symbiosis in specific sectors. In particular, our review of the sector-specific literature did not identify any evidence relating to the costs of industrial symbiosis for the cement, glass, food and drink, and agriculture sectors.

8.2.1 Cement

Stakeholders noted that investment in new equipment can be substantial. For example, a cement manufacturer undertook significant investment in four waste fuel systems (attached to kilns) that allowed it to use waste fuels in its production. Moreover, a stakeholder stated that

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[369] Neves, A., Godina, R., Azevedo, S.G., Pimentel, C., & Matias, J.C.O. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. Sustainability, 11(24), 7095. [link]

[370] Turken, N., Geda, A. (2020). Supply chain implications of industrial symbiosis: A review and avenues for future research. Resources, Conservation & Recycling 55(10), 3118-3123. [link]

[371] The exceptions mentioned were: costs associated with the time and resources spent investigating industrial symbiosis opportunities and costs of processing or transforming by-products into suitable forms.

transportation costs could also be significant when SCMs are transported over extended distances, and a model shift from rail to road transport also contributes to higher emissions.

Stakeholders also noted that the **allocation of CO_2 emissions** between different industries can affect the cost implications of using alterative materials. For example, while CO_2 emissions from using GGBS have historically been allocated to the steel industry, some of the CO_2 is now being allocated to by-products, which reduces the attraction of using GGBS from a cost perspective.

8.2.2 Glass

Stakeholder interviews indicated that investment in new furnaces entails significant costs, amounting to millions of pounds, and that the asset investment cycle typically lasts 12 to 15 years. Given the substantial investment required, the manufacturer would need to carefully consider the type of (alternative) fuels or raw materials that may be used over an investment cycle and the implications for the type of furnace to be installed, as the choice of fuels and raw materials affects the type of furnace needed.

Depending on the alternative raw materials used (e.g. bio ash), producers may also need to invest in new hoppers (containers) to store the new materials, costing tens of thousands of pounds. As noted above, producers will typically only be willing to undertake such investments once alternative raw materials, such as bio ash, have been proven to be viable in the glass manufacturing process.

8.2.3 Mining

The literature reports relatively **high investment costs for processing plants** while the lack of capital is identified as a challenge in moving towards a circular economy and the reuse of mining by-products. Similarly, a stakeholder noted that building a waste storage facility plant entails significant investment costs as well as leading to ongoing operational expenses. In addition, as mining sites are typically located in remote areas, **logistics and transportation costs** could also be significant before any by-products could be used by other industries.[372]

8.2.4 Chemicals

A key theme from our stakeholder interviews – highlighted in the barriers section – is the costs of developing many of the industrial symbiosis opportunities, including the **costs of research and development and establishing suitable supply chains**, as well as the potentially significant costs of **investing in new equipment** and processes across the industry.

In addition, the literature also highlighted some costs specific to certain symbiotic exchanges:

- For example, a report by the University of Oxford found that **sustainable carbon is up to five times more expensive** than fossil-based equivalents.[373] Carbon capture and

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[372] Kinnunen, P. H. M., & Kaksonen, A. H. (2019). Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production, 228, 153-160. [link]

[373] Collett, K.A., Fry, E., Griggs, S., Hepburn, C., Rosetto, G., Schroeder, N., Sen, A., & Williams, C. (2023). Cleaning up cleaning: policy and stakeholder interventions to put household formulations on a pathway to net zero. University of Oxford. [link]

storage requires a significant overhaul in technology and a chain of CO_2 capture, transport and storage (and also requires all technology in this process to be safe and efficient).[374] This transition is time-consuming and involves high up-front costs.

- Another study noted that during the process of a chemical plant sending a liquid waste fuel stream to a steel plant, the liquid waste fuel stream is sent to a third party for processing, for which the chemical company has to pay a fee as it negatively affects the efficiency of the third party's boilers.[375] While this is a specific case, it highlights the **costs involved in processing alternative feedstocks**.
- Finally, in the case of INEOS Hull (chemicals sector) sending liquid waste streams to CEMEX South Ferriby (cement), the main costs associated with the project were: costs associated with **plant cleaning**, costs related to the **additional storage capacity** needed to facilitate long-term operations, and also costs associated with **improving the cooling and instrumentation systems** due to the hazardous nature of the solvent (which is flammable and volatile).[376]

8.2.5 Food and drink

According to stakeholders, a common cost in the food and drink industry relates to the **equipment and processing costs** incurred in order to repurpose waste and by-products into usable materials and products. For example, a stakeholder mentioned they incurred significant costs of processing their co-products, as well as logistic costs per year moving the product between its sites. However, these costs are factored into the business case for selling the by-product and are covered by revenues from the sale.

Another stakeholder noted that while their operations reduce waste and create a number of by-products from meat processing waste, it can use a lot of energy (due to high temperatures needed for burning). It stated that other companies, such as those carrying out anaerobic digestion, have the ability to take on similar food waste without the energy costs, although they produce different outputs for different markets.

Other costs mentioned by stakeholders relate to the regulatory process for clearing products for use, such as applying for "end-of-waste" status. One stakeholder spent up to £22,000 in legal fees and resources to provide evidence to enable its product to be classified as end-of-waste.

8.2.6 Agriculture

According to stakeholders, the additional costs of obtaining waste heat and CO_2 for greenhouses through industrial symbiosis can vary significantly depending on the circumstances of the individual greenhouses and the sending company. In many cases,

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heating a greenhouse using heat from a waste sender will involve **no extra cost** compared with using other methods –water would in any case be heated in a boiler and the heated water would then be piped around the greenhouse. Additional costs might be incurred if additional piping was needed to pipe more water (e.g. if the temperature of the waste heat was lower than that generated by a gas boiler and thus a greater volume of water was required to run through the greenhouse). If a greenhouse does not use a heated water system but instead uses heat blowers, then it would need to convert its system to a water system in order to be able to use waste heat, thus incurring additional investment costs. For these reasons, it is most economical to build a greenhouse with a symbiotic heat source already in mind so that any necessary adjustments can be built in rather than retrofitted.

A stakeholder noted that carbon capture and storage costs are relevant (and significant) where greenhouses seek to use waste CO_2 from other industries. These costs can be factored into the price of the contract for the synergy.

Another stakeholder stated that it would not incur additional investment costs receiving waste CO_2 rather than CO_2 from its original sources – both would entail receiving truck deliveries of the liquefied gas. However, **transport costs** would be relevant if the gas came from farther away, as would be the cost of the actual gas.

A stakeholder also highlighted that the costs of using waste products as fertilisers can be greater than the costs of using manufactured fertilisers — for example, due to the additional time and resources required to spread manure and slurry on land (a much more difficult process than when using pelleted or liquid fertilizers).

8.3 Summary of costs

Evidence relating to the costs of industrial symbiosis is less readily available in the literature and from our stakeholder interviews than evidence relating to benefits. The key costs of industrial symbiosis cited in the literature and by stakeholders are:

- **Time and resources** to investigate opportunities and secure contracts.
- Costs of **technology development** and R&D.
- Costs of applying for **regulatory approval**, e.g. to co-locate companies.
- **Investment** in new equipment or processes to accommodate by-products, e.g. to store by-product or make use of it in the production process.
- **Transportation costs**, if the by-product is further away than the original inputs, or requires different transportation links.
- **Energy, water and carbon costs** which may be incurred in processing the by-product, incorporating it as an input, and/or transporting it.
- **Costs of processing** or transforming by-products into suitable forms.

Stakeholders identified the following costs as particularly relevant, with some variation across sectors:

- The **time and resources** required to investigate and secure symbiotic partners and contracts.
- **Transportation costs**, which were seen as particularly significant where by-products are low value, bulky and/or difficult to transport, such as in the chemicals, agriculture, food and drink, and cement sectors. In addition, some stakeholders in the cement and mining sectors also mentioned a model shift from rail to road transport (e.g. in the case of waste-derived fuels), which also contributes to higher emissions.
- **Investment** in new equipment, which can be substantial.
- The cost of obtaining **regulatory permits and approvals**, especially in terms of the significant time and resources required. These costs were highlighted as a key issue by most stakeholders across all the sectors examined.

9 Conclusions

Our evidence gathering and analysis shows significant scope for industrial symbiosis in the UK, with numerous examples of current symbiotic exchanges as well as many potential opportunities for further industrial symbiosis in the six sectors that form the focus of our research. This potential will be affected by a number of drivers and barriers.

Financial drivers and enablers are considered the most important by stakeholders and in the literature, scoring ‘very high’ in our ranking. Essentially, companies will only consider industrial symbiosis if the benefits (in terms of various cost savings and revenue creation) justify the costs. Financial drivers are linked to other drivers in that many of these will have a cost element – for example, geographic proximity is an enabler as it reduces the costs of transporting materials; and regulatory and policy-related factors can reduce or subsidise the costs of industrial symbiosis for firms, or drive them to pursue symbiotic networks as a way of reducing costs and taxes. Other important drivers were technological, such as technology to enable waste or by-products to be used as inputs, synergy optimisation technologies to match ‘senders’ to ‘receivers’, and digital platforms for collaboration among stakeholders; and knowledge and information-related enablers such as awareness of industrial symbiosis opportunities, tools for evaluating potential symbiotic relationships, technical expertise for implementing industrial symbiosis and external facilitation and management of synergies.

The literature shows that barriers to industrial symbiosis are present in the same categories as for drivers and enablers – indeed, in many cases the absence of a driver or enabler manifests as a barrier. Hence, key barriers are related to technology, knowledge and information, organisation and cultural, geography, financial impacts, and regulation / policy. The evidence from the literature and stakeholders shows that the most important barriers are a lack of knowledge of industrial symbiosis in general and a lack of awareness of specific symbiotic opportunities in particular; suitable technologies or processes being unavailable, unproven or too expensive; and other general costs of industrial symbiosis such as set-up and capital investment costs, time, transportation costs, regulatory costs and the costs of purchasing the by-products themselves.

There are numerous potential benefits from industrial symbiosis, with the key ones highlighted in the literature and by stakeholders being reduced carbon emissions, reductions in waste being landfilled and reductions in energy usage. The quantification of benefits in the literature focuses mainly on reduced emissions.

Evidence on the costs of industrial symbiosis is much more limited. The key costs highlighted in our research are transportation costs, which were seen as particularly significant where by-products are low value, bulky and/or difficult to transport; investment in new equipment or production processes to enable the use of by-products; and the cost of obtaining regulatory permits and approvals, especially in terms of the significant time and resources required.

There is relatively little evidence of risks in the literature, although stakeholders we interviewed highlighted a number. The most important risks in terms of impact or likelihood are fluctuations in the demand for or supply of by-products, particularly where this undermines investment or disrupts supply chains; and the risk that the by-products turn out to be unsuitable or environmentally damaging. Stakeholders also mentioned risks associated with government policy – for example where the viability of a symbiotic trade changes due to unforeseen changes in policy, or where the promotion of industrial symbiosis in one sector creates unintended consequences in another sector.

List of abbreviations

AD	Anaerobic digestion
CCS	Carbon capture and storage
CEH	Controlled environment horticulture
CEN	European Committee for Standardisation
CHP	Combined heat and power
CIA	Chemical Industries Association
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DEFRA	Department for Environment Food & Rural Affairs
EA	Environment Agency
GBBS	Ground granulated blast furnace slag
GDP	Gross Domestic Product
GHG	Greenhouse gases
GVA	Gross value added
ICI	Imperial Chemical Industries
LCA	Life-cycle assessment
MPA	Mineral Products Association
MSW	Municipal solid waste
Mtoe	Million tonnes of oil equivalent
NISP	National Industrial Symbiosis Programme
ONS	Office for National Statistics
PFA	Pulverised fly ash
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals.

SCM	Supplementary cementitious material
UK / EU ETS	UK / EU Emissions Trading System
UKRI	UK Research and Innovation
WRAP	Waste & Resources Action Programme

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