Cost and energy input requirement assessment of carbon capture and storage technology application in the Scottish Chemical industry

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Overview

Carbon capture and storage (CCS) technologies are deemed essential to decarbonise the hard-to-abate industrial sectors such as petrochemicals, iron, steel, cement, and other industries, where electrification, particularly from renewable sources, is not a viable alternative. CEP's research has focused on the wider economic implications of adopting post- or pre-combustion CCS technology in relation to the Scottish chemical industry. The decision on technology can have a varying impact on the sector's competitiveness in both national and international markets, and by extension on the wider Scottish economy. This study explores the capital and energy input required to integrate post- and pre-combustion CCS technologies in the Scottish chemical industry, emphasising on the carbon capture component, with a scope to provide useful data for studying the competitiveness and wider economic implications of employing these CCS technologies. The study reviews various techno-economic analyses to document and estimate the capital and energy input requirements and to provide the basis for similar calculations for the Scottish chemical industry. Stakeholder engagement with relevant industrial partners was conducted to assess and improve the reliability of the estimates.

Findings from the research suggest that:

- **Pre-combustion carbon capture is more capital intensive than post-combustion carbon capture.** On average, it costs more in terms of capital requirements (CAPEX) to integrate pre-combustion carbon capture in the electric power and industrial plant process than post-combustion carbon capture. Specifically, for the Scottish chemical industry, the additional CAPEX was calculated to be 40% for post-combustion carbon capture and 50% for pre-combustion carbon capture Steam methane reforming (SMR) and Autothermal reforming processes (ATR).
- **Post-combustion carbon capture is more energy input intensive than pre-combustion carbon capture.** For the energy input requirements, the analysis of the Scottish chemical industry shows that an estimated additional 30% natural gas and 4% additional electricity are required for post-combustion carbon capture; the corresponding energy requirements are 20% and 3% for pre-combustion SMR, and 15% and 6% for pre-combustion ATR, respectively.

The decision on which technology should be adopted will be informed by the extent in which this additional capital cost and energy input will impact the sector's broader competitiveness since these additional requirements will reduce capital and resource efficiency of the sector with potential implications on sectoral characteristics, including the output price. Furthermore, there are potential economy-wide implications, and

policy trade-offs associated with the adopted carbon capture technology, which merit further analyses. The latter will be the focus of further analytical work informed by the initial research highlighted in this report.

1. Background

The current UK Industrial Decarbonisation Strategy (BEIS, 2021) and the recent reaffirmation through the 'Powering up Britain' (DESNZ, 2023) announcements demonstrate the UK's commitment towards using CCUS as a key technology to support industrial decarbonisation. However, across the UK's industrial clusters, there are different plans on how to implement CCUS, particularly about the carbon capture component and where and when it will take place. For the industries involved, whether carbon capture will take place pre-combustion, replacing current fuels (such as natural gas) with zero carbon alternatives, or after the combustion (or the production more generally) process, using current fuels, will have implications on the equipment (capital) requirements and inputs from different sectors (e.g., build facilities to produce zero carbon fuels, upgrade equipment to operate with alternative fuels, etc.)

By extension, the carbon capture approach selected could lead to different cost and price impacts on industries and, in turn, affect their competitiveness in domestic and international markets. CEP's research aims to provide an overview of the cost and energy requirements of applying different carbon capture technologies in the chemical industry, and how they impact the wider economy. Specifically, CEP research team calculates the percentage of additional input (electricity, natural gas consumption, and capital cost) requirements for the application of pre- and post-combustion carbon capture systems in the chemical industry of Scotland to provide data for further modelling the competitiveness and economy-wide effect of these technologies application in the Scottish chemical sector.

The Scottish Chemical industry is used as an example of a key industry in the Scottish Cluster and, broadly, the Scottish economy in view that it forms part of the three main emission dominating sectors (i.e., Power, chemicals, and refining) which together accounted for 68% of total emission in Scotland in 2019 (NECCUS, 2023). The chemical sector is the second largest carbon emitting sector in Scotland, with considerable volume of process emissions, which amount to 11% of total chemical sector emissions in Scotland (DECC,2015). This sector forms part of sectors where less options are available for decarbonisation without carbon capture and storage system or fuel switching to low carbon alternatives integrating carbon capture and storage.

The insights for the chemical industry can also serve as learning for other sectors with similar characteristics in industrial operational activities, such as the consumption of natural gas as feedstock and fuel. The study focusses on introducing carbon capture in the Chemical industry in Scotland as a devolved nation, where Chemicals is a significant production sector and where any impacts driven by industrial decarbonisation of this sector may be better understood by focusing on Scottish rather than the UK level, which has been the focus of previous economy-wide analyses (Scottish Government, 2019; Turner et al., 2022). This is due to the differences in the relative scale of the Scottish and the UK economy and the comparably more significant contribution of the chemicals sector to the Scottish economy, with the implication that the same action will have a more significant and marked impact on the Scottish economy. The analysis further provides broader insights into data for methodology developments, applicable across industries and/or regions/nations, that will contribute to a better understanding of the trade-offs involved in deciding on how to implement industrial decarbonisation within the UK and abroad.

2. Characterisation of the Scottish Chemical industry

2.1 Economic importance

The Scottish chemical industry plays a significant role to the industrial contribution to the economic development of Scotland and the UK. The sector manufactures products and technologies that deliver foods, medicine, communication, transportation, and other everyday products consumed in the Scottish economy[1]. In terms of industry size, about 250 chemical-based companies are operating in Scotland in the main category of basic/commodity chemicals (such as basic plastics, polymers, fuels, alcohol, benzene, etc); speciality chemicals (such as lubricants, adhesives, agrichemicals, etc) and industrial biotech (biofuels, synthetic biology etc.)[2] as illustrated in Figure A1 in the appendix. The industry captures world-leading companies such as INEOS, Fujifilm, DSM, GlaxoSmithKline, DuPont Teijin Films, BASF Pharma and Syngenta which provide products for both domestic and international consumption. The INEOS production facility in Grangemouth, in 2023, directly employed approximately 2,000 workers to produce 1.4 million tonnes of output and generate in the process £450 million of gross value added (a 4% share of the Scottish GDP)[3]. This is a clear indication of the sector's significance in the Scottish Economy. Overall, in 2023, the Scottish chemical sector employed 10,500 workers (4% of the total employment in Scotland), generated £2.4 billion of value-added (1.1% of Scottish GDP), while exporting £3.0 billion worth of output[4]. Compared to the entire UK chemical industry, these constitute 7% of total employment, 8% of gross value added and 6% of total export in 2023. In 2020, the chemical sector employed 21% of the manufacturing workers in Scotland which contributed 12% of the sectors' gross value added[5]. The chemical sector therefore contributes significantly to the Scottish industry and the economy.

[1] https://www.cia.org.uk/Portals/0/Documents/Publications/Advantage%20Scotland%20(April%202016).pdf?ver=2017-01-09-143812-000

[2] (Scottish Economic Statistics, Scottish Enterprise February 2021): Scotland's chemicals and industrial biotech industry opportunities (sdi.co.uk)

[3] https://www.ineos.com/sites/grangemouth/about/

[4] https://www.cia.org.uk/Portals/0/Documents/CIA%20Q3%202023%20Economic%20Report.pdf

[5] https://www.gov.scot/publications/scottish-annual-business-statistics-2020/

2.2 Energy use characteristics

Natural gas and electricity are the chemical industry's primary sources of energy supply. Most chemical processes use natural gas as fuel (heat sources) and feedstock. **Table 1** illustrates the energy (natural gas and electricity) consumption and carbon emissions of the Scottish chemical and industrial sector and compares it with that of the UK. As shown in **Table 1**, the Scottish economy's total industrial natural gas consumption in 2021 was 10,010 GWh, about 21% of total national consumption. The total electricity consumption in the Scottish economy for 2021 was 27,716 GWh. The Scottish chemical industry's electricity and natural gas consumption for 2021 has been estimated as 1,276.7 GWh and 3,069.7 GWh, respectively (referred to **Table 1**). The chemical industry also represents a significant contribution to the Scottish industry's carbon emissions and in 2021, the chemical sector generated 2.3MTCO_2e of carbon emissions, 31% of total industrial emissions in Scotland, as shown in **Table 1.**

Table 1. Annual Energy Consumption and associated carbon emissions in the UK and Scottish industry, 2021[6]

	Natural gas consumption (GWh)			**Electricity consumption (GWh)**			**CO_2 emissions (MT)**		
Region	Chemical industry	Total industry	National aggregate	Chemical industry	Total industry	National aggregate	Chemical industry	Total industry	National aggregate
UK	21,036	103,294	513, 047	15,105	87,452	292,639	4.4	59.5	339.5
Scotland	3069.7[7]	10,010	46,999	1,276.7[8]	7392.3[9]	27,716	2.3	7.5	27.5

Source: Authors computation,2023

[6] Data source:1) Data for CO_2 emissions national aggregate for the UK and Scotland is taken from a database of the Department for Business, energy, and Industrial Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1134664/greenhouse-gas-emissions-statistical-release-2021.pdf while Industry and chemical sector CO_2 emissions are calculated from the database of UK's National Atmospheric Emission Inventory (2023). Note: The total industry emissions data are computed by adding emissions from industrial processes to Emissions from fuel combustion and product use in industrial and commercial sectors (reported as part of the Business sector emissions).
2)Data for Electricity and natural gas consumption is taken from A) Natural gas commodity balances (Dukes 4.1)-Excel.https://www.gov.uk/government/statistics/natural-gas-chapter-4-digest-of-united-kingdom-energy-statistics-dukes.B) Electricity commodity balancehttps://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-duk and Electricity generation and supply in Scotland https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1126101/Regional_electricity_generation_and_supply_2017-21.pdf

[7]In the absence of specific data on energy consumption for the Scottish chemical industry, this value has been calculated based on the proportion in % of total Scottish industrial carbon emissions and emissions of the Scottish chemical sector. This assumption has been taken as https://statistics.gov.scot/data/energy-consumption reports that most chemical sector's CO_2 emissions are related to natural gas use.

[8] Electricity consumption data for the Scottish chemical sector are not available, hence this value was calculated based on the proportion of industrial electricity consumption relative to national electricity consumption, which is comparable to the same ratio for the UK.

[9] This value is calculated from the 2020 electricity consumption for the Scottish industry (6,751GW), adjusted for a 9.5% increase in demand between 2020 and 2021

3. Review of cost models and performance data of carbon capture and storage technologies

3.1 Carbon capture and storage technologies applications

Carbon capture and storage is largely the separation of carbon dioxide from its point source and consequently its isolation from the atmosphere for storage or possible utilisation (Theo et al., 2016). CCS forms part of carbon capture, utilization and storage (CCUS) technologies where CO_2 is captured and concentrated from flue gas, and then compressed/liquefied at about pressure of 100 bar prior to transportation for either for industrial usage or injection and permanent storage into depleted oil and gas fields, coal beds, salt cavities or aquifers (Blomen et al., 2009). Carbon capture and storage technology has three main areas of study: pre-combustion capture, post-combustion capture, and oxy-combustion capture (Theo et al., 2016). Post-combustion involves the separation and capturing of CO_2 from fuel gas produced by burning fossil fuel, in the air (Hong, 2022) which can be applied to existing and future industrial plants (Younas et al., 2016). Pre-combustion involves capturing CO_2 prior to combustion which is mostly based on industrial processes that produce hydrogen and other chemical commodities (Eide & Bailey, 2005). The technology comprises three steps: reforming/conversion of fossil fuel to a mixture containing hydrogen (H_2), carbon dioxide (CO_2) and carbon monoxide (CO); shifting this mixture to a mixture with CO_2 and H_2; and separation of CO_2 and hydrogen (Eide and Bailey, 2005). The technology can also be applied to power plant systems such as the natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) (Hong, 2022). Oxy-fuel combustion capture involves burning fuel in a nearly pure oxygen (O_2, 95% to 99% vol.) at very high temperatures of about 1,300 °C to 1,900 °C (Rubin et al., 2012). However, there is currently no operational full-scale CCS plant applying the oxyfuel combustion system (Theo et al., 2016; Adu et al., 2019;Chao et al., 2021), contrary to post and pre-combustion CCS plants that are currently operational. Hence, this study mainly focusses on pre-and post-combustion technology due to their advancement and potential application in the Scottish chemical sector.

Each of the pre- and post-combustion CCS technologies comes with advantages and disadvantages. Regarding the adoption of the technology, pre-combustion capture technology is a relatively advanced domain compared to other carbon capture technologies since hydrogen production in refinery and petrochemical industry has existed for several decades (Chen, 2022). According to (Theo et al., 2016), pre-combustion CCS are less energy intensive, have less water requirement and can generate hydrogen as an alternative fuel. This result from high concentration of CO_2 and partial pressure which enhance efficiency of the sorption process, making its CO_2 separation and compression process associated with lesser loss or penalty of energy consumption. Unlike pre-combustion, lack of advances in absorbent materials is the primary cause of inefficiency, leading to high energy requirements and low CO_2 capture rate in post-combustion capture technology (Gizer et al., 2022; He, 2018; Bhown and Freeman, 2011). However, post-combustion capture also has the advantage of being easily retrofitted to existing industrial plant processes due to the infrastructure needs, and high maintenance expenses associated with pre-combustion (Chao et al., 2021). In terms of cost, the capture component (which mainly includes the type of capture technology, plant integration, scale of operation, maintenance and operating cost and energy requirement) is the most expensive cost element in the CCS technologies application, which can constitute about 50% of total cost without CO_2 compression and 90% when accounting for the compression component (Kearns et al., 2021). While post-combustion CCS capture mainly involve integration of additional CO_2 separation equipment, pre-combustion CCS often involves reformer and CO_2 separation equipment which could impact different on capital cost. This additional investment cost of capital requirement bottlenecks in pre-combustion makes post-combustion relatively less capital intensive (Adu et al., 2019). The CO_2 separation techniques which mainly involve, adsorption, absorption, membrane separation and chemical reaction (Chao et al., 2021) may also require different materials and accompanying energy requirement for post- and pre-combustion which impact differently on operational cost for the two technologies. This indicates that these two technologies may require different levels of energy consumption and capital and operational costs which could impact differently on the final industrial product and hence the industries' competitiveness and the wider economy. This study therefore explores these cost and energy requirements in detail to inform further research on the competitiveness and wider economy impacts in the chemical industry of Scotland.

3.2 Capital and operational cost of carbon capture and storage technologies

This section reviews and discusses the cost requirements for the use of post and pre-combustion CCS technology in general, and with a special emphasis on the chemical industry. CCS can be used to capture CO_2 from power plants, and other industrial processes at different capital and operational costs. For the case of power plant systems, IEA (2020) shows the levelised capital cost of gas-fired CCS is around USD 870/kw for post-combustion CCS and USD 1,180/kw for pre-combustion CCS. This implies that 27% more capital cost is needed for pre-combustion than post-combustion CCS for gas-fired power plant decarbonisation. Similarly, IEA (2020) shows the levelised electricity production cost for post-combustion CCS is USD 0.08/kw while that of pre-combustion CCS is USD 0.097/kw, representing an additional 18% more electricity production cost for pre-combustion CCS. Looking specifically at carbon capture applications for industrial processes, the cost of capturing CO_2 for ethanol production or natural gas processing is estimated to be USD 15-25/t CO_2 (industrial processes producing "pure" or highly concentrated CO_2 streams). For cement production, IEA (2020) estimated the cost to be USD 40-120/t CO_2 (processes with "dilute" gas streams). The cost analysis of various plants integrated with CCS in the literature is shown in **Table 2** and **Table 3**. The analysis shows that, on average, an additional CAPEX of 40% and OPEX of 54 % is required to integrate post-combustion CCS in the electric power and industrial plant process. Similarly, additional CAPEX and OPEX of 60% and 36%, on average, are needed for pre-combustion carbon capture. The implication is that while more OPEX is needed to run post-combustion CCS, higher CAPEX is required to build or integrate pre-combustion CCS[10].

Table 2. CAPEX AND OPEX for selected plant with post-combustion CCS technologies

Power/ industrial process Plant	Plant capacity	Additional CAPEX with CCS as compared to Ref case	Additional OPEX with CCS as compared to Ref case	Reference
NGCC retrofitted with CCS	822MW	43%	22%	(Iram,2017)
CHP power plant with CCGT and CCS		12%		(Suomalainen et al., 2013)
NGCC retrofitted with BLUE H2	840 MW	58%		(Díaz-Herrera et al., 2021)
Single Plant - Single Sink Natural gas plant	420MW	67%	-	(ETP, 2010)
Steel mill's power plant		26.7%	73.3%	(Garðarsdóttir et al., 2018)
Pulp mill's boiler		32.6%	67.4%	(Garðarsdóttir et al., 2018)

Source: Authors computation,2023

Table 3. CAPEX AND OPEX for selected plant with pre-combustion CCS technologies

Power/ industrial process Plant	Carbon capture system	Additional CAPEX with CCS as compared to Ref case	Additional OPEX with CCS as compared to Ref case	Reference
H2 production from Natural gas reforming with CCS	Pre-combustion	84.0%	18%	IEA (2019)
Ammonia production with natural gas	Pre-combustion	45%	45%	IEA (2019)
Standalone SMR plant with CCS (100,000Nm^3 H2/h)	CO_2 capture from syngas	34%	11%	(Collodi et al., 2017)
	CO_2 captured from PSA Tail gas	41 %	3%	
	CO_2 captured from flue gas	79%	14%	
SMR based H2 plant with CCS (100,000Nm^3 H2/h)	Pre-combustion	89%	51.2% -66.2%	(Ali Khan et al., 2021)

Source: Author's computation, 2023

[10] Refer to appendix A2 for full details on monetary cost values that was used to arrive at the % difference in post-and pre-combustion CAPEX and OPEX data in Table 2&3. Also refer to Table A3 in appendix for a cost analysis specific to chemical plants (medium-sized refinery, petrochemical, and other chemical industries). Table A3 also supports the conclusions emerging from the analysis in Table 2&3

3.3 Energy requirements for carbon capture technologies application

Table 4 shows the energy consumption characteristics of incorporating pre-and post-combustion carbon capture into various industrial plants reviewed through available techno-economic analyses of carbon capture and storage technology applications. The review shows there are additional requirements for electricity and natural gas (in some cases as feedstock) to operate the carbon capture systems in industrial plants. Our analysis of the various literature studies on carbon capture technologies shows that post-combustion carbon capture technologies require additional electricity and heat (normally in the form of steam, which could be produced from electricity, natural gas, or other industrial waste sources consumption) between 10-20% (average of 16%)[11]. For the case of pre-combustion, integrating with carbon capture will increase additional feed gas (predominantly natural gas) as well as electricity consumption with an average increase factor of 20-30% and 2-5%, respectively. These calculations are illustrated in **Table 4** below.

[11] Most literature mentions electricity consumption for post-combustion, with mentions however of two processes: Absorption and regeneration. The regeneration process is achieved with steam or direct electricity (also reducing impurities of the recovered CO_2). The heat (steam) is mainly provided locally by industrial processes through waste heat sources (including natural gas). This might explain why the literature doesn't directly mention additional natural gas consumption for most of the post-combustion carbon capture studies.

Table 4. Additional electricity and natural gas requirements for integration of post- and pre-combustion CCS in power plants and other industrial plant system

Power/industrial process Plant	Type of Carbon capture integration	Additional Electricity (Elec) consumption due to Carbon capture	Additional Natural gas (NG) (fuel and feedstock) consumption due to carbon capture	Reference & Year of Estimation	Comment
Refinery (FPSO with CCS)	Post combustion	9.7%	59%	(Cruz et al., 2023)	Heat is provided from burning of natural gas
Complex oil refinery with CCS	Post combustion	8%-13%	38%-44%	(Berghout et al., 2019)	Electricity consumption is from electricity flue gas blower and capture (pumps and fans). Heat is for regeneration heat needed for flue gas
650MW Standard natural gas combined cycle (NGCC) power plant	Post-combustion	14%	-	(Rezazadeh et al., 2015)	Net plant efficiency between reference NGCC and NGCC with CCS is 7-8%
Single Plant - Single Sink Natural gas plant	Post-combustion	16.7%		(ETP, 2010)	
822MW NGCC retrofitted with CCS	Post-combustion	9.3%	-	(Díaz-Herrera et al., 2021)	Net plant efficiency between reference NGCC and NGCC with CCS is 8%
630 MW NGCC retrofitted with CCS	Post-combustion	12.7%	-	(GC1, 2017)	Net plant efficiency between reference NGCC and NGCC with CCS is 7-8%
MEA-based scrubbing and silica PEI adsorbent-based CO_2 capture processes in cement plants	Post-combustion	22%	-	(IPCC, 2005)	
New NGCC power plant	Post-combustion	13%-18%	-	(Rubin et al., 2015)	
560MW CHP (refinery)	Pre-combustion		7.2%	(Ali Khan et al., 2021)	
100,000 Nm^3 H2 /hr Standalone SMR plant with CCS	Pre-combustion		31%	(IEAGHG, 2017)	Additional NG due to the additional heating requirement of MEA regeneration and provide the extra electricity to operate the CO_2 compressor. No external electricity source is used.
100,000 Nm^3 H2/h SMR plant with CCS	Pre-combustion	2%	26-30%	(Collodi et al., 2017)	This is a case of a plant that uses NG as fuel and feedstock to produce H2, which is used to generate Elec. Hence, the additional Elec requirement resulting from CCS is mainly resulting from the reduction of Elec produced due to integration with CCS. Here, the CO_2 captured is also used in the electroreduction process to convert the blue H2 to formic acid as a potential scenario for efficient operation.
CHP power plant employs a combined. cycle gas turbine (CCGT)	Pre-combustion	5%	19.3%	(Suomalainen et al., 2013)	Natural gas is reformed to H_2 and CO_2. The plant comprises a gas reforming process (ATR), CO_2 capture unit and power plant. Additional NG calculation based on thermal energy of natural gas with and without CCS. Additional Elec calculated from difference auxiliary electricity consumption for reference and CCS case.

Source: Authors computation, 2023

Note: The additional natural gas consumption for pre-combustion usually occurs in two main paths. Either natural gas is used as fuel or feedstock or both. When natural gas is used as feedstock alone, the energy (steam) needed to power the reformer or compressor for running the carbon capture system (CO_2 compressor) comes from an external electricity source. When natural gas is used for fuel and feedstock, the heat required to power the CCS components comes from the internal system (steam heat from CHP with natural gas as the fuel). In the second case, the additional electricity requirement is indirectly from natural gas consumption. In some cases, the high-pressure heat is recovered to generate electricity in steam turbines.

4. Cost and energy input requirements assessment of pre-and post-combustion carbon capture technologies for the Scottish Chemicals industry

From the review of techno-economic parameters available in the literature, as discussed in section 3, it is evident that CAPEX and OPEX costs for carbon capture technologies can be site and industry dependent. In the case of the chemical industry, due to the complex layout of sites where there could be a variety of production processes and outputs, it could be difficult to adequately assess the costs for pre-and post-combustion carbon capture. Therefore, we take the approach here, based on the reviewed literature in Section 3, including the analysis developed in the Flour study for the Scottish chemical industry (Hurst & Walker, 2005) and assumptions sense-checked with industry stakeholders, to assess carbon capture technologies in terms of extra CAPEX and energy input requirements in percentage terms relative to current operational levels. **Table 5** shows our assumptions for post and pre-combustion carbon capture, considering both steam methane reforming SMR and autothermal reforming ATR.

Table 5. Additional CAPEX and energy requirement for post- and pre-combustion CCS in the Scottish chemical industry

CCS technology	Additional CAPEX relative to Petrochemicals Core Asset Value	Additional Energy Requirements (Additional relative to combustion energy input)	
		Natural Gas (Feedstock or Heat)	Electricity
Post-combustion CCS	+40%	+30%	+4%
Blue H2 (SMR)	+50%	+20%	+3%
Blue H2 (ATR)	+50%	+15%	+6%

Source: Authors computation, 2023

As observed in **Table 5**, we assume that it will require an additional 40% in capital and 30% and 4% in natural gas and electricity, respectively, to integrate post-combustion carbon capture in the chemical industry in Scotland. Similarly, we assume that 50% additional capital is required to integrate SMR and ATR pre-combustion CCS in the Scottish Chemical industry. The additional natural gas input is 20% and 15%, and the electricity required is 3% to 6%, respectively, for SMR and ATR. These findings imply that while it requires more capital (+10%) to integrate pre-combustion CCS in the Scottish chemical sector, more additional input energy (+10% to 15% extra natural gas and up to 2% more electricity) is required to integrate post-combustion compared to SMR and ATR pre-combustion. These results are consistent with literature findings for post and pre-combustion CCS systems. It is necessary to emphasise that including a carbon capture system does not increase the production output of the chemical sector since no known chemical companies use the captured CO_2 to enhance production efficiency and product or raw material volume levels. Therefore, the assumed implication of these additional capital and energy (natural gas and electricity) requirements in the chemical industries is that it will reduce the capital and resource efficiency of the sector. This efficiency loss in the chemical industry would have implications for the sectoral characteristics, including the output price, and, therefore, the wider economy, such as employment, broader price levels and GDP. Thus, there is a need to explore in depth how these capital and energy consumption efficiency losses impact the chemical industry and, by extension, the wider economy.

5. Conclusions and next steps

The research estimates the percentage cost and energy (natural gas and electricity) requirement for employing post-and pre-combustion carbon capture technologies in the Scottish chemical industry. This study employs a review of relevant existing techno-economic analyses on CCS, alongside stakeholder engagement in the chemical industry, to provide the data to estimate these associated additional capital and energy requirements. The results indicate that while pre-combustion carbon capture is more capital intensive than post-combustion carbon capture, post-combustion carbon capture is more energy input intensive than pre-combustion carbon capture. For the Scottish chemical industry, the analysis shows an additional 40% CAPEX to be necessary for the post-combustion case and 50% for the pre-combustion case (SMR and ATR). Similarly, for the energy input requirements, the estimates show an additional 30% and 4% in natural gas and electricity are required for post-combustion carbon capture,20% and 3% for pre-combustion SMR and 15% and 6% for pre-combustion ATR, respectively. These findings provide useful data to further model the impact of introducing carbon capture on the competitiveness of the Scottish chemical industry and, hence, the wider economy. The insight provided in the research is relevant for investors in the Scottish chemical sector and government policymakers. First, beyond the cost and engineering implications, further economic analyses on the sector's cost performance and other market competitiveness should be considered by investors to decide which type of carbon capture systems to adopt to decarbonise operations in the Scottish chemical sector. Furthermore, policymakers in the Scottish, and the wider UK, economy should consider the broader economic implications of different CCS technologies as they formulate their industrial decarbonisation policy/strategy. Therefore, the differences in cost and energy requirement estimated in this research, and the implied potential economy-wide implications and policy trade-offs associated with the adopted carbon capture technology, merit further analyses which is the focus of CEP's research work using economy-wide modelling.

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Acknowledgements and contact

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Appendix

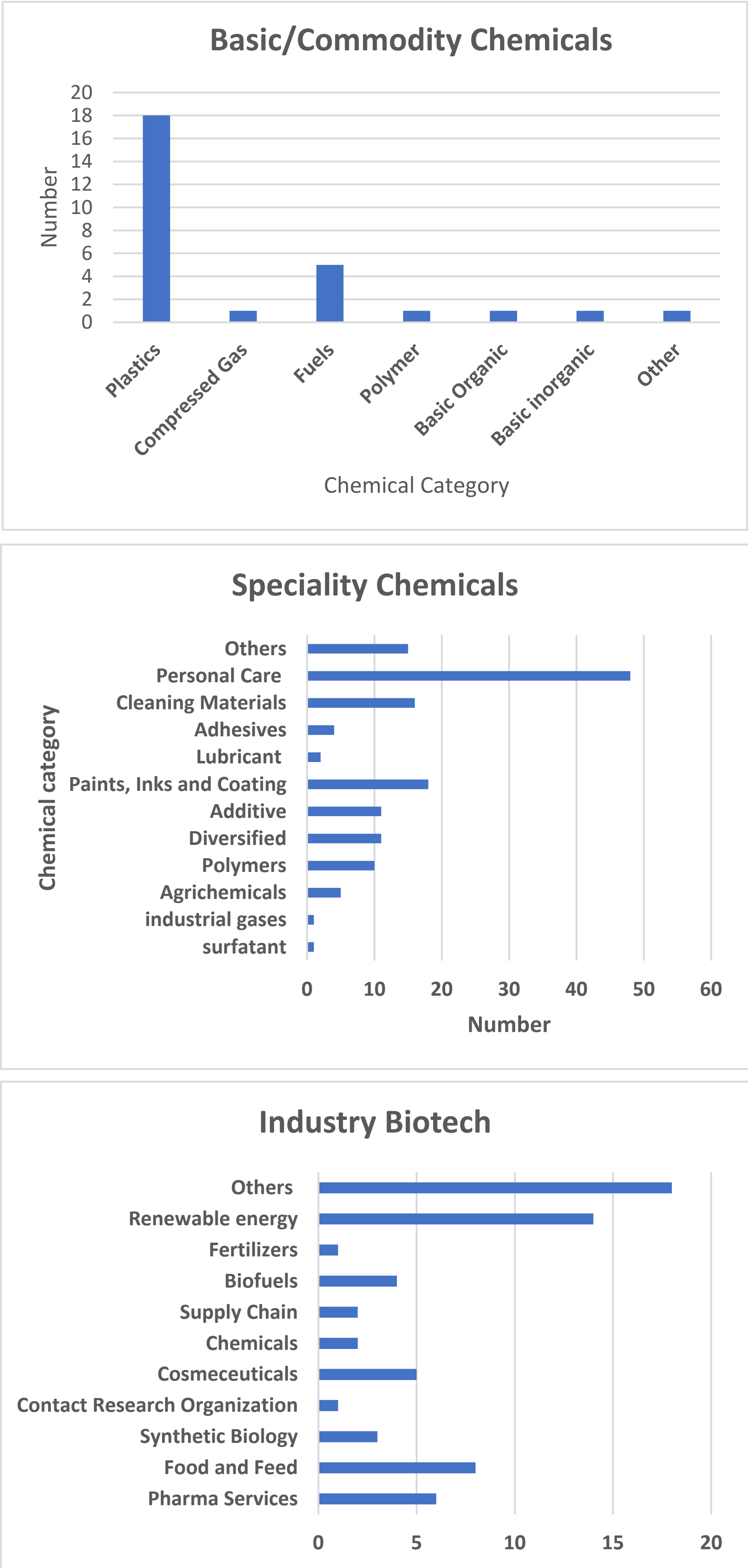

Figure A1. Company categorization in the Scottish chemical industry

Source: Authors, 2023. Data source: https://lcs.directories.scot/

Table A1. CAPEX AND OPEX for selected plant with post-combustion CCS technologies

Power/ industrial process Plant	Plant capacity	Ref CAPEX	CAPEX with CCS	Ref OPEX	OPEX with CCS	Increase CAPEX due to CCS	Additional OPEX with CCS as compared to Ref case	Reference	Year
NGCC retrofitted with CCS	822MW	$1088.4M	$1548.4	$28.4m	$34.6	43%	22%	(Iram,2017) page	2017 constant $ price
CHP power plant with CCGT and CCS		€1013M	€1135M			12%		(Suomalainen, et al.,2013) page	2013
NGCC retrofitted with BLUE H2	840 MW	$80.64M	$95.04M			58%		(Díaz-Herrera et al., 2021)	
Single Plant - Single Sink Natural gas plant	420MW	€660M	€1,100M	-	-	67%	-	(ETP, 2010) page	Indices adopted from the Second quarter of 2009
Steel mill's power plant		€81.M	€102.7M	€81.5M	€141.3M	26.7%	73.3%	(Garðarsdóttir et al., 2018) page	
Pulp mill's boiler		€100.0M	€132.7M	€81.1M	€135.7M	32.6%	67.4%	(Garðarsdóttir et al., 2018 page	
Prudhoe Bay refinery			$ 1,659M		$77.7M			(Hurst & Walker, 2005)	
Grangemouth refinery			$ 476M		-			(Hurst & Walker, 2005)	

Source: Authors computation,2023

Table A2. CAPEX AND OPEX for selected plant with pre-combustion CCS technologies

Power/ industrial process Plant	Plant capacity	Ref CAPEX	CAPEX with CCS	Ref OPEX	OPEX with CCS	Increase CAPEX due to CCS	Additional OPEX with CCS as compared to Ref case	Reference	Year
SMR with CCS	1000MW	-	£585/kW H2 HHV	-	£28.07/kW HHV	-	-	IEA (2019	All costs in USD (2017) which were converted to £ equivalent. Discount rate: 8%.
ATR with CCS	1000MW	-	£613/kW H2 HHV	-	£26.99/kW HHV	-	-		
H2 production from Natural gas reforming with CCS		$910 /kW H2	$1,680 /kW H2	$43 /kW H2	$50.4/kW H2	84.0 %	18%	IEA (2019]	All costs in USD (2017) Discount rate: 8%.
Ammonia production with natural gas		$905 /t NH3	$1, 315/tNH3	$22.6 /t NH3	$32.8 /t NH3	45%	45%	IEA (2019]	
Standalone SMR plant with CCS	100,000Nm^3 H2/h	€170.95M	€228.48M	€79.02M	€87.5M	34%	11%	(Collodi, et al., 2017)	4Q2014 price level, in euro (€) discount rate of 8% is assumed.
SMR based H2 plant with CCS	100,000Nm^3 H2/h	A$180.3M	A$342M	A$ 96.9M	A$161M (NSW Hub) A$146.9M (VIC Hub)	89%	66.2% (NSW Hub) 51.2% (VIC Hub)	[11] (Ali Khan et al., 2021) page	Cost values Converted to present value (2020) using a conversion factor of 1€ = 1.47 AUD (2017) and inflation adjustment of 1.16 (2017 to 2019).

Source: Authors computation,2023

Note: For the Standalone SMR plant, CAPEX and OPEX reported on the actual total cost of the plant (TCP) and operational cost, not levelized cost as others.

Table A3. Cost performance of plants with carbon capture and storage in the chemical industry from literature

Industrial Plant	Type of CCS	Energy cost with CCS (M€/yr)	Total CO_2 captured (tCO_2/yr)	CO_2 avoided cost (€/tCO_2)	CAPEX with CCS (M€/yr)	OPEX with CCS (M€/yr)	Reference
Medium size petroleum refinery	Post-combustion	85	2200000	80	30	28	(Berghout et al., 2013)
	Pre-combustion	88		84	55	37	
Medium size petrochemical plant (Rotterdam Aromatic chemical plant)	Post-combustion	17	400000	92	8	5	(Berghout et al., 2013)
	Pre-combustion	48		114	37	16	
small size petrochemical plant (Rotterdam Oxo-alcohol chemical plant)	Post-combustion	2.5	90000	117	2	0.5	(Berghout et al., 2013)
	Pre-combustion	3		167	5	1	
steam reforming large hydrogen plant	Post-combustion	50	800000	126	13	12	(Berghout et al., 2013)
	Pre-combustion	34		87	12	16	

Data source: calculated from reference papers indicated in Table A3

Glossary/Abbreviations

ATR	Autothermal reformer
CAPEX	Capital expenditure or investment
CCGT	Combined Cycle Gas Turbine
CCS	CO_2 Capture and Storage
CCUS	CO_2 Capture, Utilization, and Storage
CGE	Computable General Equilibrium
CHP	Combined Heat and Power
CIA	Chemical Industry Association
CO_2	Carbon dioxide
DECC	Department of Energy and Climate Change
DESNZ	Department of Energy Security and Net Zero
EU European Union	EU European Union
GVA	Gross Value Added
GWh	Gigawatt hour
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
MT	Million metric tonnes
MW	Megawatt
MEA	Monoethanolamide
NECCUS	Northeast Carbon Capture, Usage, and Storage
NGCC	natural gas combined cycle
OPEX	Operational Expenditure or investment
SMR	Steam Methane Reformer
UK	United Kingdom
USD	United state dollars
€	Euros
$	Dollar
£	Pounds Sterling

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