Low-carbon reorientation in steel, oil refining and petrochemical industries

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Preface

This report summarises the findings of the 2-year research project *'Low-carbon reorientation in steel, oil refining and petrochemical industries'* that was funded by the Industrial Decarbonisation Research and innovation Centre (IDRIC). Professor Frank Geels, who is Eddie Davies Professor of Sustainability Transitions at MIoIR at the University of Manchester, was the lead investigator of the project. He was assisted by Research Associate, Doctor Julian Gregory, also from MIoIR and the University of Manchester.

We wrote the following four articles in the context of this project, three of which have been published and one is under review.

Geels, F.W., 2022, Conflicts between economic and low-carbon reorientation processes: Insights from a contextual analysis of evolving company strategies in the United Kingdom petrochemical industry (1970-2021), *Energy Research & Social Science*, 91, 102729;

Geels, F.W. and Gregory, J., 2023, Low-carbon reorientation in a declining industry? A longitudinal analysis of coevolving contexts and company strategies in the UK steel industry (1988-2022), *Energy Research & Social Science*, 96, 102953;

Gregory, J. and Geels, F.W., 2024, Unfolding low-carbon reorientation in a declining industry: A contextual analysis of changing company strategies in UK oil refining (1990-2023), *Energy Research & Social Science*, 107, 103345;

Geels, F.W. and Gregory, J.A. 2024, Explaining varying speeds of low-carbon reorientation in UK steel, petrochemical, and oil refining industries: A multi-dimensional analysis and outlook, *Energy Research & Social Science*, submitted 27 October 2023

This report draws on these four articles, summarising their descriptive findings and analyses. We discussed the results of the project at a dissemination workshop on 22 November in Manchester, with participants from industry, policy, and academia. This report also builds on the Policy Brief that we wrote for this dissemination workshop.

We are grateful to IDRIC for their support throughout the research project and for the funding, without which this project could not have been done.

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Executive Summary

Steelmaking, oil refining and the petrochemical industries are still significant UK industrial CO_2 emitters, and to meet its net-zero obligations, the UK needs to quickly decarbonise them. They have all significantly reduced their scope-1 greenhouse gas emissions in recent decades: steelmakers by 56% between 1990 and 2021, oil refining by 46% between 1996 and 2021, and petrochemicals by 88% between 1990 and 2019. However, these reductions arose from incremental energy efficiency improvements, removal of two very strong climate-forcing chemicals (HCFC-22, N2O); and industrial decline, rather than low carbon reorientation. This decline was especially marked in the steel industry (73% since 1973) and oil refining (57% since 1973), and somewhat less in petrochemicals (32% since 2008). Deeper decarbonisation will require the implementation of radical innovations like carbon capture and storage (CCS), low-carbon hydrogen (for fuel switching or hydrogen direct reduction of iron ore), feedstock change, or electric arc furnaces (for steel).

For our research, we analysed the three industries as separate case studies for over 30 years, through a longitudinal analysis and applying the Triple Embeddedness Framework (TEF), where we initially asked two research questions:

1) What have been the main contextual developments and business strategies in the three industries since 1990?

2) What do these longitudinal developments imply for the speed and direction of low-carbon reorientation in each industry, and their commitments to various low-carbon pathways?

The TEF sees industries as operating in both an economic environment and a socio-political environment, where industry responses to contextual pressures are shaped by an industry regime. Because low-carbon reorientation costs £billions, firms in industries are understandably cautious to commit to such expenditure, and therefore low-carbon reorientation requires an increase in external pressures for firms to respond. In response, firms tend to reorient through a sequence of steps: 1) denial, 2) incremental change, 3) exploration of radical innovations, 4) deployment of radical innovations, 5) deeper change in mindset and mission. The three case study analyses showed that oil refiners have moved from phase 3 to phase 4 since 2019, but that steelmakers and petrochemical firms are still in phase 3 (although after recent announcements by both TATA Steel UK and Jingye Steel, this may be about to change).

This report presents three industry longitudinal analyses that we carried out and published as stand-alone academic studies in Energy Research and Social Science (ERSS). It also comparatively reviews the net-zero transitional performance differences between the three industries to address a third research question:

3) What explains the varying speed of low-carbon reorientation across the three industries in the 2019-2023 period?

That comparative analysis focuses on five factors: a) policies, b) technical and practical feasibility, c) international competition, d) financial justifiability, e) wider corporate strategies and mindsets.

We surmise industrial decarbonisation is a challenging and expensive process, which is shaped by multiple factors. UK refineries are presently reorienting faster than petrochemical and steel industries, although the latter two have also increased their low-carbon activities. Our in-depth longitudinal case studies suggest:

1) The strengthening and expanding policy mix since 2019 has increased low-carbon reorientation activities in industrial firms.
2) The policy focus on CCS and low-carbon hydrogen suits oil refining and petrochemical industries better than steelmakers. Other important decarbonisation pathways such as electrification, feedstock substitution, or demand reduction receive less attention than they should.
3) The policy focus on four clusters disadvantages firms in the two other clusters, including a steelmaker and two refineries.
4) Recent government deals with two steelmakers partly alleviate these biases, but the intended shift to Electric Arc Furnaces faces practical obstacles, including: a) insufficient UK supply of high-quality scrap steel, b) grid challenges in supplying sufficient electricity, c) internationally high electricity prices, d) social acceptance problems because of layoffs.
5) As the cost of industrial reorientation may be £billions, past profitability of firms is important in shaping speed and commitment.
6) Industrial decarbonisation policies need broadening to address other technologies, practical barriers, and social acceptance.
7) The South Wales and Solent clusters will require further structural policy support if they are not to be disadvantaged in a future net-zero industrial environment.

1. Introduction

Low-carbon transitions in large energy-intensive industries (LEIIs), such as steelmaking, oil refining and chemical manufacturing, are receiving ever more political and academic attention, as the international community increasingly appreciates that their decarbonisation is very significant for attaining net-zero globally. Steelmaking, on its own is responsible for 7% of the carbon emissions from the entire global energy system [IEA,2020]; chemical manufacturing is responsible for 18% of global industrial emissions [IEA, 2019] (which mostly generated from the petrochemical sector); and petroleum refining is responsible for 6% of global industrial emissions [Jing et al, 2020]. Consequently, these industries can no longer be sidelined as 'hard-to-decarbonise' [Nurdiawati and Urban, 2022; Őhman et al., 2022; Kim et al., 2022; Bauer et al., 2022; Chung et al., 2023]. Nevertheless, low-carbon reorientation by the LEII's commercial actors tends to be slow and incremental because of lock-in mechanisms such as high sunken costs in capital-intensive assets, long investment cycles and lengthy investment payback periods [Åhman et al., 2016; Wesseling et al., 2017], that can vary significantly between national contexts. For improving global transparency and progression towards net-zero, it is therefore important to better understand the drivers and barriers of more rapid low-carbon reorientation in these industries on a national basis.

Whilst existing decarbonisation research on energy intensive industries offers valuable insights about technical processes and economic dimensions of low-carbon transition pathways, it gives less attention to real-world business contexts and company strategies of industry actors that fashion the decisions about the development and deployment of low-carbon technologies**.** It is also mostly focused on future pathways and has insufficiently investigated how these pathways are shaped by longer-term developments that influence company strategies. And because of the lock-in processes discussed, such analyses should not just focus on the present and future, but also address longer-term historical trajectories and developments.

As the UK's ONS data [citation] reveals the same three industries are also the UK's most significant industrial emitters; and because of the limitations in the existing literature – we chose to examine these three industries' low-carbon reorientation in the UK context (for chemical manufacturing, we chose to focus on petrochemicals only, as this is responsible for most CO_2 emissions in the UK within that sector). For each industry, we applied a longitudinal analysis for over 30-years, by applying the Triple Embeddedness Framework (TEF), and asking two research questions:

> **1)** What have been the main contextual developments and business strategies in the three industries since 1990?
>
> **2)** What do these longitudinal developments imply for the speed and direction of low-carbon reorientation in each industry, and their commitments to various low-carbon pathways?

The three papers were then published as standalone studies in Energy Research and Social Science (ERSS): Geels, 2022; Geels & Gregory, 2023; Gregory & Geels, 2023.

Although firms in all three industries face the same legal decarbonisation pressure from the UK's 2019 commitment to net-zero targets and all have developed visions for possible decarbonisation, it is only in the oil refining industry where companies (like Essar Oil and Phillips 66) have started to commit significant resources to the actual deployment of low-carbon technologies (like hydrogen furnaces, blue-hydrogen production, and carbon capture) and to biofuel production [Gregory & Geels, 2023]. The two remaining integrated steelworks (in Port Talbot, operated by Tata Steel UK (TSUK), and in Scunthorpe, operated by British Steel), which account for 95% of the UK steel industry's emissions, have only recently announced co-ordinated decarbonisation plans with UK government financial support, to close their existing high CO2 emitting blast furnaces and replacing them with Electric Arc Furnaces (EAFs). However, there is still uncertainty over grid connectivity, and still questions over whether this will finally occur [Geels & Gregory, 2023]. Likewise, the three remaining petrochemical firms that operate steam crackers[1] (INEOS in Grangemouth, SABIC in Teesside, and ExxonMobil in Mossmorran), have developed plans but not yet committed to deployment, despite suggesting that they might be willing to invest £1bn (INEOS) and £850m (SABIC) in low-carbon innovations [Geels, 2022]. In 2022, INEOS contracted Atkins to design a Low-Carbon Hydrogen Manufacturing Plant and in 2023, planned to undertake hydrogen fuel network trials[2], which both represent possible intent but not yet strong commitment to actual deployment.

As the speed of decarbonisation is so important, and with the aim of developing wider lessons, we felt it was also important to comparatively reviews the net-zero transitional performance differences between the three industries to address a third research question:

> **3)** What explains the varying speed of low-carbon reorientation across the three industries in the 2019-2023 period?

This comparative analysis focuses on five factors: a) policies, b) technical and practical feasibility, c) international competition, d) financial justifiability, e) wider corporate strategies and mindsets.

This document reveals our two-year study of low-carbon transitions of steelmaking, oil refining and petrochemicals; and then comparatively analyses the varying speeds in low-carbon reorientation. Section 2 describes the Triple Embeddedness Framework, which our three case studies used, and the various factors that our comparative analysis will address. Section 3 explains our methodology, including our data sources and how they were analysed; section 4, 5 and 6 are the individual industry case studies; and section 7 mobilises empirical material from our case studies to consider how each factor played out in the three industries to help explain varying speeds of low-carbon reorientation. Finally, we draw conclusions: presenting our net-zero views on future outlooks for the three UK industries and advice to policy makers.

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[1] Steam crackers are the foundation of the petrochemical industry because they produce primary chemicals (like ethylene, propylene, and butadiene) that can be transformed into polymers like fibres and plastics.

[2] (https://www.ineos.com/sites/grangemouth/news/)

2. Conceptual framework

The triple embeddedness framework (TEF) combines insights from evolutionary economics, institutional theory, and strategic management [Geels, 2014; Penna & Geels, 2015], and conceptualises firms-in-industries as facing selection pressures from an economic environment (including customers, suppliers) and a socio-political environment (including wider publics, NGOs, policymakers). Firms-in-industries can respond to these pressures (as indicated with the bi-directional arrows in Figure 2) with various strategies including:

- economic positioning strategies such as supply chain management, operations management, marketing, or capital goods investments [Porter, 1980];
- innovation strategies such as R&D investments or technological development partnerships [Tidd et al, 2005];
- corporate political strategies such as lobbying, financial contributions to political parties, litigation against laws, withholding information or providing information in particular ways, or threatening policymakers with plant closures or layoffs [Hillman & Hitt, 1999; Ford & Newell, 2021];
- socio-cultural framing strategies such as public relations or advertising that aim to shape public discourses, meanings, and interpretations [Lounsbury & Glynn, 2001].

These strategic responses are enabled and constrained by an industry regime (Figure 1), which accommodates analytical categories from several sub-disciplines (see [Geels, 2014] for a more extensive discussion): a) evolutionary economics highlights the importance of industry-wide technical knowledge and capabilities in shaping what firms can do [Nelson & Winter, 1982], b) interpretive management theories emphasise industry mindsets and corporate identity, which shape corporate sense-making [Phillips, 1994], and c) (old) institutional theory underlines the role of regulations in shaping the economic rules of the game [North, 1990]. Because industry regime elements lock incumbent firms into behavioural and strategic templates [Greenings & Hinings, 1993], developmental trajectories usually consist of incremental cumulative changes.

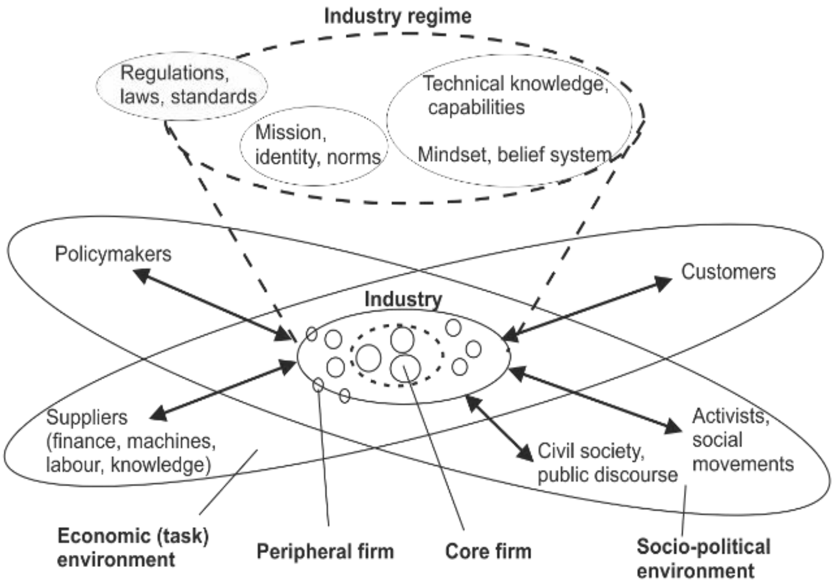

Figure 1: Triple embeddedness framework of industries [Geels, 2014: 266]

Because of lock-ins and attachments to existing industry regimes, incumbent firms are usually reluctant to engage in major strategic reorientation to address a particular issue. Strategic reorientation therefore tends to require increasing external pressures from economic and socio-political environments, which gradually 'unlock' firms from existing industry regimes and lead to successively deeper changes. Strategic reorientation to address an issue is therefore conceptualised as progressing through different phases [Penna & Geels, 2015, Geels and Penna, 2015]. Large incumbent firms are not only economic entities but also political actors with substantial 'structural power' since policymakers depend on them for jobs, taxes, and economic growth [Ford and Newell, 2021]. These firms are therefore likely to use political strategies to resist significant regime change in the early phases.

In the first phase, firms tend to downplay problems arising from external pressures or mis-interpret them as temporary and therefore take *no action* [Ford & Baucus, 1987]. Overconfidence, complacency, or reluctance to admit mistakes may also drive initial (mis)interpretations [Sutton, 1990].

In the second phase, when continuing problems can no longer be ignored, firms tend to adjust existing industry regimes with *incremental changes* such as retrenchment (e.g., downsizing, cost-cutting, tighter controls) or improvements in existing technologies [Barker & Duhaime, 1997]. For societal or environmental problems, firms may also use framing strategies to portray these problems as not so important or as difficult and expensive to remedy [Greenings & Hinings, 1993]. Firms may also use corporate political strategies to reduce policy pressures or create 'closed industry fronts' and associations to protect the industry's interests [March, 1991].

In the third phase, when external pressures are perceived to require more significant responses, firms tend to adopt *hedging strategies*. On the one hand, "their main strategy remains the defence of the existing regime, both through incremental technical innovations and through political strategies such as: (a) downplaying the problem and the need for public policies, (b) claiming that certain solutions are too costly or technologically infeasible, (c) exploiting policymakers' lack of technical knowledge ('information asymmetry') and purposively withholding relevant information" [Ford & Baucus, 1987, p. 71]. On the other hand, to prepare for future eventualities firms, begin to explore new kinds of knowledge and radical innovations [March, 1991] through internal R&D activities or external alliances. Penna and Geels [2015] suggest that the exploration activities are mostly private, while the regime defence strategies are more public.

In the fourth phase, when external pressures begin to shape the economic (task) environment (through new regulations, incentives, or user demands), firms begin to *diversify* to the new technology. They may "embrace the new technology more enthusiastically to 'jockey for position' in the expectation of growing markets. This could cause cracks in the closed industry front and lead to an 'innovation race'" [Penna & Geels, 2015, p. 1032]. They also continue to operate the old technology to 'milk' the assets [Harrigan, 1980].

In the fifth phase, firms *fully reorient* to the new technology and may also change their core beliefs, mission, and identities, which is a difficult process that involves second-order learning and foundational rethinking of the company's business model, market positions, and values [Grinyer & McKiernan, 1990].

Application of this framework to the US car industry [Penna & Geels, 2015; Geels & Penna, 2015], UK coal industry [Turnheim & Geels, 2013], and German electricity industry [Kungl & Geels, 2018] not only showed its general usefulness for analysing longitudinal reorientation processes, but also, that the shift from phase 3 to phase 4 is the most significant because it entails a strategic change from defending the existing regime to deploying alternative technologies and changing regime elements (like knowledge or mindsets). This change also involves increased capital expenditures, which may be risky, and an acceptance that existing technologies and assets are not fit for the future. Firms therefore tend to delay the shift from phase 3 to phase 4. Previous applications also confirmed that firm's strategies may be multi-directional during reorientations, with some strategies like economic positioning defending the existing regime, while other strategies like innovation or framing explore alternatives.

Our three industry case studies not only confirm this general pattern, but also showed that firms in these industries moved back from phase 3 to phase 2 after the 2007/8 financial crisis and subsequent austerity years, which caused financial difficulties that changed corporate priorities to focus on survival and retrenchment. All three industries then moved back to phase 3 after 2015, when UK policymakers started to focus more on industrial decarbonisation and published industry roadmaps for the UK's most energy intensive industries. But only in the oil refining industry did (some) firms start to move to phase 4 after 2019 through significant resource commitment to deployment.

To further explain this more recent difference in speed and commitment, the comparative analysis in Chapter 7 uses the Triple Embeddedness Framework to focus on two *external pressures* that varied significantly between the three industries: 1) specific policy support instruments to help firms with low-carbon reorientation, 2) the degree international competition in UK and foreign markets. We do not address external decarbonisation pressures from civil society, suppliers, or customers, which are either small or relatively similar across the three industries and thus irrelevant for explaining different responses. The comparative analysis will also address the following factors that shaped *endogenous responses* of firms: 3) financial health and economic feasibility of low-carbon technologies, 4) technical feasibility of low-carbon options, and 5) wider corporate strategies and mindsets.

3. Methodology

3.1. Case study selection and demarcation

3.1.1. Petrochemicals

The UK was selected as country-case because it still has a substantial petrochemical industry, which increasingly faces policy pressures to decarbonise. The industry also experienced substantial business flux in recent decades due to plant closures, asset sales, takeovers, the exit of traditional firms (e.g., ICI, Shell, BP), and the entry of new firms (e.g., INEOS, SABIC) with particular identities, competencies, and mindsets. The UK petrochemical industry thus provides an excellent country-case to investigate the business strategies with regard to economic and low-carbon reorientations.

The UK petrochemical industry is also an interesting case because it reduced emissions by 88% from 46,683 ktCO2e in 1990 to 5,753 ktCO2e in 2019 (Figure 2). The bulk of these GHG emission reductions came from the fitting of abatement equipment on two plants in 1998 and 1999, which substantially reduced emissions of N_2O and HCFC-22 (Figure 3), which are very strong climate-forcing gases.[3] Direct CO_2 emissions from fuel combustion also gradually decreased since 1990 (Figure 3), because of several drivers [44], including: a) energy efficiency improvements, b) petrochemical plant closures as part of a wider UK shift from bulk chemicals to speciality products, c) fuel switching from coal and oil to natural gas and electricity. Despite these CO_2 emission reductions, the UK petrochemical industry still accounted for 51% of all GHG emissions from the chemical sector in 2019. It has therefore become an important focus of UK climate policy.

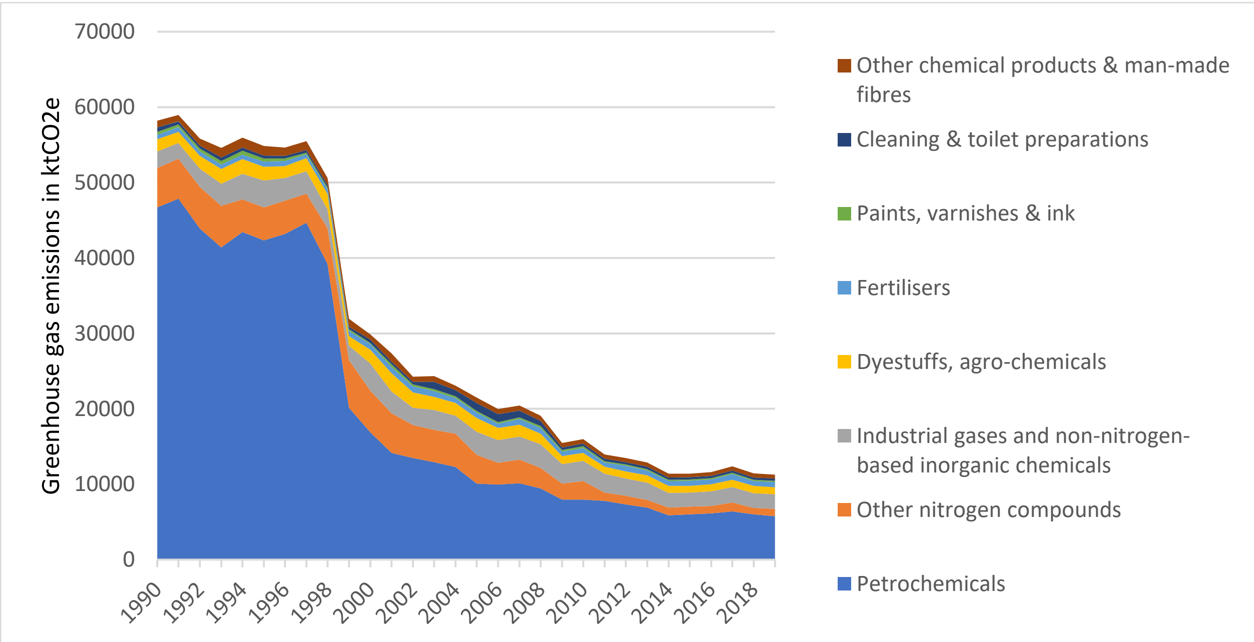

Figure 2: Greenhouse gas emissions (ktCO2e) from the UK chemicals industry, 1990-2019 (constructed using data from Statistics at BEIS; industrial greenhouse gas emissions dataset)

[3] N_2O has radiative forcing potential that is 300 times greater than CO_2. In 1998, the fitting of N_2O abatement equipment at a major adipic acid manufacturing facility (Invista) substantially reduced N_2O emissions. HCFC-22 has radiative forcing potential that is 1760 times greater than CO_2. In 1999, the installation of a thermal oxidiser at the UK's only HCFC-22 plant (in Runcorn) substantially reduced these HCFC-22 emissions.

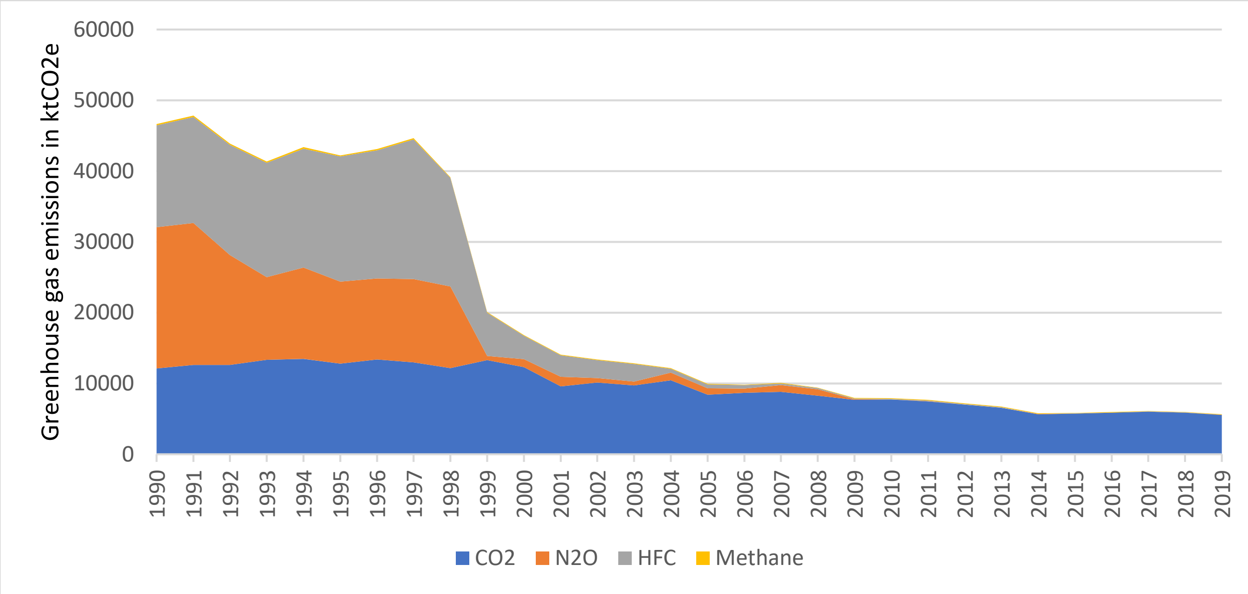

Figure 3: Different types of greenhouse gas emissions (ktCO2e) from the UK petrochemical industry, 1990-2019 (constructed using data from Statistics at BEIS; industrial greenhouse gas emissions dataset)

3.1.2. Steelmaking

The UK was chosen as a country case-study because it is well suited to explore decarbonisation challenges in a declining industry. Its steelmaking industry's output has steadily declined since 1970, although there were periods like the 1980s where output (temporarily) increased (Figure 4). Since the industry's privatisation in 1988, declining production and sales have been accompanied by closure of three integrated steelworks for primary steelmaking: Ravenscraig in Scotland in 1992; Llanwern in South Wales in 2001; and Redcar in Teesside in 2015. Two integrated steelworks remain in 2022, each with sizeable CO_2 emissions: Port Talbot in South Wales and Scunthorpe in Lincolnshire.

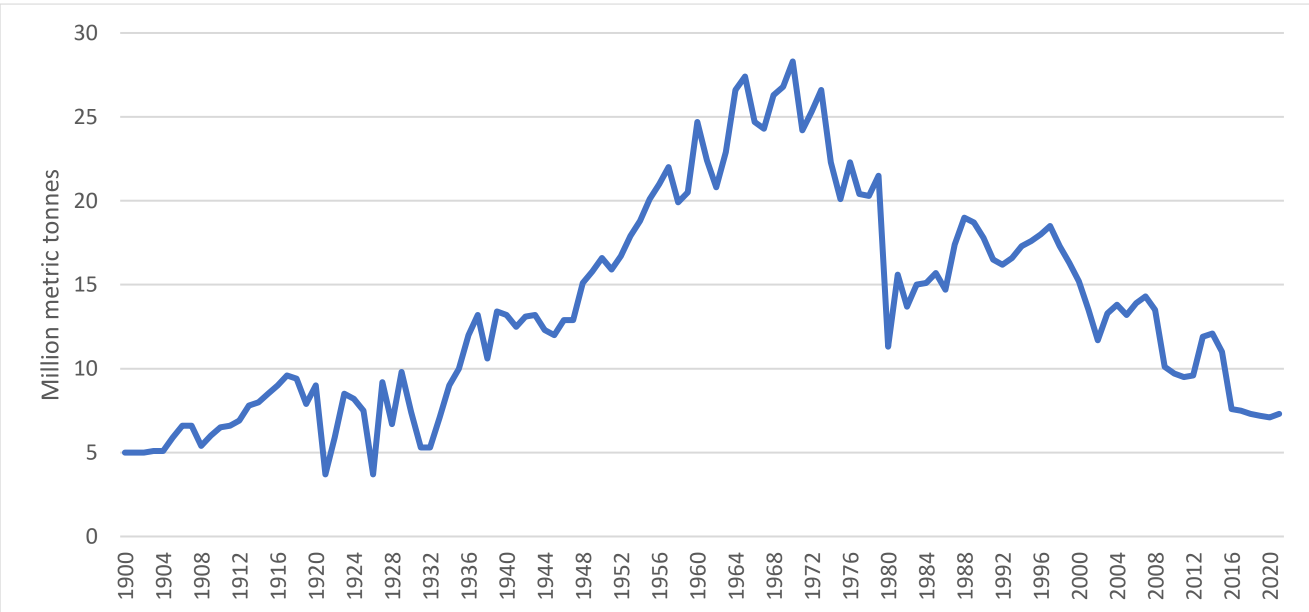

Figure 4: Steel production in Great Britain in million metric tonnes, 1900-2021 (constructed using data from the Office for National Statistics for 1900-2015 and Statistical Yearbooks from the World Steel Association for 2016-2021 (https://worldsteel.org/))

CO_2 emissions from the UK iron and steel industry decreased by 56% between 1990 and 2021 (Figure 5), which was mostly achieved through reduced production rather than through low-carbon reorientation, as indicated by the unchanged CO_2 intensity of UK steelmaking (Figure 6). CO_2 emissions from UK steelmaking were still 13.0mt in 2021 (Figure 6), making it the UK's largest CO_2 emitting industry [CCC, 2022]. Coal-based steelmaking in the two remaining integrated steelworks (Port Talbot and Scunthorpe) generate 95% of these CO_2 emissions [HMG, 2021]. The government's *Industrial Decarbonisation Strategy* [HMG, 2021: 19] articulated challenging ambitions for these two plants, stating that it "will consider the implications of the recommendation of the Climate Change Committee to set targets for ore-based steelmaking to reach near-zero emissions by 2035".

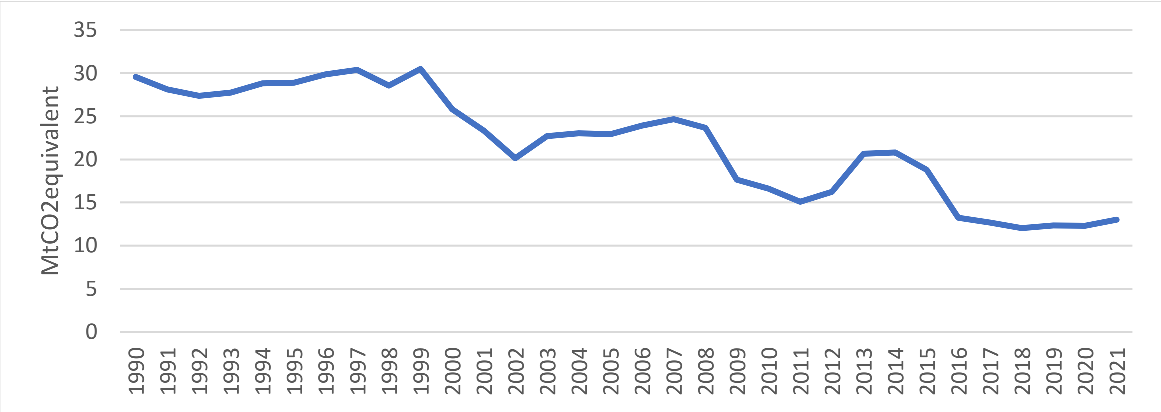

Figure 5. UK annual CO_2 emissions (in $MtCO_2e$) from iron and steelmaking, 1990-2021 (constructed using data from [CCC, 2022])

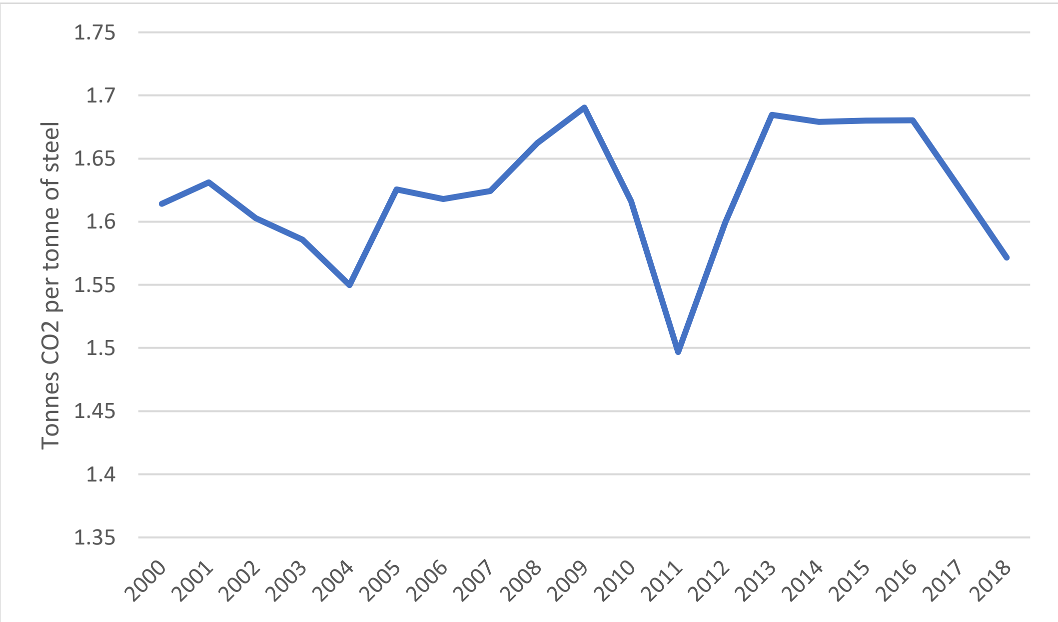

Figure 6. CO_2 intensity (tonnes CO_2 per tonne of steel) of UK steelmaking, 2000-2018 (constructed using data from [Ember, 2020])

In terms of temporal demarcation, our analysis starts in 1988, when the UK steel industry was privatised. The late 1980s are also a suitable starting point, because the UK steel industry was then characterised by relative optimism since drastic reorganisations in the early 1980s (further discussed in section 4.1) had improved the industry's productivity, while steel demand and production were growing again, after the steep declines of the 1970s (Figure 4). Our analysis will thus investigate how increasing external pressures ended the brief period of respite, triggering further rounds of decline and reorientation attempts. We end the analysis in August 2022 to bring it close to the present. Because statistical information for 2022 was not yet available at the time of writing, the analysis for that year is mostly qualitative.

We will divide the longitudinal case study into several periods (further discussed below) based on major shocks or changing strategies signifying qualitatively different developments. For most periods, the integrated steelworks were owned and operated by a single organisation, which allows for a focused analysis: British Steel PLC (1988-1999), Corus (1999-2007), Tata Steel (2007-2011). Steel industry ownership began to fragment in the 2010s as Tata Steel sold the Redcar steelworks to Sahaviriya Steel Industries in 2011 and the Scunthorpe plant to Greybull Capital in 2016. For the later periods, our analysis will thus investigate multiple organisations and their strategic responses to contextual pressures.

3.1.3. Oil Refining

We chose the UK as a country case-study because it is well suited to explore decarbonisation challenges in a declining industry. UK refinery output started to decline after the first oil crisis in 1973 (*Figure 7*), when the UK started to abandon oil products to generate electricity; recovered during the 1980s and early 1990s due to increasing road and air mobility; and then declined further as vehicle efficiency and fuel switching changed demand dynamics leading to misconfiguration with UK refineries. The number of refineries decreased from 19 in 1973 to 6 in 2023. The six remaining refineries, which are all of the conversion type, are located in five of the UK's six main industrial clusters (*Figure 8*).

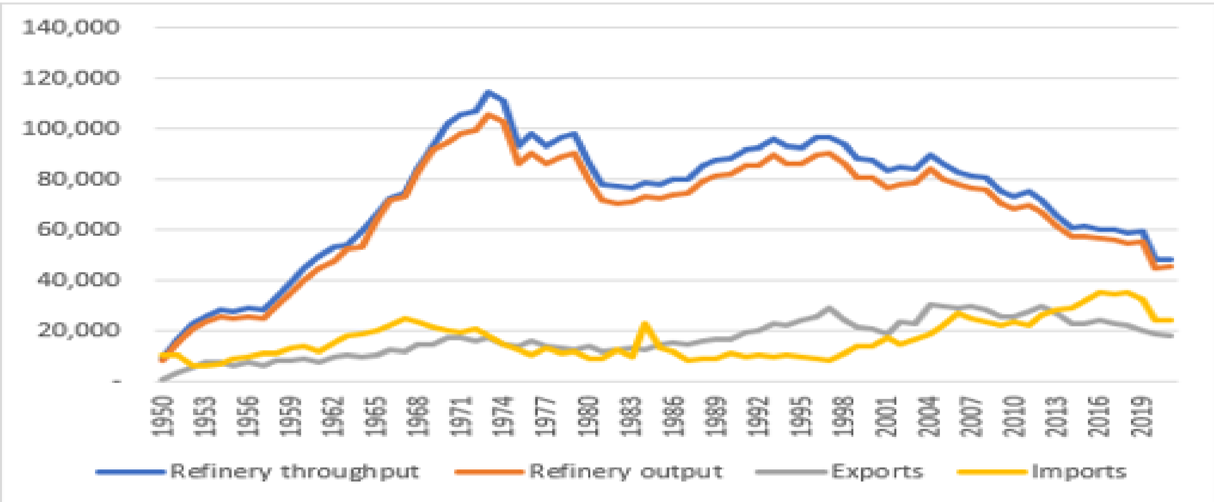

Figure 7: Refinery throughput; refinery output; imports; and exports of petroleum products (in thousand tonnes); 1950-2021 (constructed using data from BEIS; Oil Statistics; Historical Time Series Data; Crude oil and petroleum products: production, imports, and exports 1890 to 2021)

Figure 8. Locations of current UK refineries, with corporate ownership identified (authors)

CO_2 emissions[4] from the UK oil refining industry have decreased by 46% from their 1996 peak to 2021 (*Figure 9*). This reduction was mostly due to refinery closures and some incremental energy efficiency improvements, as our case-study will show. In recent years, however, several refineries have started to engage significantly with low-carbon reorientation through both technological explorations and financial investments.

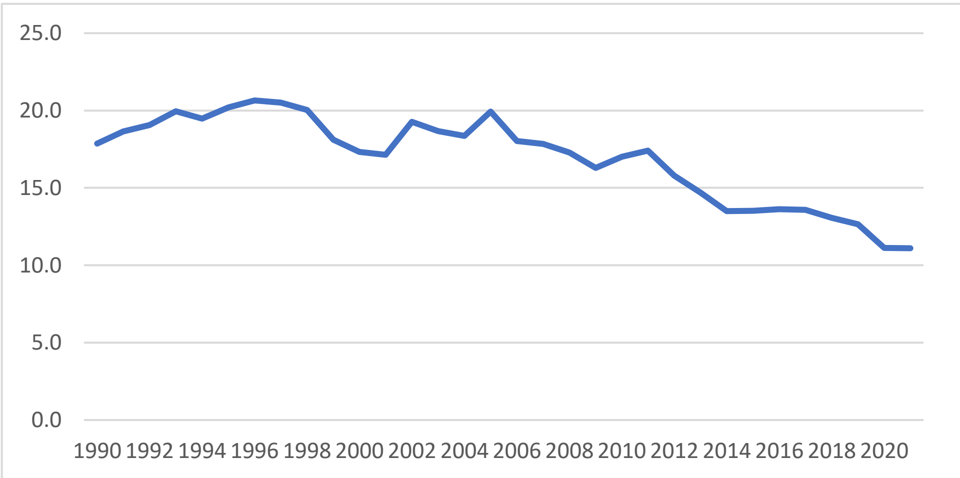

Figure 9: Territorial greenhouse gas emissions for UK refining, by million tones carbon dioxide equivalent (MtCO2e), 1990-2021 (constructed using data from Department for Energy Security and Net Zero, https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2021)

Throughout the case-study period, the UK oil refining industry has been subject to varying pressures from both economic and social-political contexts, which we will analyse in conjunction with responses from refinery firms. We divide our longitudinal case-study into several analytical periods based on shifting macro-

[4] These emissions only refer to scope-1 emissions, which refineries generate directly through their manufacturing processes. They do not include scope-2 emissions (which refineries make indirectly through purchasing and using electricity or heat) and scope-3 emissions (which are generated when consumers use a firm's products). Although the combined scope-2 and scope-3 emissions are larger than scope-1 emissions, the paper only focuses on the latter, which aligns with the government's mainstream reporting conventions.

economic or socio-political trends, signified by significant industry responses. We start with 1990-2000 period when climate-change emerged on the UK political agenda and a significant shift in market demand started to unfold (notably a shift from petrol to diesel in road transport). The next period, 2000-2008, is when seismic economic growth in Asia started to redefine the global refining industry and investment patterns, and UK refineries started to address climate mitigation. The 2008-2015 starts with the global financial crisis and continues with the subsequent austerity years that changed corporate priorities away from climate mitigation to focus on survival and retrenchment. The 2015-2019 period reflects an increase in general decarbonisation-oriented policy pressures, associated with the Paris Agreement, which led the industry to re-engage with low-carbon reorientation. In the 2019-2023 period, policy pressure further increased both through the 2019 government commitment to net-zero targets and the introduction of specific policy instruments to support industrial decarbonisation. Industry actors responded with stronger low-carbon reorientation strategies and activities.

One advantage of a multi-period longitudinal case study is that it shows that low-carbon reorientation is a long-term process that started decades ago, not years ago. Another advantage is that it helps to understand the deeper trends in an industry and the real-world tensions and trade-offs that firms need to cope with. Future-oriented analyses of refinery decarbonisation that start in the present often do not sufficiently acknowledge these deeper trends and tensions. A methodological challenge for analysing longitudinal transitions-in-the-making is that empirical information is less stabilised and more fluid for the more recent years. We therefore used different data sources for the more historical and more recent developments, as the next section discusses.

3.2. Data Sources and analysis

3.2.1. Petrochemicals

Although the petrochemical study gives most attention to the 1990-2021 period because of the interest in low-carbon reorientation, the preceding decades (1970-1990) are also investigated as a pre-development because these cover the industry's trajectory from expansion to retrenchment, which motivated long-term reorientation processes to restore competitiveness. For each period, the investigation focuses on developments in the economic and socio-political environments and company responses to these developments through multiple strategies. For the later period(s), the investigation will also focus on INEOS and SABIC, which in 2020 were the world's fourth and fifth largest chemical companies respectively [Tullo, 2021], and on the Teesside and Grangemouth clusters.

The investigation triangulated several data sources to enable a comprehensive multi-dimensional analysis. Statistical databases from DUKES (Digest of UK Energy Statistics), ONS (Office of National Statistics) and Petrochemicals Europe were used to construct longitudinal quantitative time-series of production volumes (of petrochemicals, oil, gas) and energy prices. As noted by Bennett and Page [2016], publicly available statistical data on the petrochemical industry often lack granularity because of commercial reasons and because the various product streams are hard to disentangle. The ONS Index of Production database only provides data for the petrochemical industry, not for particular products. The Petrochemicals Europe database provides European production data for ethylene, propylene, and butadiene, but does not disaggregate these for particular countries. The UK Chemical Industries Association and the UK Society of

Chemical Industry mostly focus on political lobbying and servicing members, and do not provide publicly available statistical databases. Because of these difficulties, the trends presented in section 4 do not claim to provide the ultimate quantitative analysis of the UK petrochemical industry. They do, however, provide a backbone of quantitative trends that anchor, support, and inform the qualitative analysis.

A wide range of secondary sources were used to develop a comprehensive account of contextual developments and industry dynamic for the more historical periods (1970-1990, 1990-2008). These sources include books and articles on particular companies such as BP [Bamberg, 2000], Shell [Sluyterman, 2007], ICI [Pettigrew, 1985; Owen & Harrison, 1995], and INEOS [Ratcliffe & Heath, 2018; Mah, 2021] and publications on particular chemical clusters and plants such as Teesside [Benyon et al, 1994; Greco, 2002; Chapman, 2005], Baglan Bay [Strawbridge & Thomas, 2001], and Grangemouth [Lyon, 2017; Feltrin & Mah, 2022]. Secondary sources also include the many of articles and reports on techno-economic developments in the UK (petro)chemical industry, referenced in the introduction. The investigation of the early periods (1970s, 1980s) does not aim to generate new empirical data. Instead, the aim is to concisely present information from secondary sources to enable a longitudinal pattern-matching analysis.

Additionally, multiple primary sources were used to analyse business and context dynamics in more recent periods (2008-2017, 2017-2021), including publications from industry associations, press statements and annual reports from companies, newspaper articles, and publications in the trade press (e.g., *Chemical & Engineering News; Oil & Gas Journal)*.

The longitudinal case study in Chapter 4 therefore takes the form of an analytical narrative that is guided by the triple embeddedness framework and organises empirical information under the categories of external (economic and socio-political) pressures and industry response strategies. The industry regime categories are not explicitly used in the narrative but mobilised in the analysis in the comparative analysis in Chapter 7. The phase model is also used for a pattern-matching analysis, which "compares an empirically based pattern with a predicted one" [65, p. 106]. The empirical pattern is described in Chapter 4, which divides the longitudinal developments into different periods, which are then later compared to the conceptual phase model. The pre-development section (1970-1990) is pragmatically divided into decade-long periods, whereas the 1990-2021 developments are divided into three periods based on major external shocks (such as the 2007/8 financial crisis) and major industry changes such as the replacement of incumbent firms by new companies in the 1990-2008 period, and industry reorientation towards imported gas (2008-2017). Climate change (and plastic waste) only gained momentum in the last period (2017-2021), leading to reluctant and partial low-carbon reorientation. For all periods, the available quantitative data were used to establish important trends and turning points which guide the analytical narrative.

3.2.2. Steelmaking

We employ a mixed method approach, collecting both quantitative and qualitive information from primary and secondary sources. We used publicly available databases (from the World Steel Association, World Bank, Office for National Statistics, Committee on Climate Change, and Ember, an independent energy research and think tank) and private ones (from the International Steel Statistics Bureau (ISSB), and S&P Platts) to construct quantitative time-series of production volumes, domestic and international sales, energy, iron-ore and steel prices, CO_2 emissions, CO_2 intensity). We also collected information from company annual reports to construct longitudinal time-series about financial performance.

To collect information about contextual developments and industry dynamics, we used company annual reports, policy documents, reports by industry association as well as secondary sources such as academic publications. For more recent periods, which are less well documented, we also used media reports and undertook 25 interviews with senior policymakers, academics, and industry experts. To protect the anonymity of respondents, information is attributed to generic respondent numbers (Table 1). The interview questions focused on economic competitiveness and low-carbon reorientation, and how companies aim to navigate the tensions between them. Interviews lasted between 20 and 120 minutes, were recorded, and then transcribed. They were then coded and interpreted to identify the main challenges and strategic responses.

Respondent number	Institution	Association with the UK steel industry	Date of interview
R01	University of Manchester	Academic and industry consultant	22 June 2022
R02	Materials Processing Institute	Steel technology researcher	28 June, 5 July 2022
R03	University of Bath	Academic and industry consultant	29 June 2022
R04	Swansea University	Research on decarbonisation	29 June 2022
R05	BEIS (Department for Business, Energy & Industrial Strategy)	Government	30 June 2022
R06	BEIS	Government	30 June 2022
R07	UK Steel	Industry body	1 July 2022
R08	Aldersgate Group	Industry body	5 July 2022
R09	Midrex	Technology supplier	6 July 2022
R10	University of Cambridge	Academic and consultant	6 July 2022
R11	ISSB	Steel industry data supplier	8 July 2022
R12	UK Steel	Industry body	18 July 2022
R13	Tata Steel UK	Steelmaker	19 July 2022
R14	Tata Steel UK	Steelmaker	19 July 2022
R15	Liberty Steel	Steelmaker	19 July 2022
R16	Liberty Steel	Steelmaker	19 July 2022
R17	EMR	Scrap metal industry	20 July 2022
R18	Celsa Steel	Steelmaker	21 July 2022
R19	Celsa Steel	Steelmaker	21 July 2022
R20	Community	Trade union	22 July 2022
R21	University of Warwick	Steel industry sponsored researcher	25 July 2022
R22	Green Alliance	NGO	28 July 2022
R23	British Steel	Steelmaker	2 August 2022

R24	British Metals Recycling Association	Industry body	19 August 2022
R25	British Metals Recycling Association	Industry body	19 August 2022

Table 1: Respondent profiles (the full interview guide, including 11 questions, is available on request)

We used the data to construct an analytical narrative that accommodates the data's richness and multi-dimensionality. Longitudinal case studies often face this issue, as Langley [Langley, 1999: 694] notes: "This is where the central challenge lies: moving from a shapeless data spaghetti toward some kind of theoretical understanding that does not betray the richness, dynamism, and complexity of the data". Poole et al. [2000: 54] further observe that: "Process methods must convert a heap of confusing data into a synthetic account in which the reader can comprehend all the data in a single act of understanding".

We have attempted to address this challenge in two ways. First, we ensured that our analytical narrative was guided by a theoretical plotline, based on the triple embeddedness framework that organises information under the analytical categories of external (economic and socio-political) pressures and industry response strategies. Second, to select the most important information from the data heap, we used triangulation, employing various time-series to generate quantitative backbones for the analytical narrative and secondary sources to create a first overview. We then confronted and deepened the initial interpretations with actor-focused information from annual reports and interviews. These procedures require interpretation and thus introduce a degree of subjectivity, which is inevitable in processual analysis involving theory-guided creativity and craft aspects [Langley, 1999; Poole et al, 2000].

The longitudinal narrative is organised into four periods, based on major external shocks and significant industry changes. In the 1988-1997 period, which ranges from privatisation to the Asian Financial Crisis, British Steel PLC implemented incremental strategies in response to moderate pressures. In the 1997-2007 period, external pressures further increased, starting with the 1997 Asian crisis, leading to shrinking markets and the 1999 merger that created the Corus Group. In the 2007-2015 period, the 2007/8 financial crisis and other pressures created existential problems that required the new owner Tata to take drastic measures. The last period, which starts with the 2015 steel crisis (due to Chinese overproduction and steel dumping) and the 2015 Paris climate agreement, sees steelmakers navigating both economic and climate change pressures, leading to tentative low-carbon reorientation strategies.

Section 5 further analyses the case study narrative through pattern-matching, which "compares an empirically based pattern with a predicted one" [Yin, 1994: 106]. To answer the second research question, we will compare the developments in the different empirical periods with the phases in our conceptual phase-model.

3.2.3. Oil Refining

To gather data for the various analytical categories, we utilise a mixed methods approach, collecting both quantitative and qualitative data from primary and secondary sources. The quantitative data come from publicly available statistical databases from both UK and US government sources, and other providers such as the UK Office of National Statistics, Energy Trends, International Energy Agency, UK Petroleum Industry Association (UKPIA), Digest of UK Energy Statistics and Companies House (for company financial data).

We use these data sources to identify commercially relevant trends in economic environments (such as oil prices, market developments, domestic production, imports) and company performance and strategies (such as profits, refinery margins, exports). Concerning the company financial data attained through Companies House, we only use data from Fawley (ExxonMobil), Humber (Phillips 66), and Stanlow (Essar) refineries, as the other three refineries' financial data had frequently changing parameters and sometimes obscure reporting (especially Petroineos), making interpretation difficult.

For historic contextual developments and industry dynamics, we use company annual reports, policy documents, industry association reports, NGO, and academic publications. For more recent industry and individual refinery activities, where less published material is available, we supplemented our desk-based examination with 24 semi-structured interviews with senior academic and industry experts. We deliberately focused on industry actors (or people close to them), because they make the actual investment decisions to deploy low-carbon technologies. To protect interviewee anonymity, information is attributed to generic respondent numbers (Table 2). Although we approached all six refineries, those firms that are more actively reorientating were more willing to be interviewed, which created some imbalance in our interviews. To mitigate this imbalance, we also interviewed academic experts and industry associations, which took an industry-wide view. We also gathered information from industrial cluster actors.

Interview code	Profile	Organisation profile	Interview Date
R26	Retired Academic and refinery engineer	Refinery and University	23/03/2023
R27	Academic and Consultant	University	27/03/2023
R28	Editor	Industry Journal	29/03/2023
R29	Former senior oil refining executive	Refinery	21/04/2023
R30	Senior refinery engineer (Sustainability)	Refinery	Written Ans
R31	Project developer	Carbon Capture specialist	22/05/2023
R32	Senior executive	Industry Trade Body	24/05/2023
R33	Policy Analyst	Industry Trade Body	30/05/2023
R34	NGO	Hydrogen advocates	02/06/2023
R35	Decarbonisation lead	Refinery	12/06/2023
R36	Former senior oil refining executive	Refinery	13/06/2023
R37	Refining net-zero Specialist	Engineering Consultancy	13/06/2023
R38	Net-zero lead	Refinery	14/06/2023
R39	Academic	University	14/06/2023
R40	Policy Analyst	Industry Association	15/06/2023
R41	Former senior oil refining Executive	Refinery	16/06/2023
R42	Asset developer	Oil Company	16/06/2023
R43	Senior executive	Independent petroleum product importer	21/06/2023
R44	Senior consultant	Sustainability Consultants	22/06/2023
R45	Head of innovation and growth	Regional Industry Cluster	26/06/2023
R46	Project Manager	Hydrogen	27/06/2023
R47	Academic	University	10/07/2023
R48	Academic	University	12/07/2023
R49	Corporate Affairs	Refinery	26/07/2023

Table 2: Respondent profiles (interview guide and questions available on request)

We asked each interviewee to answer 11 questions: one general, two historical, and eight focussed on industrial low-carbon reorientation (addressing technologies, pathways, and commercial dynamics that influenced past and present strategies and actions). Interviews were carried out between March and July 2023, lasted between 30 and 120 minutes, were mostly recorded (not all respondents gave permission) and transcribed (one respondent only replied to our questions in writing).

We used the various data to construct an analytical narrative that accommodates the richness and multi-dimensionality of the case. This analytical narrative uses the triple embeddedness framework as theoretical plotline, which means that our analysis is partly deductive as it organises information under the analytical categories of external (economic and socio-political) pressures and industry response strategies. But the analysis is also partly inductive because the synthesis of multiple types of information is a creative interpretive process that also allows new insights to arise. Triangulating different data, we used various time-series to generate quantitative backbones for the analytical narrative and secondary sources to create a first overview. We subsequently elaborated desk-based interpretations with actor-focused information from annual reports and interviews.

The longitudinal narrative is organised into five periods, as indicated above, based on major external pressures and significant industry changes. Section 5 will further analyse the longitudinal narrative through pattern-matching [Yin, 1994], in which we compare the five empirical periods with the conceptual phases from our conceptual model of industry reorientation. That will enable us to answer the second research question by assessing in what reorientation phase the refining industry is and how fast they have progressed through different phases.

4. Petrochemical industry

4.1. Brief description of industry specifics

The petrochemical industry is the largest industrial energy-using sector, using approximately 14% of global oil and 8% of gas [IEA, 2018]. Just over half of these inputs are used as material feedstock in petrochemical production processes, the remainder as fuel source. About 60% of the chemical industry's CO_2 emissions, which were 1.5 gigatons in 2017, relate to a handful of primary chemicals [ibid]: three olefins (ethylene, propylene, butadiene), three aromatics (benzene, toluene, xylene), methanol, and ammonia. Except for ammonia, these primary chemicals, and their immediate derivatives (e.g., synthetic fibres, synthetic rubber, plastics) are produced by the petrochemical industry, which thus is a major contributor to global climate change.

The petrochemical industry, which forms the foundation of organic chemistry (Figure 10), not only produces primary chemicals and immediate derivatives, but also provides inputs into pharmaceuticals, dyes, agricultural chemicals, soaps, and food ingredients. Plastics, which come in many different forms, account for 70-80% of petrochemical products [Mah, 2022]. The IEA [2019] estimates that global demand for primary petrochemicals could increase between 40% and 60% by 2050. Analysing recent industry plans, Bauer and Fontenit [2021] identified 88 projects for new petrochemical plants, mostly multibillion dollar (poly)ethylene-producing steam crackers, which suggest that companies are also expecting, and actively working towards, further expansion of the industry, especially in the United States and Middle East (which have relatively cheap feedstocks) and China (where markets are rapidly expanding). The importance of the petrochemical industry for climate change is thus likely to increase in the coming decades.

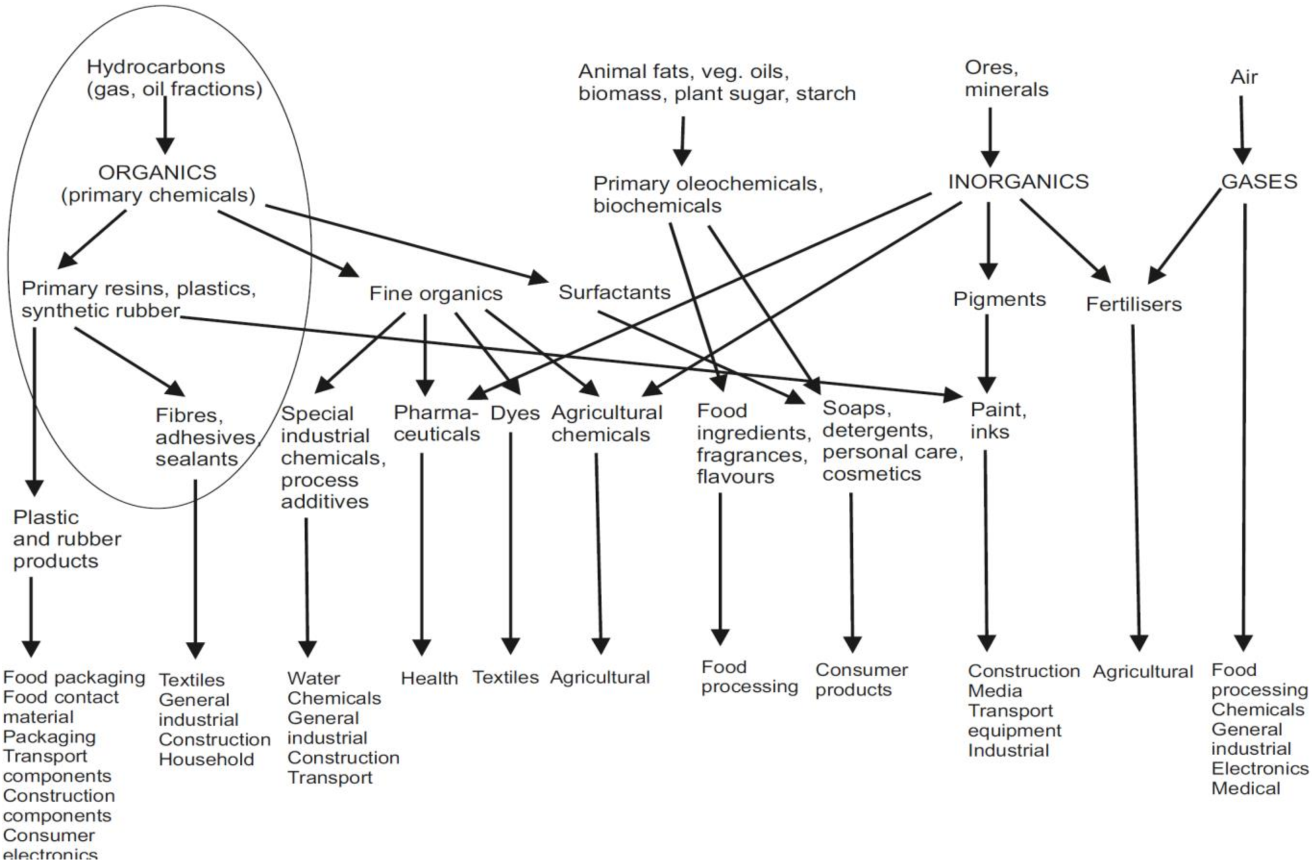

Figure 10: Chemical sector supply chain links from feedstock inputs to end users, with the circle highlighting the petrochemical sector [DECC, 2015a: p.11]

In the UK there are several petrochemical clusters with specific local contexts. Petrochemical clusters are traditionally located close to oil refineries, which provide feedstock inputs and produce some aromatics during the refinery process (Figure 11). They also centre around steam crackers, which are large installations that apply heat and pressure to break naphta or gas inputs into smaller hydrocarbons like ethylene, propylene, and butadiene (Figure11), which can then be transformed into polymers like fibres and plastics (Figure 10). Steam cracking is at the heart of the petrochemical industry and by far the largest energy-using process in terms of fuel and feedstock [Griffin et al, 2018]. It therefore is the focus of the case study.

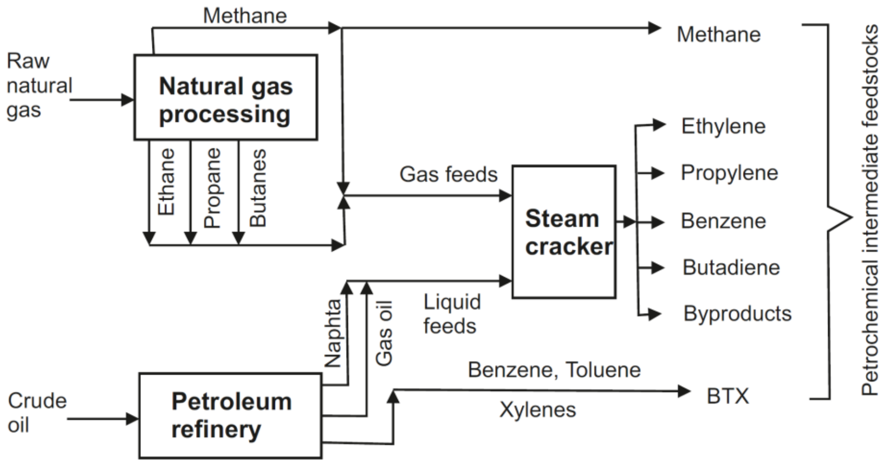

Figure11: Basic petrochemical feedstocks and processes (adapted from [CEFIC, 2013])

Figure 6 identifies the four main petrochemical complexes at the following locations: 1) Grangemouth and the Firth of Forth in Scotland (including Mossmorran), which has one oil refinery (co-owned by INEOS and PetroChina) and two steam crackers (owned by INEOS and ExxonMobil), 2) Teesside, which has a very large cracker (called 'Olefins 6'), owned by SABIC, which supplies primary chemicals to multiple processing companies; the Teesside oil refinery closed in 2009; 3) Humberside on the East coast of Yorkshire, which has two oil refineries but no steam cracker, 4) Merseyside in North West England, which has a major oil refinery (Essar), but no longer a steam cracker, after Shell closed its Carrington site in 2007.[5] The four UK clusters are connected by a pipeline system (represented with blue lines in Figure 6) that distributes ethylene, which has been described as the "world's most important chemical" [Chapman, 1991]: 60], from the main production centres (Teesside and Grangemouth/Mossmorran) to other petrochemical clusters that do not (or no longer) have steam crackers. Because of their importance, the paper will dedicate more attention to the Teesside and Grangemouth clusters, and their main companies (presently INEOS and SABIC), than to the other two clusters.

[5] Another steam cracker in Fawley at the South Coast closed in 2013. The cracker was operated by ExxonMobil and limitedly fed into other chemical firms.

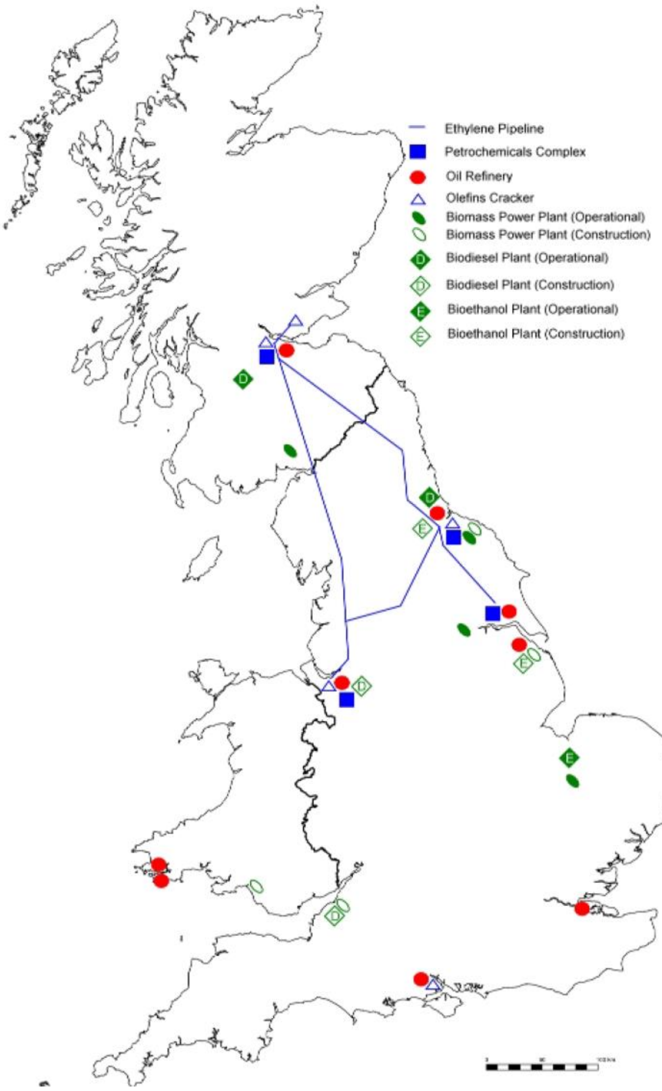

Figure 12: Distribution of existing petrochemical clusters, steam crackers, and oil refineries in the UK [Bennett, 2009: 136]

Table 1 further highlights the importance of the four clusters, showing that they host the 11 chemical plants with the highest CO_2 emissions, which together accounted for 48% of all of CO_2 emissions from the chemical sector in 2019. It further shows that the petrochemical sector, which includes the first three processes in Table 3 (represented in italics), generates most CO_2 emissions, especially the three olefin producing plants. Table 3 further shows that Teesside, Grangemouth/Mossmorran, and Humberside are the most important petrochemical clusters (in terms of emissions and underlying energy use) and that INEOS and SABIC are the most important companies (owning several high-emission plants), which reinforces the rationale for focusing on these clusters and firms.

Process, product	**Number of UK plants**	**Cluster locations**	**Company name**	**CO_2 emissions (tonnes)**	**Input for manufacture of:**
Olefins (ethylene,	3	Teesside (Wilton)	SABIC	1,153,526	Plastics and polymers
		Grangemouth	INEOS	522,000	

propylene, butadiene)		Mossmorran (Firth of Forth)	ExxonMobil	659,996	
Acetic acid (made from methanol)	1	Humberside	INEOS	364,062	Reactive agent in other chemical processes
Acrylonitrile (made from propylene)	1	Teesside	INEOS	381,803	Nylon, acrylics
Ammonia	2	Teesside	CF Fertilisers	855,157	Fertilisers
		Merseyside (Ince)	CF Fertilisers	751,572	
Soda ash	1	Merseyside (Lostock)	Tata Chemicals	136,696	Cleaning products, soap, glass
Titanium dioxide	2	Teesside	Tioxide Europe	163,818	Paints, sunscreen, food colouring
		Humberside	Millennium Inorganic Chemicals	196,640	
Hydrogen	1	Teesside	BOC Linde	231,053	Ammonia
Total emissions				**5,416,323**	

Table 3: Direct CO_2 emissions (in tonnes) of the most significant UK chemical processes and plants in 2019, with petrochemicals represented in italics (constructed using data from the Large Industrial Installation database from the UK National Atmospheric Emissions Inventory (https://naei.beis.gov.uk/laco2app/) and the Scottish Pollution Release Inventory (https://informatics.sepa.org.uk/SPRI/))

4.2. Pre-developments (1970-1990)

4.2.1. Industry emergence and expansion in the 1950s and 1960s

Supported by high economic growth rates and demand for synthetic products, oil companies and chemical firms build more and larger petrochemical plants and ethylene steam crackers in the 1950s and 1960s (Table 2). BP invested mostly in Grangemouth and in Baglan Bay, Shell in Merseyside, Esso in Fawley, and ICI in Teesside.

Year	**Location**	**Company**	**Maximum production capacity (tons/year) at time of opening**
1951	Wilton (Teesside)	ICI	30,000
1951	Grangemouth	BP	30,000
1951	Carrington (Merseyside)	Shell	30,000
1956	Wilton (Teesside)	ICI	30,000
1956	Grangemouth	BP	30,000
1958	Fawley (on UK South coast)	Esso	40,000
1959	Wilton (Teesside)	ICI	70,000

1960	Grangemouth	BP	70,000
1963	Baglan Bay (in South Wales)	BP	60,000
1966	Carrington (Merseyside)	Shell	150,000
1967	Wilton (Teesside)	ICI	200,000
1967	Fawley	Esso	120,000
1968	Baglan Bay	BP	340,000
1968	Grangemouth	BP	250,000
1969	Wilton (Teesside)	ICI	450,000
1979	Wilton (Teesside)	ICI with BP	500,000
1985	Mossmorran (near Grangemouth)	Shell and Esso	500,000

Table 4: Construction of new ethylene steam crackers in the UK (constructed using data from [Bamberg, 2000; Bennett & Pearson, 2009])

Two oil price shocks (1973, 1979) slowed macro-economic growth rates, and two recessions created a more challenging economic environment for the petrochemical industry, because they reduced demand for its products and increased feedstock and energy costs [Aftalion, 2005]. Because several new ethylene plants had just been completed (Table 4), the petrochemical industry experienced substantial overcapacity which further depressed profits [Bamberg, 2000].

A positive economic development for the industry was the discovery and exploitation of substantial oil fields in the North Sea, which boosted domestic oil production from the mid-1970s (Figure 13). The new oil and gas pipelines benefited petrochemical plants on the UK east coast (Grangemouth, Teesside, Humberside), but not those in Baglan Bay (west coast) or Fawley (south coast).

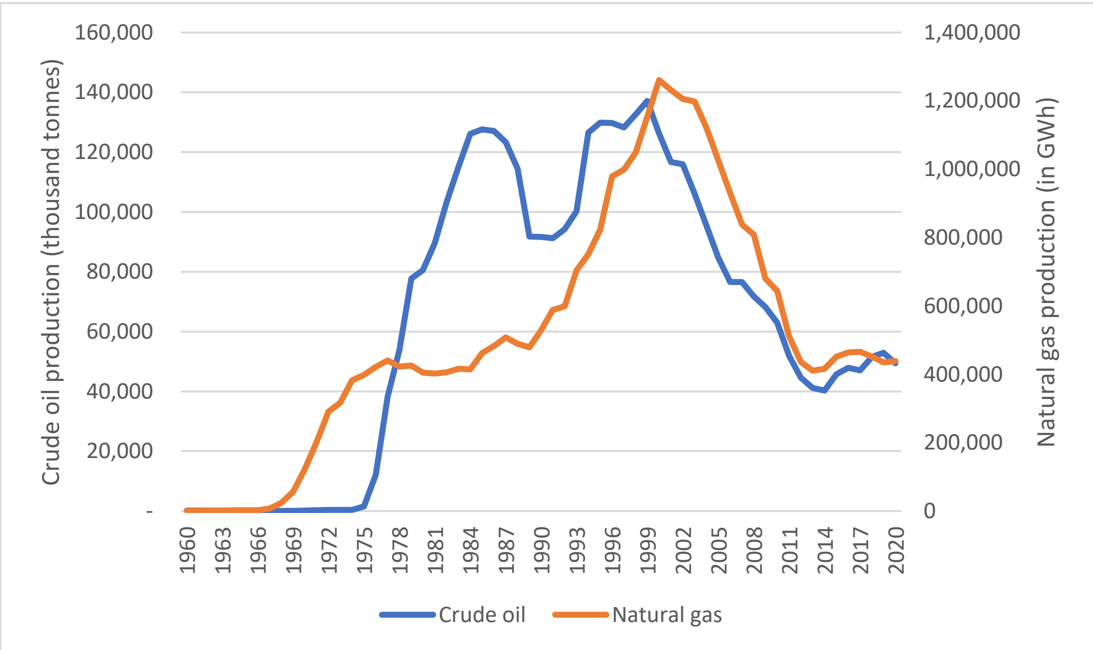

Figure 13: UK production of crude oil in thousand tonnes (left-hand Y-axis) and natural gas in GWh (right-hand Y-axis), 1960-2020 (constructed using data from DUKES, oil statistics and gas statistics; historical time series data)

4.2.2. Industry responses and strategies in the 1970s

Company managers, who had become accustomed to continuous steady growth, did not immediately recognise the worsening economic developments as structural trend breaks: "It was not until 1980 that people woke up to the fact that they were not in the same worlds as the 1960s. The second oil shock of 1979 hit the chemical industry hard and brought to the surface a structural overcapacity crisis that had been pending for some time" [Grant, 2007: 303]. The misperceptions in the 1970s, which resonate with phase 1 in the analytical model, led to continuation of economic positioning strategies such as capacity-increasing investments. ICI and BP, for instance, announced in 1974 that they were jointly going to build a huge new steam cracker at Wilton (Olefin 6), which came onstream in 1979 [Bamberg, 2000]. BP also build the Forties Pipeline System that connected North Sea oil fields to its Grangemouth complex.

The oil price volatility also stimulated innovations strategies in the late 1970s, aimed at developing new crackers that could switch between naphtha, gas oil, or liquified petroleum gas (LPG) feedstocks, depending on relative prices and availability [Sluyterman, 2007].

4.2.3. Economic environment in the 1980s

The UK petrochemical industry faced multiple pressures in the 1980s. Oil prices remained high after the 1979 oil shock, increasing the industry's feedstock and energy costs. A deep recession in early 1980s decreased demand for petrochemical products, which remained suppressed throughout the decade. Overcapacity in the UK and Europe depressed prices and profits. Furthermore, Asia and the Middle East emerged as major producers of key products like ethylene (Table 5): "During the 1980s, (…) Asia seemed to be the place where things happened, where one had to be" [Sluyterman, 2007: 151]. The resulting internationalisation of the petrochemical industry increased global competition [Aftalion, 2005] as well as UK import penetration, which rose from 18% of home demand in 1970 to 29% in 1980 and 42% in 1988 [68].

	1970	1990
United States	45%	35%
Western Europe	37%	28%
Japan	13%	11%
Rest of world (including Middle East and Asia)	5%	26%

Table 5: Relative size (in %) of ethylene production capacity in different parts of the world (data from [50, p. 152])

4.2.4. Socio-political environment in the 1980s

The Thatcher administration (1979-1990) offered limited support, because of its ideological belief in free market forces. The industry's relations with policymakers became more distanced and antagonistic [Grant, 2007]. The government also privatised BP in stages, which paved the way for a different management style [Bamberg, 2000].

Public perceptions of the chemical industry deteriorated in the 1980s because of chemical pollution incidents and accidents such as the 1984 explosion at the Bhopal chemical plant [Mol, 1995; Hoffman, 1999; King &

Lenox, 2000]. Although the Bhopal accident happened in India, it was widely discussed in the UK media and contributed to negative perceptions that began to erode the industry's cultural legitimacy.

4.2.5. Industry responses and strategies in the 1980s

The economic pressures led to financial losses for UK petrochemical companies in the early 1980s. Companies therefore implemented incremental cost-cutting strategies such as reducing employee benefits, introducing more flexible labour and sub-contracting, and reducing the work force [Beynon et al, 1994]. These strategies, which resonate with phase 2 in the analytical model, accelerated the decline of employment in the petrochemical industry, which had started in the late 1960s with scale increases and automation (Figure 14).

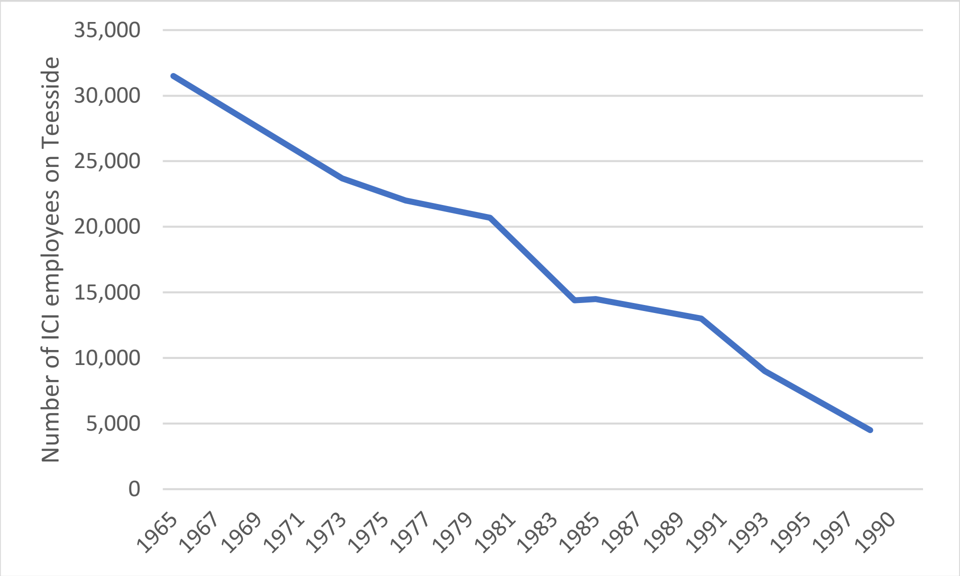

Figure 14: Number of ICI employees on Teesside (constructed using data from [Greco, 2002: 60])

In response to high international oil prices, petrochemical companies also incrementally changed their economic positioning strategies, shifting towards increased use of North Sea oil and gas feedstocks [50]. They also made technological adjustments in steam crackers, which increased feedstock flexibility and enabled a shift from naphtha (from oil) to ethane (from natural gas) in subsequent decades [Greco, 2002; Figure 15]. Taking advantage of the new feedstocks, Shell and Esso even decided to build an ethylene cracker and a Natural Gas Liquids (NGL) plant in Mossmorran, which opened in 1985.

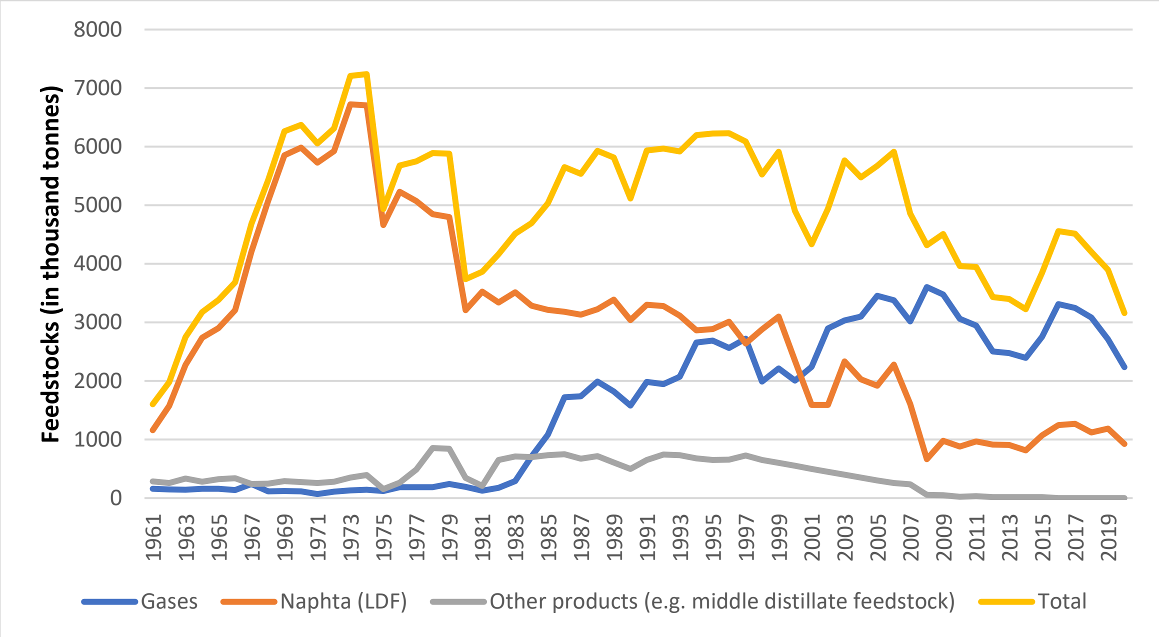

Figure 15: Feedstocks (in thousand tonnes) into the UK petrochemical industry (created using data from: a) DUKES Energy Trends: UK oil and oil products; Table ET 3.13 'Deliveries of petroleum products for inland consumption' for 1998-2020 period, and b) historical time series data; Oil statistics; Inland deliveries of products for 1961-1997 period)

Another economic positioning strategy was to diversify from bulk chemicals towards more profitable market segments like specialty chemicals. "It was foreseen that Europe would not be able to compete with Middle Eastern production of base chemicals because of the latter's easy access to cheap feedstock. However, Europe could hope to compete in higher technology products, such as speciality chemicals, where quality and performance were paramount" [Sluyterman, 2007: 140]. This diversification strategy accelerated in the 1990s, leading incumbent companies to sell their petrochemical assets to generate money for the acquisition of specialty chemical plants. "Whereas up to the mid-1980s, ICI had pursued a strategy of diversification, covering a wide range of products, the decade from the mid-1980s to the mid-1990s marked its search for niche and less volatile markets" [Greco, 2002: 61].

4.3. Fundamental industry restructuring (1990-2008)

4.3.1. Economic environment

International competition rose further in this period [Aftalion, 2005], increasing chemical import penetration from 42% of UK home demand in 1988 to 57% in 1996 [Grant, 2007]. Additionally, a prolonged recession in the early 1990s reduced demand for petrochemical products, reinforcing overcapacity problems. In 1993, there were 53 European crackers, which produced 17,4 million tonnes of ethylene against a demand of around 15,5 million tonnes [Strawbridge & Thomas, 2001].

After the 1991-1992 recession, demand picked up and European production of primary petrochemicals increased steadily until the 2007/8 financial crisis (Figure 16).

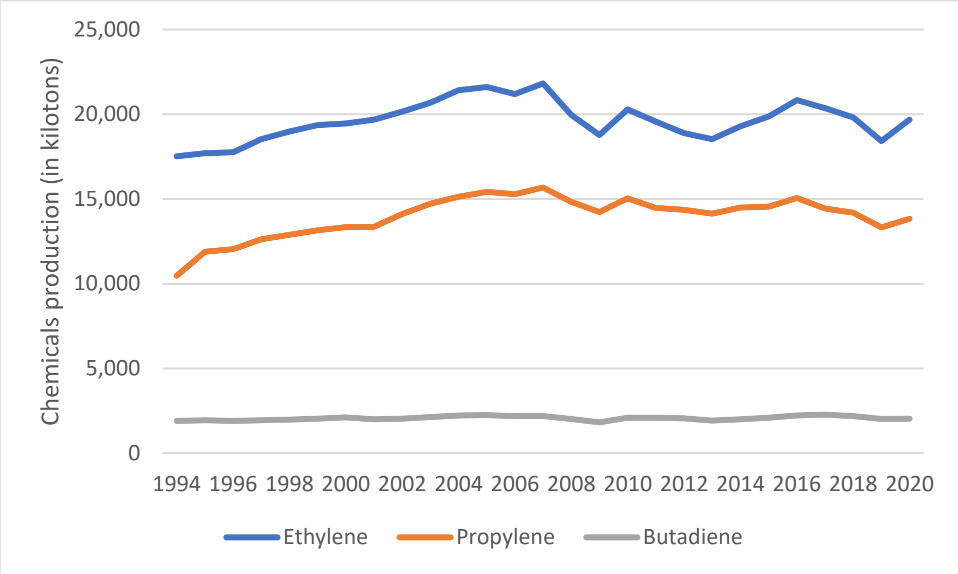

Figure 16: Production of ethylene, propylene and butadiene (in kilotons) in Western Europe (defined as EU15 + Hungary, Norway, Slovakia), 1994-2020 (constructed using data from Petrochemicals Europe (https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/)

Oil (and gas) prices decreased substantially after 1986, remained relatively low during the 1990s, but started increasing from the early 2000s (Figure 17), which raised energy and feedstock costs.

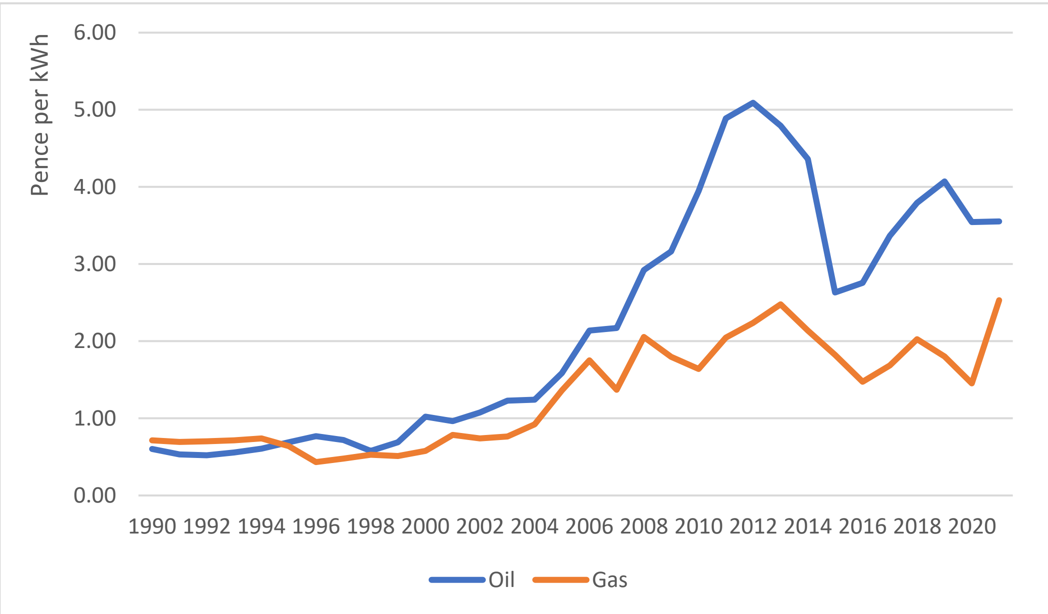

Figure 17: Prices of fuels (in pence per kWh) purchased by large manufacturing industries in Great Britain, 1990-2021 (constructed using data from DUKES Industrial energy price statistics)

4.3.2. Socio-political environment

Socio-political concerns about environmental pollution further increased, and also came to include climate change. The Labour government (1997-2010) made climate change an important political issue, adopting a target of 60% GHG emission reduction of in 2003 and an 80% target in 2008. Climate policy focused mostly on the electricity, mobility, and building sectors, and did not (yet) express much concern about the petrochemical industry.

4.3.3. Industry responses and strategies

International competition reduced profitability in the UK petrochemical industry, while the 1991-1992 recession generated financial losses in both primary petrochemicals and speciality chemicals. Petrochemical companies responded with drastic economic repositioning strategies including rationalisation, plant closure, selective investments, and selling off assets, which together generated a fundamental restructuring of the UK petrochemical industry, including the withdrawal of incumbent firms and the entry of new organisations such as Huntsman, SABIC, INEOS. Because these organisations introduced new mindsets and (venture capitalist) management styles, this period has elements of phase 5 of the analytical model.

ICI continued its economic reorientation towards specialty chemicals, acquiring Unilever's specialty business in 1997. ICI also sold off its successful pharmaceutical division in 1993, which led to a new company, Zeneca [Greco, 2002], and many of its petrochemical assets in Teesside (Table 4). This included the 1999 sale of the Wilton steam cracker (Olefin 6) to Huntsman, ICI's aromatics assets, and Tioxide, which was renamed Huntsman Tioxide [ibid]. In 2006, Huntsman sold several assets on to SABIC, including the Olefin 6 naphtha-based cracker, its paraxylene plants, a polyethylene plant under construction, and the aromatics complex. The $700 million deal enabled the Saudi company, which was half-owned by Saudi Aramco, to advance its strategy of global diversification [Seznec, 2020]. By the early 2000s, the business repositioning strategy left ICI with no significant businesses in Teesside and only some assets in paints, adhesives, performance specialities, and food ingredients [Greco, 2002]. ICI expired in 2008 when it was taken over by AkzoNobel.

Acquirers	Date	Activities/business
Du Pont	1993	Nylon chain
Terra	1997	Ammonia/fertilisers
Sembcorp	1998	Wilton site/utilities
Threadneedle	1998	Wilton Centre
Du Pont SA	1998	Polyesters
Huntsman	1999	Olefins
Huntsman	1999	Aromatics
Lucite International	1999	Acrylics
Dow	2001	Ethylene oxide/derivatives

Table 6: Buyers of ICT assets on Teesside [Chapman, 2005: 603]

One consequence of the restructuring at Teesside was a "fragmentation of corporate control" [Chapman, 2005: 611], as multiple foreign-owned firms operated a plurality of chemical productions. Another consequence was a shift to a new corporate governance style because many of the new companies used venture capital approaches, buying struggling plants at the trough of the cycle and trying to "turn them into profitable businesses by relentlessly cutting costs" [Da Rin, 2007: 106]. Cost-cutting strategies included reducing investments (in R&D and capital expenditure) and reducing labour costs (through pay cuts, removing management layers, and reducing pension schemes).

BP's chemicals division initially tried to improve profitability by focusing its economic positing strategy on Grangemouth. This involved closing the Baglan Bay complex, which was deemed uncompetitive and too far removed from North Sea feedstock supplies [Strawbridge & Thomas, 2001]. It also involved investing in Grangemouth, including opening of new ethylene plant (with 350,000 tons/year capacity) in 1993, adapting the refinery, and renewing the pipeline from the Forties Field. In 1997, BP expanded the new cracker's capacity to 450,000 tons/year and in 2001 further increased capacity to 730,000 tons/year. BP also upgraded its acetyl and aromatics plants in Saltend Chemicals Park in Humberside.

Despite its repositioning strategy, BP's chemicals division struggled to achieve the high rates of profitability expected in oil companies [Sluyterman, 2007]. BP management therefore decided to sell petrochemical assets across 19 manufacturing sites, including the oil refinery and two gas-based steam crackers in Grangemouth [Ratcliffe & Heath, 2018]. These 'unloved' assets were snapped up in 2005 by INEOS, which was a relatively new chemical company, created in 1998 by venture capitalist Jim Ratcliffe. The $9 billion deal tripled the size of INEOS overnight, requiring it to borrow heavily from banks [ibid].

Shell also restructured its chemical division, because it struggled to meet the 12% return on capital considered normal in the oil company [Sluyterman, 2007: 146]. Shell sold about 40% of its chemicals businesses in this period, including agrochemicals and fine chemicals [Sluyterman, 2007]. Shell also withdrew from the Merseyside petrochemical complex, first closing its steam cracker, and then the Carrington site (in 2007). In 2011, it sold the Stanlow refinery to the Indian company Essar, and in 2012 it shut its Thornton R&D facility [Marriott & Macalister, 2021].

Despite the fundamental restructuring, UK petrochemical production output increased steadily in the 1990s and early 2000s (Figure 18), following a similar pattern as the European petrochemical industry (Figure 16).

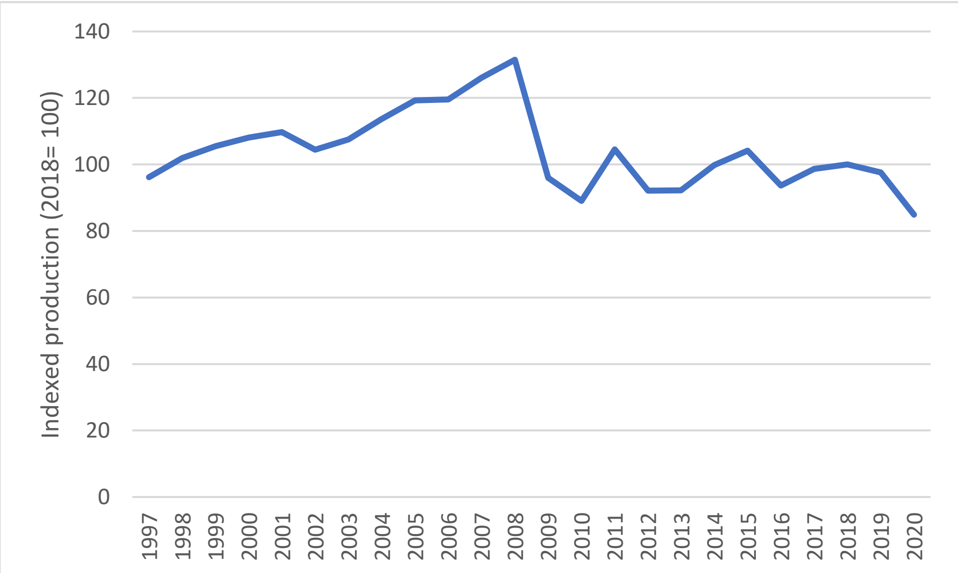

Figure 18: Relative volume of UK production of petrochemicals, 1997-2020 (constructed using data from the Index of Production time series from the Office of National Statistics; https://www.ons.gov.uk/economy/economicoutputandproductivity/output/datasets/indexofproduction; version 13 October 2021)

Despite increasing production, combustion-related CO_2 emissions from the petrochemical industry decreased by 38% between 1996 and 2008 (Figure 2), because of energy-efficiency innovations and a relative shift from naphtha to gas-based feedstocks (Figure15). These changes were not motivated by climate mitigation goals but by economic concerns such a desire to reduce overall fuel inputs and the choice of cheaper feedstocks such as ethane [Griffin et al, 2018].

Industry actors also deployed socio-political strategies to address environmental sustainability concerns. The UK chemical industry signed up to the Responsible Care program in the 1990s, which articulated voluntary standards for health, safety, and environmental performance [Mol, 1995; Hoffman,1999; King & Lennox, 2000]. This self-regulation program aimed to improve public perceptions and legitimacy and preclude the need for formal regulations.

Regarding climate change, BP was an industry frontrunner, acknowledging the problem earlier than other firms. Under John Browne's leadership (1995-2007), BP rebranded itself as 'Beyond Petroleum' in the early 2000s and piloted an internal CO_2 emissions trading scheme which enabled BP business units to buy and sell carbon credits to each other. This incentivised BP's Grangemouth complex (particularly its refinery) to deploy energy efficiency innovations that substantially reduced carbon emissions [Marriott & Macalister, 2021]. In 2005, Browne also launched innovation strategies, announcing plans for a pioneering CCS scheme at Peterhead (in the north of Scotland) and the development of wind power, solar energy, hydrogen, and gas-fired power stations [ibid]. Browne was sacked in 2007, however, and BP's green plans were derailed by the 2007/8 financial crisis and the 2010 Deepwater Horizon oil spill, which changed the company's strategic priorities.

4.4. External disruptions and industry reorientation towards imported gas (2008-2017)

4.4.1. Economic environment

The industry's economic environment worsened substantially because the 2007/8 financial crisis and subsequent recession strongly reduced demand for petrochemical products, leading to a 32% reduction in UK petrochemical production between 2008 and 2010, and subdued growth in subsequent years (Figure 12). Another external shock was the US shale gas revolution, which boosted the production of (relatively cheap) natural gas in the 2010s, restoring the competitiveness of the US petrochemical industry, which thus became an additional foreign competitor for UK firms [CEFIC, 2013; Oxford Economics, 2014]. Additionally, the declining production of North Sea oil and gas (Figure 13) increased the industry's dependence on expensive oil imports, which increased production costs and reduced competitiveness.

4.4.2. Socio-political environment

After the financial crisis, policymakers became more interested in supporting manufacturing industries like chemicals because of a desire to 'rebalance the economy'. They supported the creation in 2013 of the Chemistry Growth Partnership (CGP), which improved coordination between policymakers and UK chemical companies with regard to addressing long-term challenges and opportunities, including growth and climate change [CGP, 2013].

The 2008 Climate Change Act introduced an 80% GHG emission reduction by 2050 and strengthened climate policies, especially for electricity, mobility, and buildings. In 2015, the UK Department of Energy and Climate Change made several industrial decarbonisation road map exercises, which indicates that civil servants began to consider hard-to-decarbonise sectors like the chemical industry [DECC, 2015a].

4.4.3. Industry responses and strategies

In response to the financial crisis and reduced demand, companies implemented retrenchment strategies, which resonate with phase 2 of the analytical model. SABIC mothballed its Teesside steam cracker in 2008, while INEOS temporarily closed one of its Grangemouth crackers. SABIC reopened its cracker in April 2009 and in October 2009 commissioned the 'System 18' low-density polyethylene plant, which would use about half of the ethylene output from its Olefins 6 cracker [Oxford Economics, 2014]. Reduced demand also led to the suspension of oil refinery operations in Teesside in 2009, which were permanently closed in 2012. ExxonMobil closed its Fawley steam cracker in 2013.

Petrochemical firms also faced pressure from cheaper competitors, particularly in the Middle East and United States, which made it "difficult for the UK to increase its market share over the past five years [i.e., 2010-2015; FWG]" [DECC, 2014: 31].

INEOS also faced struggles with banks who were concerned about the effects of the financial-economic crisis on the company's ability to repay its $9 billion loans for the 2005 BP deal. INEOS "struggled to survive and in late 2008 needed a six-month extension to avoid defaulting" [Jervis, 2017: 6]. Negotiations not only led to higher bank fees, but also to a new business plan, which required INEOS to implement a cost-reduction programme across the entire business [Ratcliffe & Heath, 2018]. The latter, in turn, led to struggles with labour unions which especially in Grangemouth resisted worsening conditions such as the removal of final pension salary schemes. The industrial dispute culminated in a 2-day strike in 2008, which led the unions to win the dispute [Lyon, 2017].

To generate cash, INEOS sold half of its Grangemouth refinery to PetroChina for £1 billion, leading to a joint venture called Petroineos. The Grangemouth complex continued to struggle, however, and by 2012 was losing £10 million per month [Ratcliffe & Heath, 2018]. In 2013, INEOS management provoked another fight with the Grangemouth unions, which it won due to procedural preparations and the threat to permanently close the complex [Lyon, 2017]. Workers were forced to accept a 'survival plan', which included a wage freeze for three years, no bonuses, and a money purchase pension scheme. In exchange, INEOS promised to invest £400 million in a new ethane-based terminal infrastructure and various plant upgrades.

These investments were part of a wider economic repositioning strategy aimed at importing cheap ethane from the United States. This £1.5 billion strategy, which was supported by a £237 million UK government loan guarantee and a £9 million Scottish government grant, involved constructing a 300-mile pipeline from US shale gas fields to the coast, building deep-water port terminals, and purchasing 8 new gas-carrier ships. This technological diversification strategy resonates with phase 4 in the analytical model. The first ethane-filled ships arrived in Grangemouth in 2016, which enabled a return to profitability and the re-opening of its mothballed cracker [Ratcliffe & Heath, 2018]. The sizeable investments and the 15-year gas supply contracts locked INEOS deep into fossil fuels-based petrochemical production.

UK petrochemical firms markedly increased their socio-political strategies in this period. INEOS and SABIC were founding members of the Chemistry Growth Partnership (CGP), an industry-led sector council, which was created in 2013 to enhance interactions with policymakers. Energy Minister Michael Fallon became one of CGP's co-chairs, which thus increased the (petro)chemical industry's political access and power. INEOS was influential in shaping the CGP's strategies because one of its directors, Tom Crotty, led the organisation's energy work.[6] Playing into policymakers' new interest in manufacturing industries, the CGP's strategy document [CGP, 2013] suggested that the chemical industry could be an important growth engine for the UK economy, potentially delivering 50% more growth in 2030 if policymakers provided supportive policies (e.g., financial support schemes, export promotion campaigns, shale gas support).

Although petrochemical firms initially ignored the climate change problem, their engagement increased in the early 2010s, which represents a shift from phase 1 to phase 2 in the analytical model. The CGP [CGP, 2013], for instance, advanced a discursive framing that positioned the chemical industry as part of the solution rather than as part of the problem, because of its ability to develop new materials and coatings for wind turbines, electric vehicles, and home insulation. This framing strategy was subsequently repeated by other UK lobby groups such as the Chemical Industries Association (CIA), which emphasised that the UK chemical industry had already improved its energy efficiency by 35% in the past 20 years and was also "helping other sectors to reduce their emissions by using chemical products and technologies" [CIA, 2015: 2]. Adopting similar voluntary strategies as in its earlier Responsible Care program, the industry argued that formal climate regulations were not needed because firms were already working on low-carbon transitions. These industry efforts would, however, benefit from "the right policy framework" [CIA, 2015: 2] such as financial support for the development and implementation of low-carbon technologies.

A more pro-active innovation strategy was Teesside Collective's vision for CCS in industrial clusters, where multiple companies were co-located close enough to warrant CO_2 capture and transport from multiple sources (www.teessidecollective.co.uk). Between 2013 and 2016, this vision was elaborated into technical engineering designs by five chemical companies with substantial assets in Teesside: BOC (operating the UK's largest hydrogen plant), CF Fertilisers (operating the UK's largest ammonia plant producing fertiliser), Lotte Chemical (whose Teesside plant produces PET for 15 billion plastic bottles every year), Sembcorp (which manages the Teesside site and provides industrial utilities), and SABIC (which joined the Collective relatively late). Although the initiative attracted much attention, it dissipated after the government cancelled the funding for a CCS demonstration project in 2016 because of cost concerns [HoC, 2019].

4.5. Deeper fossil fuel integration and reluctant low-carbon reorientation (2017-2021)

4.5.1. Economic environment

International competition continued to create a challenging environment for the UK petrochemical industry. Additionally, the 2016 Brexit referendum created deep uncertainties about possible effects on trade with the European Union, which was the destination of 63% of the chemical industry's exports and the source of 75% of imports [Grylls, 2020]. Potential trade tariffs would substantially affect the sector's already tight profit margins. Increasing oil prices also created pressure on the industry between 2015 and 2019, while skyrocketing gas prices in the last quarter of 2021 substantially raised operational costs. The industry also experienced declining demand, because economic growth slowed after 2016, while the COVID-19 pandemic caused a deep recession in 2020, leading to a 13% output reduction (Figure 18).

1. https://www.soci.org/news/sci/collaborators/chemistry-growth-partnership

4.5.2. Socio-political environment

Socio-political pressures also substantially increased in this period. Public attention for climate change climbed due to the 2015 Paris Agreement and public protests in 2019 by school children and civil society organisations, leading to new framings like 'climate emergency'. Public concern about plastic waste also exploded after 2017, delegitimating a core petrochemical product [Mah, 2022]. Social movement organisations also directly targeted the petrochemical industry, with climate activists from Extinction Rebellion blockading the entrance to the INEOS Grangemouth complex in October 2021 [Mah, 2021]).

In response to public concerns, policymakers introduced a raft of climate policy documents focused on energy intensive industries, including the petrochemical sector. The government's 2017 *Clean Growth Strategy* stated that energy intensive industries "will require steps beyond energy efficiency" such as switching to low-carbon fuels and the "deployment of new technologies, for example carbon capture, usage and storage" [HMG, 2017: 64]. In 2017, the Department of Business, Energy and Industrial Strategy (BEIS) published seven *Industrial Decarbonisation and Energy Efficiency Action Plans* that were jointly developed with industry, including one for the chemical industry [BEIS, 2017c]. This voluntary action plan also emphasised that meeting 2050 climate targets would require the chemical industry to implement more radical innovations such as CC(U)S and biomass (for energy and feedstock). The action plan also mentioned hydrogen, but this option did not (yet) figure prominently. The action plan also emphasised collaborations between policymakers and industry and the need for innovation, transformation, and leadership, including visions.

In 2019, the government increased its legal commitment to net-zero GHG emissions by 2050, which further enhanced policy interest in the industrial sector that accounted for 23% of UK emissions in 2019. In response to the COVID-induced recession, the government introduced its *Ten Point Plan for a Green Industrial Revolution* [HMG, 2020], which aimed to boost both the production and use of low-carbon hydrogen in industry, homes, and transport, and the deployment of CCUS in two industrial clusters by 2025 and four clusters by 2030. To support these technologies, it also introduced a £240 million Net Zero Hydrogen Fund, and a £1 billion CCUS Infrastructure Fund.

The 2021 *Industrial Decarbonisation Strategy* [HMG, 2021a] aims to reduce GHG emissions from energy intensive industries by "at least two thirds by 2035" (p. 8) and therefore further emphasises "key technologies" (p. 6) such as CCUS, hydrogen, and electrification, which can "accelerate the green transformation in industry" (p. 6). Moving further towards implementation, the subsequent *UK Hydrogen Strategy* [HMG, 2021b] and *Net Zero Strategy* [HMG, 2021c] introduced the £140 million Industrial Decarbonisation and Hydrogen Revenue Support scheme to accelerate hydrogen projects and industry adoption of carbon capture and storage. It also selected the Merseyside industrial cluster and the East Coast Cluster (which includes Teesside and Humberside) as potential first locations for CCS deployment in the mid-2020s. The Grangemouth cluster was selected as a reserve cluster. The government is currently negotiating specific technical, operational, and financial details with the two winning 'track-1' clusters for accessing the £1 billion CCUS Infrastructure Fund. Late 2021, the government also launched a track-1 phase-2 subsidy scheme for hydrogen and CO_2 capture projects for industrial plants.

Although policymakers thus increased decarbonisation pressure on energy-intensive industries, they also emphasised collaboration with industries and provided financial support and exemptions. Between 2013 and 2017, for instance, the government relieved energy costs for energy intensive industries with over £500 million, and in 2017 promised another £100/year million support by reducing their contribution to renewable electricity support schemes [BEIS, 2017b]. The 2017 *Clean Growth Strategy* [80] also intended to lower energy costs for businesses to improve their international competitiveness, besides driving industrial decarbonisation.

4.5.3. Industry responses and strategies

In response to the diverging pressures, UK petrochemical companies enacted multiple, partly contradicting strategies. In terms of economic positioning strategies, INEOS and SABIC further diversified towards cheap US ethane gas, which resonates with phase 4 in the analytical model. SABIC completed the first phase of its Teesside Gas Cracking Project in 2017, which involved technical modifications in the Olefin 6 cracker to allow it to process ethane, the building of an ethane terminal at its North Tees site, and the commissioning of two gas-carrier ships [NEPIC, 2017]. The second phase, which was scheduled to start in 2019/20, was halted when SABIC mothballed the cracker in October 2020 in response to the COVID-induced recession and closed several older operating assets in Teesside [Barnard, 2020]. In 2020, Saudi Aramco, one of the world's largest oil companies, also completed its acquisition of a 70% majority stake in SABIC, which thus represents stronger integration between oil and petrochemical industries.

In terms of economic positioning strategies, INEOS also moved upstream into fossil fuel production. In 2014, it created an Upstream business division, which by 2017 held 36 licenses for exploring shale gas deposits, making it the largest UK shale explorer in terms of acreage [Ratcliffe & Heath, 2018]. INEOS's fracking strategy was hampered by protests from local communities and environmental groups, and the introduction of a moratorium by the Scottish government in 2015, followed by a ban in 2017 [Mah, 2021]. In 2019, the UK government also placed a moratorium on fracking, because of ongoing protests, legal challenges, and local planning rejections.

In 2017, INEOS also moved into conventional fossil fuels, acquiring the four decade-old Forties pipeline system from BP for £200 million, as part of a strategic bet that new technologies for exploiting ageing fields would extend the life of North Sea oil and gas fields [Dickie, 2019]. Later in 2017, it also bought the entire North Sea exploration and production business from DONG[7] Energy for $1.05 billion, which "redefined INEOS as a chemicals and energy giant in equal measure" [Ratcliffe & Heath, 2018: 241]. In 2019, INEOS said it would invest £500m in upgrading the Forties Pipeline System, which links about 85 oil and gas field to Scotland and Grangemouth, to "ensure it operates into the 2040s" [Dickie, 2021]. This upstream integration strategy further deepened the firm's fossil fuel commitments and lock-ins [Jervis, 2017].

In 2019, INEOS also announced a £350 million investment to replace one of its two Grangemouth power stations with a new state-of-the-art steam and power plant with higher energy efficiency. In 2020, INEOS bought BP's remaining aromatics and acetyls operations across 14 facilities around the world, including in Humberside, for $5 billion [Raval & Pooler, 2020]. This represented a doubling down on plastics, despite

[7] DONG stands for Danish Oil and Natural Gas.

high-profile campaigns against plastic waste. Later that year, Petroineos closed two oil refining units in Grangemouth, halving its capacity in response to reduced demand.

With regard to climate change, petrochemical industry actors both defended the existing industry regime and started exploring low-carbon alternatives, which resonates with phase 3 of the analytical model. On the one hand, the industry's framing strategies acknowledge that climate change is an important issue that requires a response. For instance, SABIC's annual Sustainability Reports, which the company published since 2011, show a steep increase in attention for climate change and plastic waste since 2017[8] (Figure 19), followed by statements that express positive intentions[9] and mention projects on recycling, bio-feedstocks, energy efficiency, and low-carbon technologies (without clearly indicating the amount of resource allocation though).

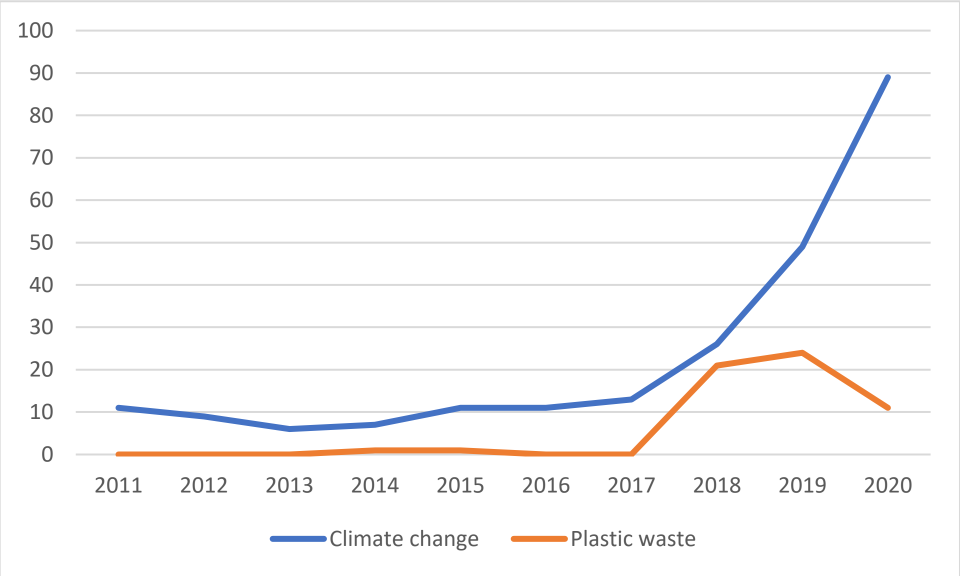

Figure 19: Number of times the words 'climate change' and 'plastic waste' appear in SABIC's annual Sustainability Reports, 2011-2020 (reports available at https://www.sabic.com/en/sustainability)

Even INEOS, which has been a laggard in low-carbon transitions [Mah, 2021], piously states in its first 2020 Sustainability Report (p. 4) that the company has "put in place roadmaps to lead the transition to a net zero economy in our industry by no later than 2050", is "investing in new products and technologies to drive the industry to a circular economy", and "is part of the solution to the challenges the world faces". Singing from the same hymn sheet, industry associations [Chemistry Council, 2018[10]; CIA, 2020a; 2020b] repeat this: 'being part of the solution' framing, which suggests that the industry is already working on low-carbon transitions, which precludes the need for regulations.

On the other hand, industry actors also increased their corporate political strategies to resist and delay low-carbon transitions. As one of the largest and politically well-connected chemical firms, INEOS was particularly combative, using a range of direct and indirect strategies, including synchronised political

[8] Attention for plastic waste decreased in 2020, because the COVID-19 pandemic gave plastics a somewhat more positive framing because of its role in protective materials.

[9] SABIC's 2020 sustainability report, for instance, says that: "At SABIC, we recognize that our success increasingly depends on taking ambitious action on issues like climate change, on embracing the promise of the circular economy, and on integrating environmental, social and governance (ESG) principles into every aspect of our business".

[10] The Chemistry Council is the successor of the Chemistry Growth Partnership since 2018.

messaging with the Chemical Industries Association, which INEOS director Tom Crotty presided over since 2017.

- Industry actors used information strategies to hamper climate policymaking. INEOS, for instance, has underreported CO_2 emission information since 2016 [Edwards, 2021]. More generally, the editors of the *Oil & Gas Journal* (2015; volume 113, number 7) explained that they had to discontinue their survey series of international steam crackers because "heightened government regulations and policies have discouraged voluntary response from some global operators, which have expressed concerns that disclosure of detailed capacity data could attract greater scrutiny to their operations from government regulators".
- Industry actors warned that low-carbon transitions would increase costs and lower the industry's competitiveness [CIA, 2019]. INEOS's Annual Reports from 2011 to 2020, for instance, emphasise the 'additional cost' framing, repeating the same sentence in all reports: "Existing and proposed regulations to address climate change by limiting greenhouse gas emissions may cause us to incur significant additional operating and capital expenses". INEOS also lambasted the European Commission for green policies that increased energy costs and reduced the bloc's competitiveness [Pooler, 2019]. Some industry reports even threatened that high transition costs might lead to "offshoring" [CIA, 2020b].
- INEOS actively lobbied for shale gas, threatening in 2014 that it might have to close factories without fracking in the UK [Macalister & Carrington, 2014]. INEOS also used legal strategies, seeking a court injunction against anti-fracking protest activities [Ward, 2017] and challenging the Scottish moratorium decision in court; it lost that case in 2018 [Mah, 2021]. INEOS also attacked the English government's 2019 moratorium [Thomas, 2021]. In 2022, INEOS renewed its push for UK shale gas, threatening that high gas prices might force the company to move production to America [Dempsey, 2022].
- INEOS led (successful) political lobbying activities for financial support and (green) tax exemptions [Vaughan, 2017], while successive industry association reports [CIA, 2015; 2019; 2020a; 2020b] complained about high energy prices and the need for more policy support.

In terms of innovation strategies, petrochemical companies are working on low-carbon technologies that focus on fuel inputs like hydrogen or post-combustion add-ons like CCS [CIA, 2018; 2020a; 2020b], but pay less attention to low-carbon innovations that require deeper operational changes like feedstock decarbonisation and recycling. Incongruencies with economic positioning and political strategies raise doubts, however, about the seriousness of their commitments to low-carbon innovation.

In 2019, SABIC and five other petrochemical companies (BASF, Borealis, BP, Total, LyondellBasell) created the international Cracker of the Future Consortium to investigate and develop steam crackers that use renewable electricity for heating instead of fossil fuel [Jasi, 2019]). The consortium aims to have a pilot low-carbon cracker operational by 2030, and to achieve widespread commercial production by 2050. After prolonged talks with UK ministers about financial sweeteners [Lynch, 2021], SABIC also announced in November 2021 that it planned to re-open its Teesside cracker and invest £850 million in low-carbon conversions [Jasi, 2021]. In the first phase, these conversions aim to reduce the plant's carbon footprint by about 60%. In the second phase, hydrogen will be *considered* as a carbon-neutral fuel source.

In 2021, INEOS announced a net-zero roadmap for its Grangemouth site, which aims to reduce CO_2 emissions with 60% by 2030 and reach net-zero by 2045. The roadmap mentions well-known technologies (like the efficient new energy plant, to be completed in 2023, electrification of key equipment, and incremental optimisations) and radical innovations such as "a move to the production and use of hydrogen by all businesses at the Grangemouth site accompanied by carbon capture and storage of at least 1 million tonnes per annum of CO_2 by 2030" [INEOS 2021]. Their commitment to this roadmap remains unclear, however, because of ambiguities about how much different technologies are expected to contribute to emission reductions and how the promised £1 billion investments (additional to the energy plant) will be spend over time and on which technologies.

As part of their net-zero plans, INEOS joined the Scottish 'Acorn' CCS project, which could repurpose existing onshore and offshore gas pipelines to transport CO_2 from Grangemouth to St Fergus gas terminal and from there to North Sea storage sites (Figure 20). In a potential second stage, the St Fergus terminal could also process natural gas into 'blue' hydrogen (using the same CCS infrastructure) and distribute that to Grangemouth and into the wider gas network (https://theacornproject.uk/; accessed 10 November 2021). The Acorn project was not selected in the first round of the government's CCUS Infrastructure Fund in October 2021. Although this creates major uncertainties about INEOS's hydrogen and CCS plans, the company nevertheless said it would continue with its zero-carbon plans [Nutt, 2021]. INEOS did not, however, submit any proposals to the government's track-1 phase-2 subsidy scheme for hydrogen and CO_2 capture projects, which it could feasibly deploy on its Humberside assets as part of the selected Zero-Carbon Humber cluster.

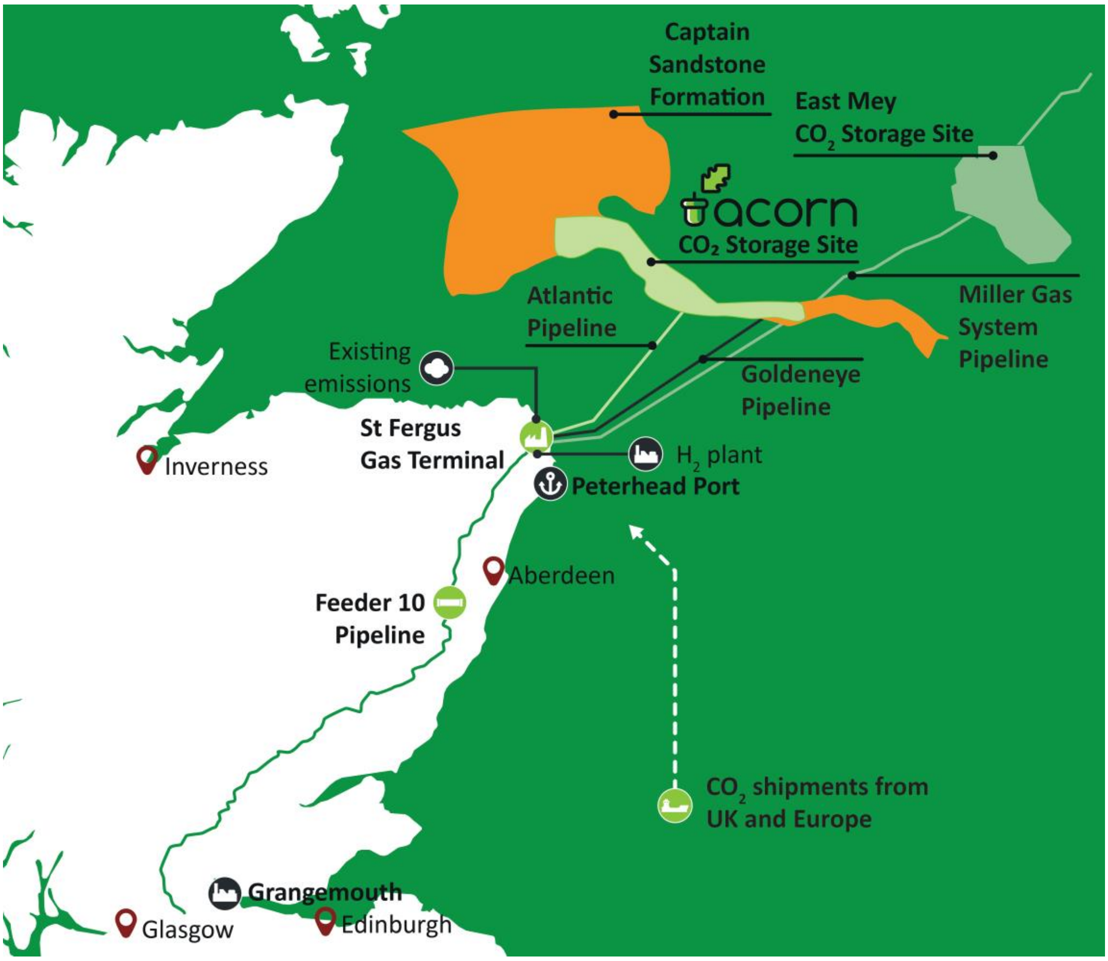

Figure 20 Schematic representation of the Acorn CCS project linking Grangemouth, St Fergus gas terminal, and North Sea storage sites (from: https://theacornproject.uk/; accessed 10 November 2021)

The Net Zero Teesside (NZT) initiative (https://www.netzeroteesside.co.uk/), which is part of the East Coast Cluster project that was selected in the first round of the CCUS Infrastructure Fund, aims to build a pipeline infrastructure that would collect CO_2 from multiple companies in Teesside and transport this to offshore sequestration sites. Although petrochemical companies led the Teesside Collective's CCS plans in the mid-2010s (discussed in section 4.3), they play a much more limited role in NZT. Only a few chemical companies (e.g., CF Fertilisers, BOC) have signed Memorandums of Understanding with NZT, with CF Fertilisers also submitting a proposal to the government's track-1 phase-2 subsidy scheme for CO_2 capture projects. Other chemical firms including SABIC did not show formal interest or submit a track-1 phase-2 project proposal.

4.6. Analysis and pattern matching

The longitudinal case study answered the first research question by describing the co-evolution of UK petrochemical company strategies and changing economic and socio-political environments in the last half century. To assess deeper patterns in this co-evolution process, I compare the empirical periods with the conceptual phase-model, discussed in section 2, which suggests that industry reorientation progresses through five phases if issue-related external pressures continue to increase: 1) inaction due to misinterpretation or denial, 2) incremental change, 3) hedging and exploration of alternative technologies, 4) diversification to new technologies, while continuing to operate existing assets (and business model), 5) full reorientation to new technologies, possibly complemented by changes in mission, identity, and mindset.

Confronting this conceptual phase-model with the empirical periods, I conclude that the UK petrochemical industry experienced two parallel reorientation processes in relation to two different issues. The first is a long-term reorientation process, which started in the 1970s and continues today, in response to economic competitiveness problems. The second is a low-carbon reorientation process, which started in the 2010s, in response to increasing climate mitigation pressures. Table 7 provides a schematic summary of the different periods and their relation to conceptual phases, which is elaborated below.

	External pressures	**Responses strategies**	**Reorientation phase**
1970s	- slowing demand and higher oil prices, which increased input costs	- changes perceived as temporary - firms continued building new plants, creating overcapacity	phase 1: misperceptions of changes lead to inaction
1980s	- depressed markets, high oil prices, increasing international competition - limited political support - increasing public concerns about chemical pollution and accidents	- financial losses led to cost-cutting strategies - shift to North Sea oil and gas inputs - attempted diversification from bulk to speciality chemicals	phase 2 of economic reorientation: retrenchment and incremental technical changes
1990-2008	- stronger international competition worsens	- low profitability and competitiveness problems	Phase 5 of economic reorientation: change in

	European overcapacity problems - stronger socio-political concerns about sustainability and climate change	- fundamental restructuring - incumbent firms withdrew, selling assets to new entrants - adopted voluntary environmental standards to pacify publics and prevent legislation	mindsets and management styles due to take-overs and venture capitalist approaches (e.g., relentless cost-cutting and reorganisation)
2008-2017	- financial crisis and recession reduce demand - US shale gas revolution increases international competition - strengthening climate policy (but limited industry focus)	- cost-cutting, mothballing - ethane imports from US (and adjusting steam crackers) - created industry associations to protect interests - political lobbying (for financial support) and framing strategies (to delay climate policies) - energy efficiency	- phase 2 (retrenchment) and phase 4 (technological diversification) for economic reorientation - phase 1 and 2 for low-carbon reorientation: move from inaction to problem acknowledgement and incremental change
2017-2021	- slowing demand, rising energy prices, international competition - COVID-19 shock - stronger industrial decarbonisation policies	- upstream fossil fuel integration (ethane, shale gas, oil) - increased political lobbying and framing strategies to delay low-carbon transition - articulate visions and explore CCS, hydrogen and electric furnaces, but limit investments	- phase 4 for economic reorientation: diversification - phase 3 for low-carbon reorientation: explore alternatives

Table 7: Summary of pressures and responses in different periods, and their relation to conceptual phases

Table 5 shows that the competitiveness-oriented reorientation process went through the conceptual phases in a non-sequential fashion which included returns to previous phases. The 1970s period aligns with conceptual phase 1, as petrochemical firms misinterpreted the economic problems as temporary (related to oil crises) rather than structural (related to weaker demand growth and over-capacity) and thus continued on their expansion trajectory.

The 1980s period aligns with phase 2, as companies recognised the economic problems and made incremental change in business operations (e.g., cost-cutting, flexible labour arrangements, tighter management controls, automation) to reduce costs in response to lower profits and increased foreign competition.

The 1990-2008 period aligns with important elements of phase 5, because the exit of incumbent firms (ICI, Shell, BP) and the entry of new companies led to a change in industry mindsets, norms, and management styles, with INEOS in particular using venture capitalist approaches such as buying struggling plants and restructuring them through cost-cutting and removing management layers. This period did not see reorientation to new technologies, however, and in that sense does not resonate with phase 5 predictions. This mismatch will be discussed in section 5.3 below.

The 2008-2017 period aligns with phase 2 for the immediate post-financial crisis years, when firms focused on survival through retrenchment, cost-cutting, and mothballing, and with important elements of phase 4 from 2013 onwards, when firms diversified to ethane imports from the United States to lower feedstock costs and attempted to move into upstream fossil fuels production (UK shale gas). This technological diversification strategy could skip phase 3 (exploration of new knowledge base), because it mostly involved (substantial) *economic* repositioning that did not require radically new technical knowledge. The 2017-2021 period also aligns with phase 4, as firms expanded the use of imported ethane and moved into North Sea oil production (INEOS) or strengthened links with oil companies (SABIC).

The UK petrochemical industry has also started to reorient in low-carbon directions, but this process is more recent and more tentative. The 2008-2017 period aligns with phase 1 and 2, in which firms first tried to keep the petrochemical industry out of climate mitigation debates and then emphasized that they are already implementing (incremental) energy efficiency innovations so that no regulations are needed. The 2017-2021 period resonates with phase 3, as firms started to explore more radical low-carbon technologies such as CCS, hydrogen, and electric furnaces through long-term visions and R&D projects.

Although both industry reorientation processes are presently unfolding in parallel, the competitiveness-oriented process is deeper and more long-standing than the low-carbon process. It has received more strategic attention, commitment, and investment from petrochemical firms, and has led to some industry regime changes (e.g., in mindsets and management styles) and technological diversification. This finding underlines the importance of making longitudinal analyses that not only focus on post-1990 developments but also place these in longer-term contexts, which in this case involved going back to the post-war decades.

4.7. Conclusions

The UK petrochemical industry reduced its GHG emissions by 88% between 1990 and 2019. Although impressive, this reduction did not result from an industrial low-carbon reorientation process but was mostly caused by abatement equipment installation on two plants in the late 1990s, which substantially reduced N_2O and HCFC-22 emissions. Although CO_2 emissions from fuel combustion also gradually decreased since the late 1990s, this was mainly due to incremental changes (such as energy efficiency improvements and some fuel switching) and plant closures, which were both driven by economic considerations.

The paper's analysis showed that the UK petrochemical industry has since 2017 engaged more with climate mitigation than in the preceding period (2008-2017). In terms of the conceptual phase-model, firms have moved from inaction (phase 1) and incremental change (phase 2) towards the exploration of more radical low-carbon technical alternatives (phase 3), especially CCS, hydrogen, and electric furnaces. However, the analysis also showed that their low-carbon reorientation is *tentative* and *reluctant*, because firms are delaying large financial commitments to low-carbon deployment in the present and are actively lobbying against green policies and try to hamper and slow down low-carbon transitions. The analysis also showed that the industry's main trajectory is oriented towards deeper fossil fuel commitments through investments in ethane imports, North Sea oil production, and oil pipeline upgrades. These commitments are deeper and more substantial than the industry's low-carbon reorientation as expressed through R&D projects and long-term future visions.

The industry's low-carbon reorientation is also *partial* because current exploration activities selectively engage with the four decarbonisation pathways, described in the introduction. These activities primarily focus on CCS, hydrogen-as-fuel, and electric furnaces, which relate to changing *fuel inputs* and capturing emission *outputs*. They pay much less attention to (mechanical and chemical) recycling, bio-feedstocks, and synthetic feedstocks, which are less developed and would require deeper changes in operational processes and plants.

One explanation of the industry's reluctant, slow, and partial engagement with low-carbon reorientation is that recent upstream integrations into fossil fuels created new interests, which firms try to protect. Another explanation is that firms are simultaneously engaged in a parallel reorientation process, which aims to address persistent competitiveness problems. This economic reorientation process started in the 1970s and is more salient for companies than the low-carbon reorientation, leading to two kinds of conflicts. First, the recent investments in ethane imports and North Sea oil aim to improve the industry's competitiveness but point in high-carbon rather than low-carbon directions. Second, firms perceive investments in low-carbon innovations as hampering their competitiveness, which is why they have so far focused more on future visions and technical exploration than on real-world deployment, which would require substantial financial resources.

These conclusions reinforce the importance of making longitudinal and multi-dimensional analyses of company strategies and contexts in order to understand their commitment to low-carbon reorientation. Investigations that only look at current low-carbon activities are likely to miss the industry's deeper trajectories and strategic considerations, which may lead to over-optimistic assessments of their commitments.

The article's findings resonate with other studies of low-carbon reorientation in upstream industries like oil refining [Nurdiawati & Urban, 2022] or shipping [Stalmokaite & Hassler, 2020], which also found that incumbent firms are beginning to move from implementing incremental innovations (phase 2) towards exploring more radical innovations (phase 3) but have not yet committed to wider deployment of the latter (phase 4) because of high cost, technical uncertainties, and broader competitive pressures. While the shift from phase 3 to phase 4 thus appears challenging for many upstream industries, the petrochemical industry arguably has greater economic and political power that enables it to deploy political resistance strategies to a greater extent.

Future low-carbon developments of the UK petrochemical industry will strongly depend on industrial decarbonisation policies, particularly with regard to CCS and blue hydrogen in industrial clusters which the government has been pushing in recent years. Two industrial clusters are currently negotiating CCS infrastructure implementation details, while 41 projects for hydrogen and CO_2 capture have been submitted in relation to these two clusters.[11] If these clusters will indeed be developed and deployed by 2027, which

[11] https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc#industrial-carbon-capture-icc.

is not guaranteed, petrochemical companies in these clusters may align with them, which would facilitate a deeper low-carbon reorientation pathway that suits their interests. SABIC and INEOS have, so far, shown limited interest in this alignment, but this may change in the coming years if these low-carbon clusters materialise, and policymakers introduce attractive incentives (or stronger regulations) for companies to join.

5. Steel industry

5.1. Brief description of industry specifics

Global steelmaking is the principal industrial consumer of coal [IEA, 2021b] and the largest industrial CO_2 emitter, responsible for 7% of carbon emissions from the entire global energy system, generating 2.6 GtCO_2 annually [IEA, 2020]. Global steelmaking has grown rapidly in the past twenty years, driven by steel demand in construction, automotive, mechanical equipment, and packaging, especially in developing and industrialising countries. China has emerged as the dominant steel producer, manufacturing 53% of the world's crude steel in 2021 (Figure 22). The steel industry's importance for climate change is likely to increase in the coming decades, as global output is forecast to grow by a further 30% by 2050 [IEA, 2020].

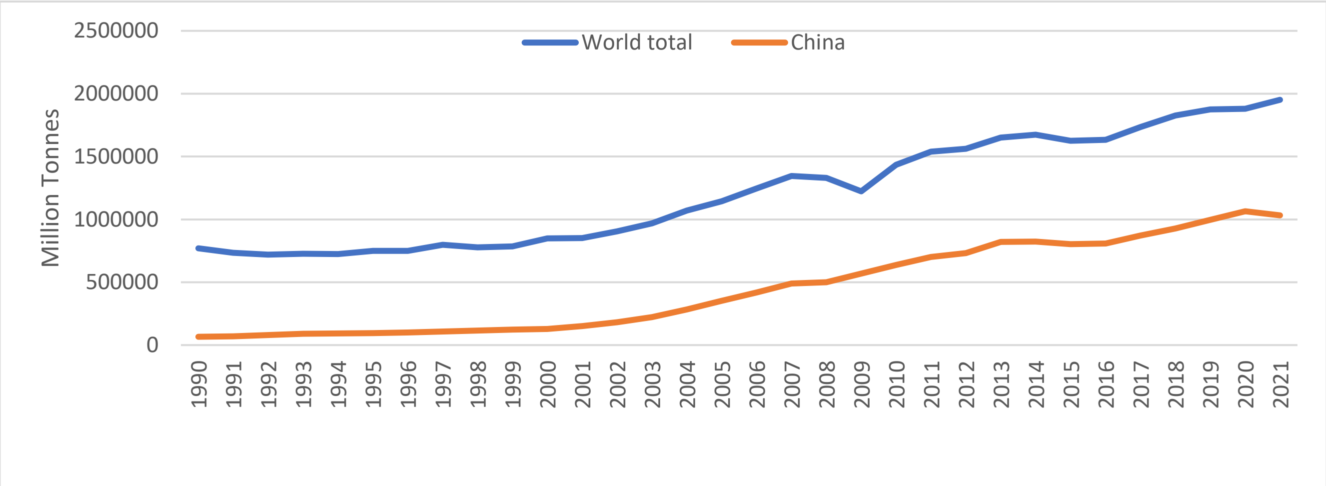

Figure 22. Global production of crude steel in million tonnes (data from the Steel Statistical Yearbooks from the World Steel Association)

The steel industry has long been characterised as 'hard to decarbonise' because *primary steelmaking* is very capital intensive and deeply locked-in to using carbon-intensive, technologies in its three main production stages (Figure 23), generating high levels of CO_2 emissions. The first stage involves the preparation of coal and iron-ore feedstocks through coking and sintering. The second stage entails ironmaking in a blast furnace, using the prepared coal as a heat source to smelt iron-ore and as a chemical reductant to extract iron (Fe) from iron-ore (Fe_2O_3). This step produces molten pig-iron (hot-metal) and substantial amounts of CO_2. This hot metal contains excess carbon levels, making the metal brittle when cooled. Consequentially, there is a third (steelmaking) stage that uses a basic oxygen furnace (BOF) to force oxygen through the molten iron, under pressure, to bind with and remove excess carbon, converting the hot metal into usable steel and producing further CO_2 [Griffin & Hammond, 2019; Griffin & Hammond, 2021; Pei et al, 2020]. To reduce heat loss and simplify handling processes, the three stages of primary steelmaking are usually combined in large-scale 'integrated steelworks', which are among the largest investments found on any single site, making primary steelmaking very capital intensive and difficult to change.

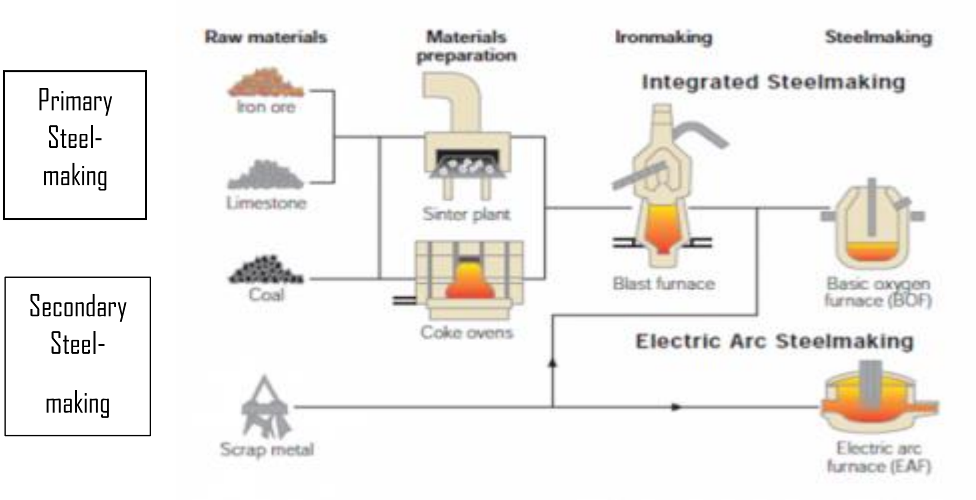

Figure 23. Illustration of the primary and secondary steelmaking processes (substantially adapted from [Griffin & Hammond, 2019])

A smaller but substantial amount of steel is produced through *secondary steelmaking* (Figure 23), which processes recycled scrap steel in an electric arc furnace (EAF) [Griffin & Hammond, 2019; Griffin & Hammond, 2021; Pei et al, 2020]. EAF technologies, which have been used on an industrial scale since the 1920s, produce heat with externally controlled electrodes that permit better heat control over molten metal than the BOF process, enabling superior alloy crafting for more valuable finished steel. However, it is not an effective method for removing oxygen and therefore not suitable for primary iron-ore processing [Allwood et al, 2019]. EAFs operate on smaller scales than integrated steelworks and generate few emissions.

The UK also has four electric arc furnace (EAF) steelmakers (Liberty Steel, Celsa Steel, Sheffield Forgemasters, Outokumpu), which have minimal direct CO_2 emissions and therefore receive less attention in our investigation. Their production has also decreased since 1988, with their percentage of UK steel production decreasing from 26% in 1988 to 18% in 2021 (Figure 24).

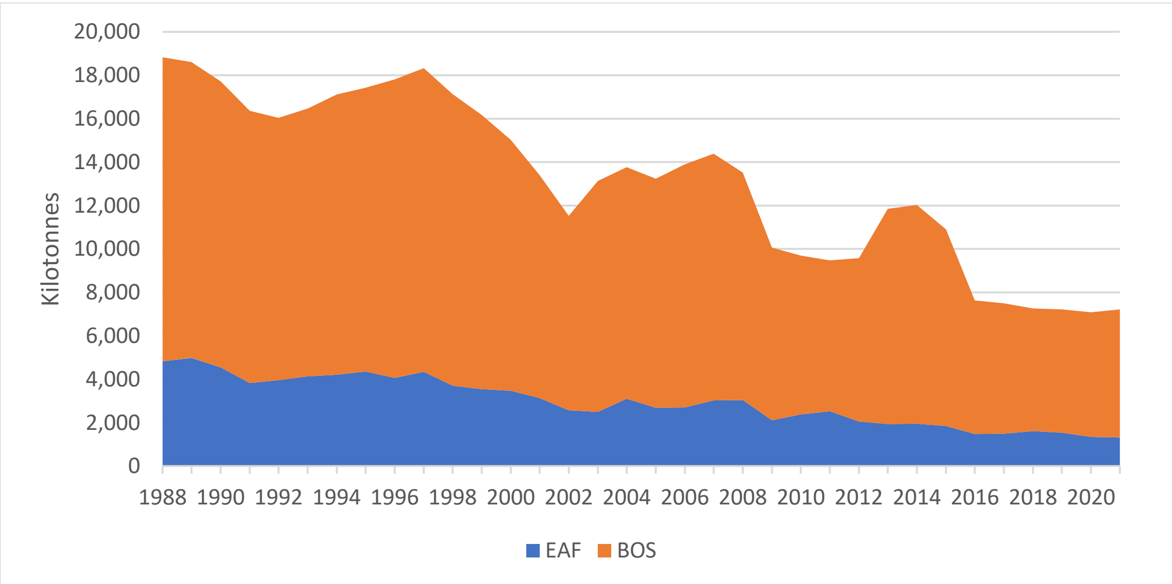

Figure 24: UK crude steel production by electric arc furnace (EAF) and basic oxygen steelmaking (BOS), 1988-2021 (constructed using purchased data from the International Steel Statistics Bureau (ISSB))

5.2. Predevelopments (1970-1988)

5.2.1. External pressures

After decades of expansion, the UK steelmaking industry started to decline in the early 1970s due to increasing external pressures. One economic pressure was declining domestic steel demand from traditional manufacturing industries such as shipbuilding, whitegoods, and car-making, which began to shrink due to foreign competition [Beauman, 1996; Blair, 1997]. Another economic pressure came from two oil price shocks (1973, 1979), which further weakened domestic and global demand for manufactured goods, and increased energy costs for the steel industry [Beauman, 1996; Blair, 1997].

5.2.2. Industry responses

Declining production and sales consequentially caused financial problems for the state-owned British Steel Corporation (BSC), which controlled most UK steelmaking assets. In response, the government helped the industry with £3.3bn in financial support between 1975/76 and 1979/80 [British steel, 1988]. BSC also restructured and repositioned itself between 1980 and 1985, which the government facilitated with further financial support of £4.5bn [British steel, 1988]. The restructuring involved a rationalisation of steelmaking locations, workforce reduction (Figure 8), and reduced labour costs. It also involved technological modernisation, notably more widespread use of continuous casting[12], which increased from 22% of liquid steel output in 1980 to 70% by 1988 [British steel, 1988].

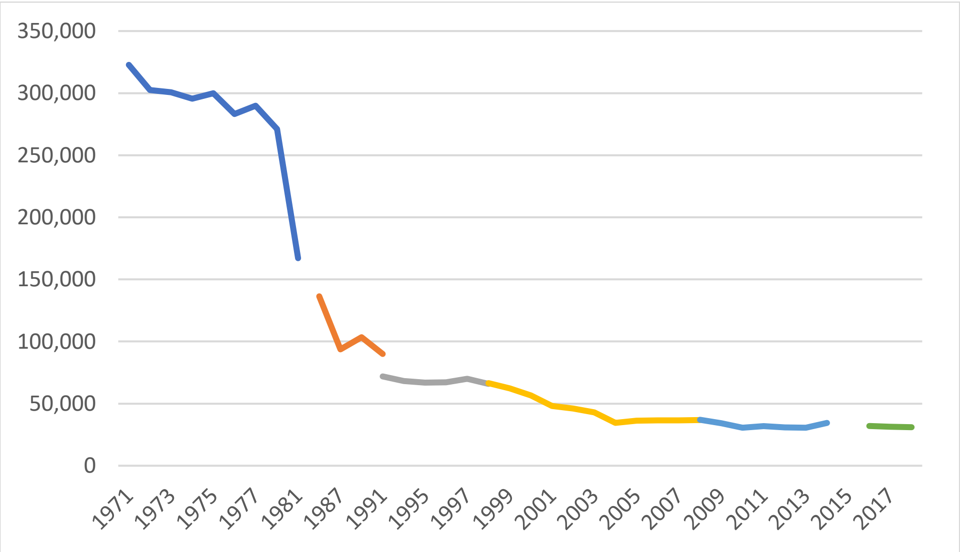

Figure 25: Number of employees in UK steelmaking, 1971-2018 (data from Census of Employment (1971-1991), the Annual Employment Survey (1991-1998), the Annual Business Inquiry (1998-2008); the Business Register and Employment Survey (2009-2014); and Ember UK Steel Production Dataset [26])

The repositioning delivered a 3-fold productivity increase and gave the BSC a leading position globally in their cost of steel-production [British Steel, 1988]. The BSC also benefitted from increased demand for domestic steel during the 1980s as UK industrial production recovered. When the BSC was privatised in 1988, it had become the second-largest liquid steel producer in Europe and the fourth largest producer

[12] Continuous casting allows molten metals/alloys to be shaped, stretched, and rapidly cooled directly from the furnace, enabling substantial cost savings in energy, time, and workforce. It also has the added benefit of producing steel products with a constant grain structure, which improves performance [Aylen, 1988].

in the non-communist world [British steel, 1988]. BSC made a healthy £419 million profit in the 1987-88 fiscal year, which was forecast to improve the following year [Blair, 1997].

5.3. Incremental strategies in response to variable external pressures (1988-1997)

5.3.1. Economic environment

The privatised UK steel industry (British Steel PLC) faced several economic pressures in this period, which varied for domestic and export markets (Figure 26). *Domestic markets* shrank in the early 1990s, due to a recession that reduced demand from UK manufacturing industries. Although domestic demand rebounded after 1992 (Figure 26), UK steel products also faced increasing pressure from foreign steel imports, as imported steel increasingly penetrated British Steel's domestic markets (Figure 27).

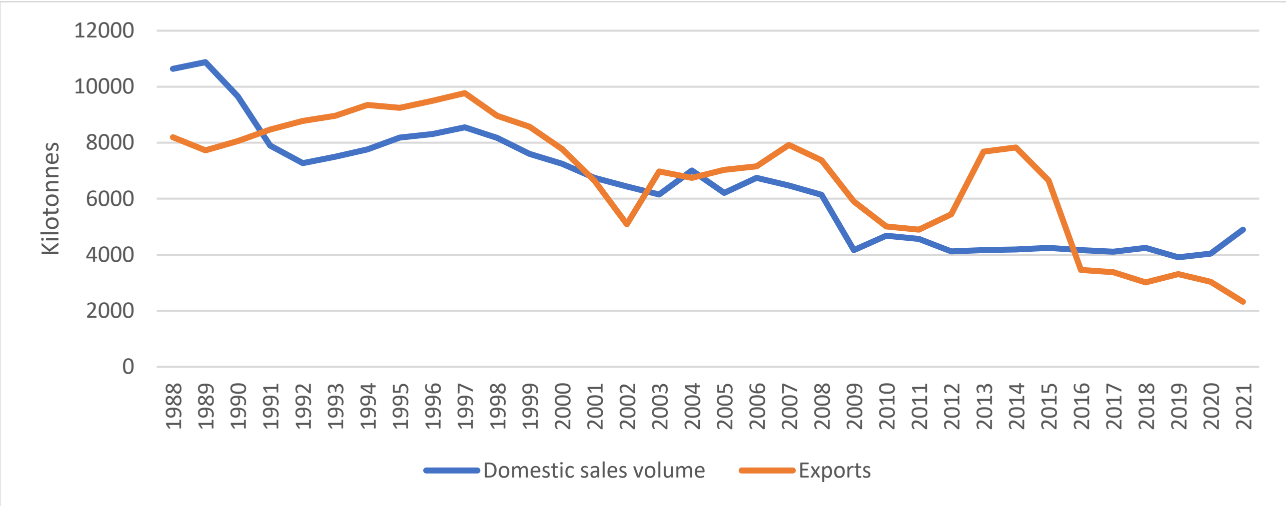

Figure 26. Sales volumes (in kilotonnes) for domestic and export markets of UK steel products, 1988-2021 (constructed using purchased data from ISSB)

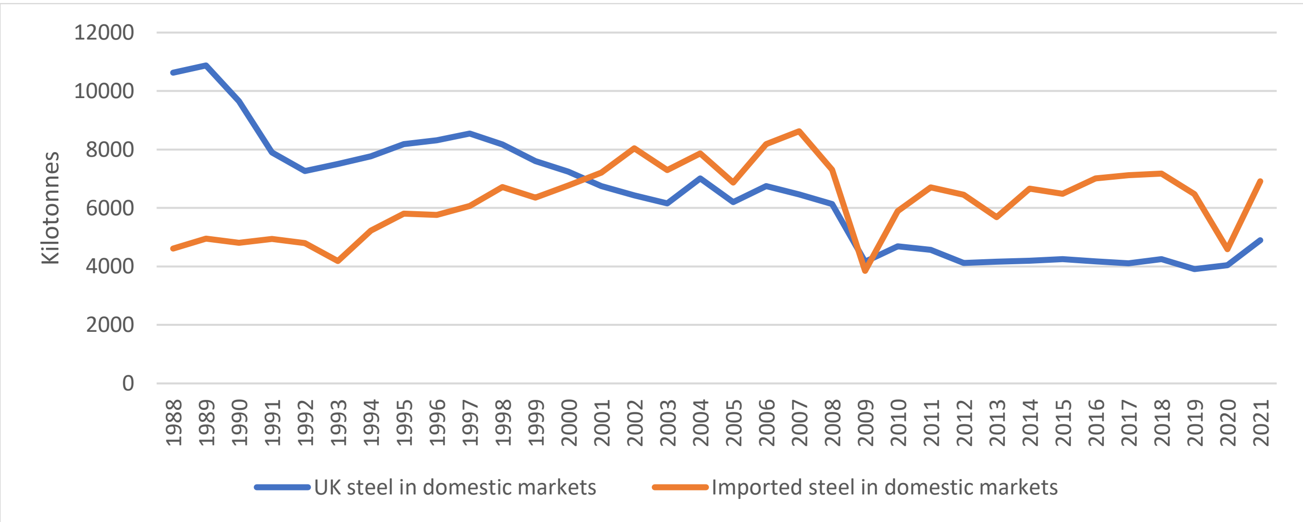

Figure 27. Sales volumes (in kilotonnes) of UK steel and imported steel in domestic markets, 1988-2021 (constructed using purchased data from ISSB)

This import substitution happened first in the market for 'flat steel', which is used in packaging and car-making. Japanese automakers, which opened UK plants in the 1990s, increasingly sourced cheaper flat steel from global markets [Van Os, 2005]. Other UK-based automakers followed, which gradually increased import substitution in the UK flat steel market. Similar dynamics unfolded in the packaging industry [Van

Os, 2005]. The Dutch steelmaker Koninklijke Hoogovens, which tailored its business model to global supply-chain consolidation, benefitted from these developments, becoming the second-largest steel supplier in the UK after British Steel [Van Os, 2005].

Although *export markets* for UK steel products increased until 1997 (Figure 9), international pressures increased in this period. One pressure stemmed from the UK government's opt-out from the European Union integration processes (further discussed below), which disadvantaged British Steel PLC competitively, because German steelmakers benefitted from reduced transaction costs in trade [British Steel, 1996; 1997; 1999]. Another pressure was the entry of new suppliers onto international steel markets after the collapse of the Soviet Union in 1991. The subsequent recession in that region reduced domestic steel demand, leading its steelmakers to focus on exports. Collectively, the former Soviet countries became the world's largest net exporters of steel, exporting around 50mt by the end of the 1990s [OECD, 2016].

5.3.2. Socio-political environment

One important socio-political development was the implementation of neo-liberal policies, first by the Thatcher government (1979-1990) and then by the Major government (1990-1997). These policies were unsympathetic to heavily unionised industries such as steelmaking [Aylen, 1988]. British Steel PLC thus received little policy support regarding increasing pressures in the economic environment [Blair, 1997].

Another important development was increasing political hostility towards the European Union. Since Thatcher's 'Bruges Speech' in 1988, the UK progressively disengaged from the EU's ongoing integration narrative, leading the UK to opt out of frameworks such as the *Schengen area* and the *Exchange Rate Mechanism*, which morphed into the *Monetary Union* in 1999. The disadvantages increased after the 1993 start of the 'Single Market', when the opt-outs increased transaction costs for the UK steel industry over its principal European competitors, notably the German steel industry [Blair, 1997].

A third development was the emergence of climate change on the UK political agenda. To reduce emissions and coal use, the UK government introduced the Fossil Fuel Levy on electricity companies in 1989, which increased electricity prices, impacting EAF steelmakers.

5.3.3. Industry responses

Economic pressures directly shaped the financial performance of British Steel PLC in this period (Figure 28). Profits increased in the immediate post-privatisation years as the momentum from the strategic repositioning carried through [Beauman, 1996; Blair, 1997] and steel demand grew. The 1991-1992 recession and decreasing domestic steel demand made the company loss-making, whilst growing domestic markets from 1992 and growing export markets from 1989 until 1997 improved profitability again.

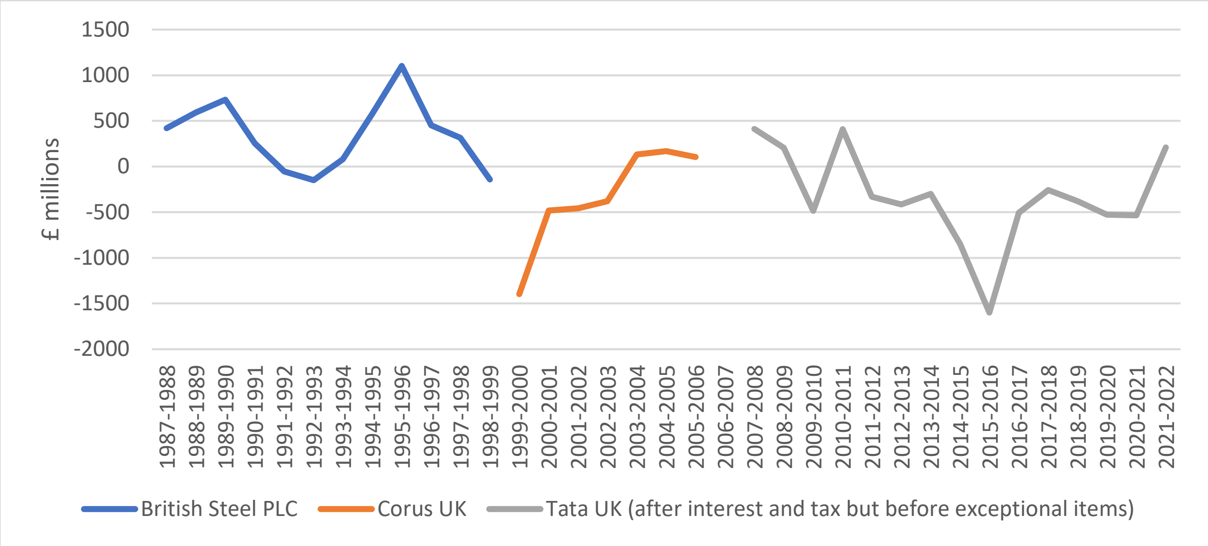

Figure 28. Annual consolidated financial earnings (in £ millions) before tax of successive owners of UK steel industry assets (constructed using annual report and accounts of British Steel PLC, Corus UK, Tata Steel UK)

British Steel responded to the financial performance problems through various incremental strategies, which resonates with phase-2 of the TEF model. Retrenchment was the first strategic response, leading to the closure of the struggling Ravenscraig integrated steelworks in 1992. Incremental technological improvements to enhance operating efficiencies was another strategy. In 1990, the company invested £70m to install a second continuous caster at Port Talbot [British Steel, 1990]. It also installed a second continuous caster at Llanwern in 1995, which increased capacity from two to three million tonnes per-annum [British Steel, 1995]. And it invested in a new bloom caster at Scunthorpe, whilst also rebuilding its blast furnace for £30m [British Steel. 1997]. In 1998, a new continuous annealing line was commissioned at Port Talbot, costing £121m [British Steel, 1999].

Thirdly, the company used economic positioning strategies to attempt international expansion. In the early 1990s, the company increased steel sales into Southeast Asia, benefiting from new markets in the 'tiger' economies, particularly from increased construction. This strategy terminated when the Asian market collapsed in 1997 [OECD, 2016].

Although climate change appeared on socio-political agendas in the early 1990s, the company never mentioned it in its annual reports until 1999 and took no action. This perception and inaction resonate with phase 1 in our conceptual model. The company did, however, complain throughout the 1990s that the Fossil Fuel Levy increased electricity costs and eroded its competitiveness [British Steel, 1993]. It also lobbied for it to be removed or for commercial effects to be mitigated [British Steel, 1993].

Its 1999 annual report finally acknowledged climate change but warned that climate levies would threaten jobs and were not needed because the industry was already reducing emissions through incremental improvements, which fits with phase 2 in our model: "For many years British Steel has led a major programme to improve progressively the energy efficiency of the UK steel industry. We lead the way with a 6% reduction in carbon dioxide emissions since 1990, already halfway to the Kyoto target. The application of an onerous levy or tax will effectively amount to a fine for making steel in the UK. It will place at risk thousands of jobs in the UK steel industry without reducing global carbon dioxide emissions" [British Steel, 1999: 1].

5.4. Economic repositioning to withstand increasing external pressures (1997-2007)

5.4.1. Economic environment

In this period, significant economic pressures reduced international sales of UK steel products by 48% between 1997 and 2002 (Figure 26). First, the 1997 Asian Financial crisis reduced steel demand from Southeast Asia [OECD, 2016]. The crisis also reduced local demand for steel products from Asian steelmakers, who had expanded capacity in previous years. These Asian steelmakers therefore re-focused on export markets, which combined with increasing exports from former Soviet Union countries contributed to the second pressure: increasing overcapacity in global steelmaking. This overcapacity increased international competition and reduced international steel prices[13] by 20% between 1997 and 2002 (Figure 26).

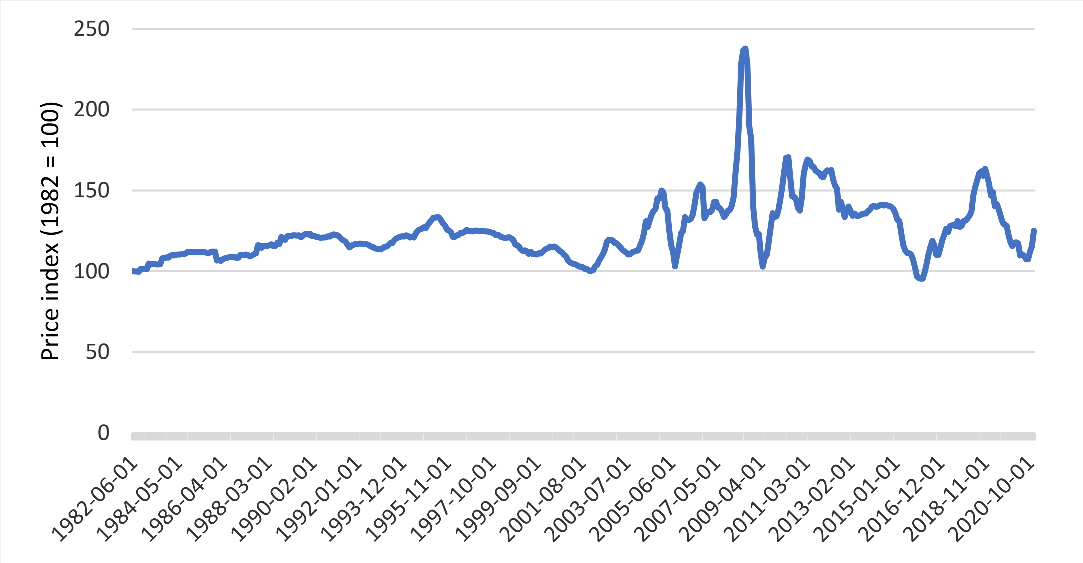

Figure 29: Price index of US hot rolled steel (1982=100), 1982-2020 (constructed using data from the Federal Reserve Economic Data; https://fred.stlouisfed.org)

A third pressure was that the Pound-Sterling strengthened by 36% between 1995 and 2000 against the Deutschmark and the Euro from 1999 [Wise et al, 2017], making UK steel products more expensive in Europe and reducing the competitiveness of the UK steel industry against Germany's in particular [TISC, 2001]. The introduction of the Euro also reduced transaction costs for German steel compared to its British competitors within mainland Europe.

Domestic sales also decreased in this period, falling by 28% between 1997 and 2003 (Figure 26). The main pressure was continued import substitution in UK domestic markets (Figure 27), where foreign steel increasingly replaced UK products. Not only automakers (discussed in 4.2.1.), but also construction companies and Railtrack (responsible for rail infrastructure) increasingly sourced cheaper international steel [TISC, 2001].[14]

[13] Although there is no single global steel price, the price for US hot rolled steel is often taken as global proxy.

[14] Railtrack later reversed this strategy, so that by 2013-14, 95% of UK rail-related steel was bought from Tata's UK operations [Tata Steel, 2014].

International conditions for the UK steel industry improved after 2002/3, as overcapacity problems eased, partly due to increasing steel demand from China's rapidly growing economy and the recovery of the Asian 'tiger' economies [Corus, 2003; 2006]. UK steel exports grew by almost 50% between 2002 and 2007 (Figure 27), while the international steel price also increased substantially (Figure 29).

5.4.2. Socio-political environment

Policymakers did little to protect UK steelmakers from economic pressures because the Labour government (1997-2010) mostly continued the neo-liberal stance from previous administrations [R23]. It did, however, further increase the political profile of climate change. In 2001, it introduced the Climate Change Levy (CCL), which was an environmental tax on energy use by businesses with the aim of improving energy efficiency. In 2001, the government also introduced Climate Change Agreements (CCA), which were voluntary agreements with sectors (including steelmaking) to mitigate the effects of the CCL on energy-intensive sectors like steel by enabling firms to receive a tax discount in return for achieving target energy efficiencies or emissions reductions. Furthermore, most of the tax was recycled back to the CCL-paying-industries through reductions in employer contributions to social security taxation. The CCL and CCA thus had limited effects on modifying behaviour of energy-intensive firms [NAO, 2007]. In 2003, the Blair government also introduced a target for a 60% GHG emission reduction, but this included nothing specific to the UK steel sector.

Climate change pressure also came from the European Emission Trading Scheme (ETS), which commenced in 2005 and applied to steelmaking, which was designated an energy-intensive industry. However, to prevent carbon leakage, existing steelmaking companies were granted free emission allocations for over a decade [Demailley & Quirion, 2008].

5.4.3. Industry responses

The various economic pressures caused large financial losses in the late 1990s and early 2000s (Figure 28). It was not until 2003 that financial performance became positive again, because of growing exports (Figure 26) and rising steel prices (Figure 27). In response to the financial problems, British Steel first reduced the workforce by 15% and outsourced its IT and data-management services, saving about £200m [British Steel, 1999]. In 1999, British Steel's management executed a drastic economic positioning strategy by merging with the Dutch steel company Koninklijke Hoogovens (KH) to acquire expertise from the latter's more successful business model. The merger created the Corus Group, which had a combined production of 24mt of liquid steel [Corus, 1999], making it the largest steel producer in Europe and the third largest in the world, with a diversified portfolio of carbon steel, engineering steel, stainless steel, and aluminium.

The repositioning strategy of the new company focused on three areas [Van Os, 2005; Corus, 1999] establish a superior global supply-chain solution for its clients by applying KH's successful global supply-chain business model to the combined group; 2) improve product R&D to better fulfil anticipated customer needs for lighter, stronger, and more durable metals; 3) further cost savings and better currency management. Implementation of this three-fold strategy encountered problems.

1) Corus-wide diffusion of the KH business model was to be executed by the Dutch management. When UK staff, trade unions and politicians learned that this was to involve substantial rationalisation of British-

based assets, the strategy became framed as a Dutch versus British action, which created push-back and resistance to its implementation [Van Os, 2005].

2) With regard to R&D and innovation capability, the merger also had negative effects for the UK steel industry. In 2000, Corus planned to combine its three UK R&D centres (in Port Talbot, Rotherham, and Teesside) into one site in Sheffield, leading to 250 job losses. This compared to only 30 R&D job losses in the IJmuiden Technology Centre [STSC, 2001], which further exacerbated Dutch versus British tensions in the company.

3) Cost savings were achieved by closing unproductive assets or selling plants to raise cash. In 2001, Corus announced a 3mt UK capacity reduction, with 7,000 jobs cuts, by closing Llanwern's integrated steelworks and the Ebbw Vale tinplate works [TISC, 2001, Corus, 2001]. The Avesta Sheffield stainless steel business was merged with Outokumpu Steel to create Avesta Polarit [Corus, 2002]. Corus also attempted to sell its aluminium assets, but this failed due to tensions and disagreements between Dutch shareholders and the management [Van Os, 2005].

These implementation problems and continuing financial losses led to a management crisis and appointment of a new CEO in 2003. His new economic positioning strategy, called *Restoring Success*, focused on core competencies in carbon steel and engineering steel (rather than a wider range of products). This strategy directed the Corus UK business to focus on just three sites (Rotherham, Port Talbot, Scunthorpe) and involved a significant investment in the engineering steels business at Rotherham, a focus on flat products at Port Talbot and on long products in Scunthorpe [Corus, 2003]. The underperforming Redcar steelworks was to be ringfenced and develop a stand-alone business plan with an export focus. The group's aluminium assets were to be sold. This repositioning and streamlining strategy helped to improve financial performance after 2003 (Figure 28).

With regard to climate change, Corus initially continued earlier political resistance strategies. But after 2003, the new CEO shifted the company towards more constructive engagement [R13, R14, R23] and framing strategies that acknowledged the problem and the need for the steel industry to be responsive: "Climate change is one of the most important issues facing the world today. Corus recognises that the steel and aluminium industries are significant contributors to man-made greenhouse gas emissions. (…) Increasing attention is being focused on developing products that have a better environmental profile or that have inherent environmental advantages" [Corus, 2006: 34].

Corus also adopted a more constructive political strategy, agreeing with the UK government that it would reduce its energy consumption by 14.7% by 2010, compared to 1997 levels [Corus, 2006]. Additionally, Corus oriented its innovation strategies towards more environmentally friendly steel. Respondents 1, 2, and 14 indicated that Corus contributed to the World Auto Steel ULSAB program (UltraLight Steel Auto Body), which through incremental improvements aimed to create a lighter, robust, safe, and affordable steel car body template.[15] And in 2004, Corus helped set up the European ULCOS program (Ultra Low CO_2 Steelmaking), which was a €35m steel industry-led initiative with academia to explore more radical innovations for reducing primary steelmaking CO_2 emissions by 50%.[16]

[15] https://worldautosteel.org/projects/ulsab/
[16] Ultra-Low CO2 steelmaking | ULCOS Project | Fact Sheet | FP6 | CORDIS | European Commission (europa.eu) (https://cordis.europa.eu/project/id/515960)

These strategies suggest that Corus was beginning to enter phase-3 of our conceptual model with regard to low-carbon reorientation, in which the company both defends the existing regime through incremental improvements and explores more radical innovations. The wider economic repositioning and streamlining strategy, however, mostly fits with phase-2 of our model because it builds on existing technical capabilities and focuses on downsizing and cost-savings.

In 2005, the company's board determined that Corus should look beyond Western Europe for a successful future [46] to compensate for anticipated future disadvantages of its European asset base. The board felt that Corus should be able to access its own iron-ore and operate in high-growth markets in Asia [46]. The board therefore decided to put Corus up for sale. After a competitive auction, in which Tata Steel of India and Companhia Siderúrgica Nacional (CSN) of Brazil made offers and counteroffers that drove up the price, Corus was bought by Tata Steel in 2007 for US$12bn [Tata Steel, 2007] or £6.7bn.

5.5. Major pressures trigger further retrenchment, hampering low-carbon reorientation (2007-2015)

5.5.1. Economic environment

The 2007/8 financial crisis was a major shock for the UK steel industry, causing substantial losses and a strategic focus on survival rather than low-carbon reorientation [R13, R14]. The crisis and subsequent recession caused a 36% decrease in *domestic* sales of UK steel products between 2007 and 2009 (Figure 9), because automakers, housebuilders, and packaging industries reduced their demand. When domestic markets increased again in the early 2010s, domestic sales remained at much-reduced levels because of continued pressure from import substitution, which absorbed the small domestic market growth (Figure 27).

The financial crisis also depressed *international* steel demand, causing a 38% decrease in export sales of UK steel products between 2007 and 2011 (Figure 26). Export sales rebounded between 2012-2014 as international steel demand increased again [OECD, 2016] but decreased by 48% between 2014 and 2016 due to the global steel crisis.

Further economic pressures came from seismic growth in Chinese steel production (Figure 22), which continued during the 2007/8 financial crisis, causing over-supply and a steep decrease in global steel prices in late 2008 and early 2009 (Figure 27), which reduced sales income.

Additional pressure came from rising input costs, especially for iron-ore (Figure 30) and metallurgical coal (Figure 31). After many years of relative stability, increasing Chinese demand caused both prices to escalate from 2005, peak in 2008 and in 2011, and remain elevated and volatile in subsequent years.[17] The escalation of iron-ore and coal prices in 2008 forced steel producers to increase steel prices, which peaked in mid-2008 but then decreased with the financial crisis and over-supply (Figure 27).

[17] The more detailed explanation is that increasing Chinese demand enabled producers to shift from annual benchmark price negotiations to a market-indexed pricing model for iron-ore [Wilson, 2012] and a quarterly price benchmark for metallurgical coal [Ozga-Blaschke, 2021], which allowed them to increase prices.

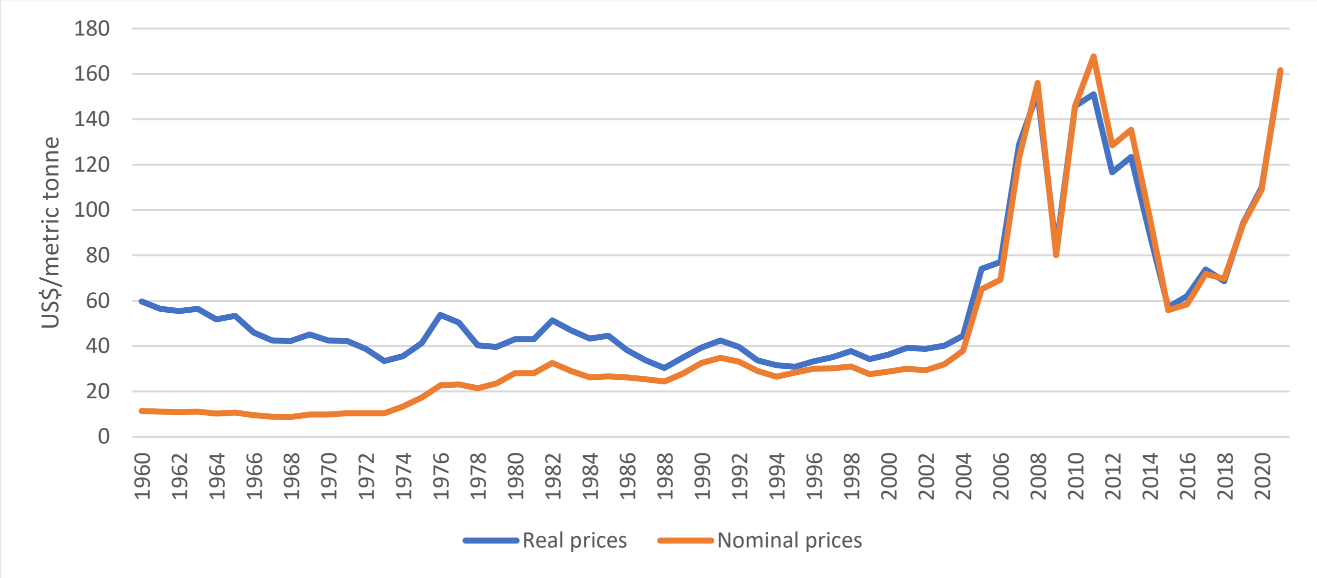

Figure 30: Iron-ore price (in US$/metric tonne), 1970-2021 (constructed using World Bank commodity markets data)

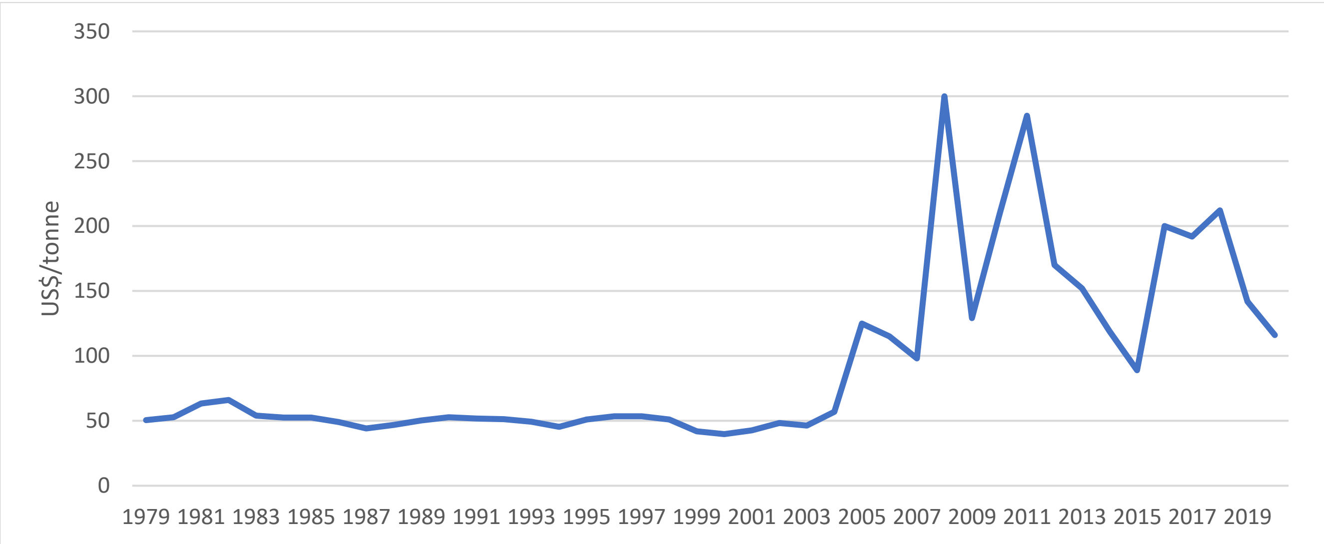

Figure 31: Annual benchmark metallurgical coal price (in US$/tonne) 1979-2020 (constructed using data from Coal Week International (Platts) and Coal Information (IEA) for 1980-1990, and International Coal Report (Platts) and Platts Coal Trader International for subsequent years)

5.5.2. Socio-political environment

UK policymakers offered little relief during and after the 2007/8 financial crisis, because steelmakers were not a priority. For instance, when Sahaviriya Steel Industries bought the mothballed Redcar steelworks from Tata Steel in 2011, it only received £1.2m in government support for the purchase [SSI, 2011].

Increasing public and political climate-oriented pressure culminated in the 2008 Climate Change Act, which set an ambitious GHG-reduction target of 80% by 2050. Subsequent climate change policies, however, focused mostly on electricity, mobility, and housing, so that domestic policy pressure on steelmakers remained limited. Policymakers did introduce a second round of Climate Change Agreements (2013-2023), which enabled firms to receive CCL reductions if they made sufficient energy efficiency improvements or lowered energy use. Although the second CCA scheme generally had more effect than the first CCA scheme, it had "less influence on firms that were very large/energy intensive" [BEIS, 2020b:

4] because firms like steelmakers were already trying to save energy for cost reduction reasons. Policymakers also reduced pressure on steelmakers in 2014 by introducing exemptions from the Climate Change Levy for certain metallurgical processes [TSE, 2014].

The European Emission Trading Scheme also exerted limited pressure because phase 2 (2008-2012) still allowed free emission permit allocations to existing steel companies, while phase 3 (2013-2020), which auctioned emission permits, included relief measures for steelmakers as a result of successful lobbying and rent-seeking strategies [Okereke & McDaniels, 2012].

5.5.3. Industry responses

Tata Steel's purchase of Corus in 2007 was part of a wider globalisation strategy of the Tata conglomerate, which embarked on an overseas shopping spree in the early 2000s [Parkin et al, 2020]. Tata Steel was willing to pay a relatively high price for Corus (£6.7bn), because it wanted to be a leader in the global steel industry's consolidation process, based on the assumption that global steel demand would continue to grow in subsequent years [Ahuja, 2012]. The 2007/8 financial crisis and subsequent economic pressures shattered this expectation and instead led to declining (domestic and export) sales and major financial problems. Tata Steel UK (TSUK) experienced cumulative losses of £3.6bn between 2009 and 2016 (Figure 28).

In response, TSUK embarked on relentless cost-cutting strategies and attempted asset sales, which resonates with phase-2 in our conceptual model. In 2010, TSUK mothballed the Redcar steelworks to adjust capacity to reduced demand and in 2011 sold it for US$469m to Sahaviriya Steel Industries (SSI) of Thailand. SSI reopened it to produce steel slabs for export to Thailand and invested US$1bn ($600m borrowed from Thai banks) to purchase the steelworks and upgrade its blast furnace [SSI, 2011].

Despite the retrenchment strategies, TSUK also invested in incremental asset upgrading and maintenance. In 2013, for instance, TSUK invested £250m in rebuilding blast furnace No 4 in Port Talbott and in energy efficiency enhancements, including a £55m energy-from-heat scheme [Tata Steel, 2013]. R&D budgets and capacity were reduced, however, first when Redcar was mothballed and sold to SSI [R13, R14], and then when 'long products' and 'speciality steel' businesses were divested in 2016 and 2017 [R13, R14].

Compared to the previous period, corporate actions on climate change decreased, because financial problems and survival strategies were the management's core focus, and because there was limited policy pressure for decarbonisation. This suggests that low-carbon reorientation shifted back to phase-2 of our conceptual phase-model. In its framing strategies, TSUK acknowledged climate change as an important issue and the steel industry as a significant contributor [TSE, 2014]. In 2013, TSUK even entered a new Climate Change Agreement to reduce their energy consumption by 7% by 2020, compared to 2008 [ibid], which was easy to meet because of reduced output. But R&D assets and staff working on decarbonisation was increasingly outsourced in response to shrinking budgets. The Teesside Technology Centre was transferred to the new Materials Processing Institute [TSE, 2015]. The Advanced Coatings Knowledge group, which did some work on low-carbon technologies, transferred to Warwick University [TSE, 2016]. And the Swindon Technology Centre, which also worked on low-carbon innovation, was shrunk, and then closed. According to R13 and R14, these transfers and closures substantially reduced TSUK's decarbonisation R&D capabilities.

5.6. Tentative low-carbon reorientation encountering headwinds (2015-2022)

5.6.1. Economic environment

Chinese steel production, which had been expanding since the early 2000s (Figure 22), contributed to the 2015 global steel crisis, which a significant external shock. The steel crisis was caused by slowing economic growth and reduced steel demand in China in 2014/15, which led Chinese steelmakers to dump surplus steel on global markets [Brun, 2016], causing massive over-supply and a 40% decrease in global steel prices in 2015 (Figure 29). Export sales of UK steel products fell by 56% between 2014 and 2016 (Figure 26), causing major problems including the demise of the Redcar steelworks.

After 2016, UK steel exports continued to decrease (Figure 26) due to declining international competitiveness, especially in Europe, which partly related to UK industrial electricity costs that were higher and increased faster than in European competitor countries (Figure 32). International competitiveness and exports were also hampered by the UK's 2016 Brexit decision, which increased trade frictions with the EU, which was the steel industry's biggest export market.

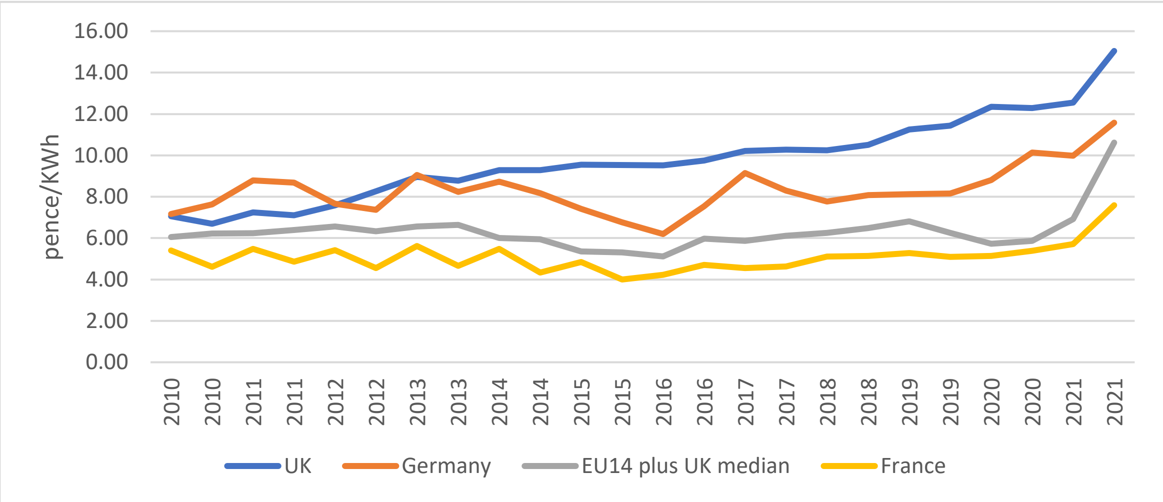

Figure 32: Industrial electricity prices in pence/KWh (for January and July of each year) in selected European countries for extra-large electricity consumers including taxes (excluding VAT and other recoverable taxes and levies) (constructed using data from [66])

In 2020, the COVID-induced lockdowns and economic recession created further major pressure on UK steelmakers, reducing both domestic and global steel demand. UK steel demand fell by 45% during the country's first Covid lockdown [HoC, 2021], but this mostly affected steel imports rather than domestic steel production (Figure 27). Declining international demand, however, further reduced UK export sales in 2020 and 2021 (Figure 26).

The Covid-pandemic also disrupted international trade and global steelmaking, which could not be restarted quickly when the economic recovery commenced in 2021 [OECD, 2022]. Returning demand and restocking therefore led to rapidly rising global steel prices (Figure 29). Potential windfall profits were not attainable, however, as prices of iron-ore (Figure 30), coal (Figure 31) and electricity (Figure 32) also increased in 2021 and 2022 [OECD, 2022].

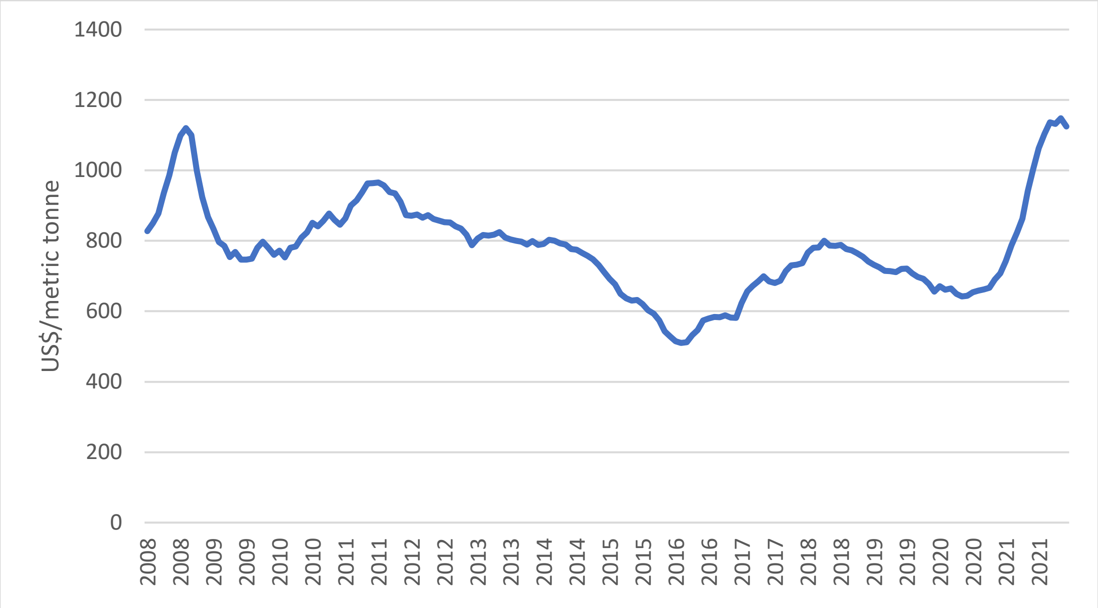

Figure 33: Global average steel price (in US$/metric tonne), derived from an average of 6 principal steel finished products, monthly fob export price (constructed using purchased data from steelonthenet.com)

5.6.2. Socio-political environment

Policymakers did not provide any assistance when the 2015 steel crisis caused major problems for the Redcar integrated steelworks. In fact, UK government actions initially prevented the introduction of European steel tariffs to counter Chinese steel dumping [Perraudin, 2016], which contributed to Redcar's collapse. One reason for the hands-off approach was that policymakers deemed Redcar unviable. Another reason was that financial support was likely to go to Thai banks who, by then, were owed US$790m [SSI, 2017].

Redcar's closure triggered many criticisms of the government's hands-off approach, which contributed to a change in orientation, as policymakers became more supportive of steelmakers [R02]. R23 explained that: "What's different now is that there's more discussion around, and more interest in, retaining the steel sector than there was seven years ago". In 2016, the government offered £80m redundancy support for Redcar employees, organised a steel summit to discuss supportive policy framework, and reversed its policy of blocking Chinese steel tariffs, leading to the introduction of EU tariffs of 73.7% in 2016 [Ruddick, 2016]. Steelmakers also received more help with energy costs, amounting to about £780m between 2013 and 2022 [Bryant, 2022]. Policymakers also supported steelmakers during the COVID-pandemic through the Coronavirus Job Retention Scheme, government-backed business loans, and *Project Birch*, a last-resort financing scheme for strategically important companies [HoC, 2021].

These support measures suggest that UK policymakers in this period shifted from a hands-off orientation towards a greater willingness to intervene. This change in approach arguably related not only related to the Redcar debacle but also to the 2016 Brexit decision, which led policymakers to perceive foundational industries (such as steel, chemicals, oil refining) as strategically important for the UK economy [Geels, 2022]. In 2017, this revised perception also led UK policymakers to reintroduce industrial policymaking.

Decarbonisation pressure also increased significantly in this period. In 2015, international policymakers adopted the Paris agreement and domestic policymakers published industrial decarbonisation roadmap exercises, including one for iron & steel [DECC, 2015b]. The 2017 *Clean Growth Strategy* emphasised the importance of radical innovations, stating that energy-intensive industries should move "beyond energy efficiency" and make steps towards fuel switching and the "deployment of new technologies, for example carbon capture, usage and storage" [HMG, 2017: 64]. Increasing public attention for climate change also stimulated the government to adopt economy-wide net-zero targets in 2019, which meant that 'hard-to-decarbonise' sectors like steel also had to reduce emissions. For steelmaking in particular, the Climate Change Committee recommended in 2020 that it should try to "reach near-zero emissions by 2035" [CCC, 2020: 53].

To help energy-intensive industries deploy low-carbon technologies, policymakers introduced the £289m *Industrial Energy Transformational Fund* in 2019, which provided grants to Celsa Steel and Sheffield Forgemasters [EAC, 2022a]. The 2021 *Industrial Decarbonisation Strategy* and 2021 *Net Zero Strategy* further developed plans for CCS deployment in two industrial clusters by 2025 and a £1bn *CCS Infrastructure Fund*. In October 2021, policymakers selected two industrial clusters as potential first CCS-locations, which included Humberside, where the Scunthorpe steelworks is located.

To support a low-carbon steel transition, BEIS in 2019 launched a call for evidence for a £250 million *Clean Steel Fund*. In 2021, the government also reconstituted the Steel Council to improve dialogue between BEIS, steelmakers, and unions on how best to decarbonise steelmaking [EAC, 2022a]. The Council met four times (in March 2021, May 2021, July 2021, and Feb 2022) to discuss 'near-zero' emission targets for ore-based steelmaking by 2035 (which the Climate Change Committee recommended), energy and low-carbon transition costs, and operational details of the *Clean Steel Fund* [EAC, 2022a]. As of June 2022, however, no decisions have been made about the size, timing, and specific focus of the Fund, because the government is awaiting more clarity on the industry's decarbonisation investment plans [EAC, 2022a].

The Parliamentary Environment Audit Committee (EAC) investigated *green steel* technologies in early 2022, concluding that "decarbonisation presents an opportunity for the UK steel industry" and that "this opportunity depends on the creation of the right policy framework and Government support" [EAC, 2022b]. Responding to the Minister's replies to their report, the EAC subsequently concluded that: "The Government's action to decarbonise the steel sector, does not yet meet its ambition. (…) Decarbonising steel production will be no easy feat. (…) the actions the Government is planning, all have long lead times. This is particularly true for the incorporation of hydrogen in production, and there are numerous carbon-intensive processes, such as the continued need for coking coal for certain steel products, where the Government needs to work actively with the sector to pick up the pace" [EAC, 2022c].

5.6.3. Industry responses

The 2015 global steel crisis led to the collapse of the SSI-owned Redcar integrated steelworks. TSUK responded to the crisis with further retrenchment, leading to the closure of the hot strip mill at Llanwern, and the plate mill and one of two coking works at Scunthorpe [64]. In 2016, TUSK announced 750 job-losses at Port Talbot steelworks and 300 at the steel mills in Trostre, Corby and Hartlepool. In 2016, Tata Steel Europe tried to sell its entire UK steel industry portfolio [Tata Steel, 2016], but it struggled to find a buyer and was persuaded by UK policymakers to stay [Parkin et al, 2020].

Despite cost-cutting, economic pressures led TSUK to experience financial losses during most of the 2015-2022 period (Figure 28), except for 2022. In response, Tata continued to divest. In 2016, it sold Scunthorpe integrated steelworks, which produced long products like steel beams and rail, to Greybull Capital (an investment company) for £1. The divested entity was renamed British Steel. In 2017, TSUK sold its high-value engineering and specialty steels business for £100m to Liberty House [TSUK, 2018], which was renamed Liberty Steel UK.

In terms of economic positioning strategies, Tata agreed in 2018 to merge its UK and Dutch assets with ThyssenKrupp of Germany, forming a new 50:50 joint venture that would benefit from economies-of-scale and lower cost [Tata Steel, 2019]. However, the European Commission blocked this merger on competition grounds in 2019. Subsequently, Tata Steel split its European operations in 2021, so that the Dutch and British assets would operate independently [Tata Steel, 2022]. In 2019, TSUK also made some capital investments, including £56m to rebuild blast furnace number 5 at Port Talbot [TSUK, 2019] and £20m to replace one of two steel converters.

The newly divested British Steel endured financial difficulties, entering liquidation in 2019. It was acquired in 2020 for £24.1m by Jingye Group of China [British Steel, 2020a], who pledged to invest £1.2bn over 10 years in the development of an Electric Arc Furnace, the construction of a new 250MW power plant, new rolling mills, and new rebar line [British, Steel, 2020b].

With regard to climate change, the 2015 steel crisis and subsequent problems initially hampered decarbonisation strategies, according to R07, R21 and R23. But rapidly increasing decarbonisation pressures after 2019 led the six steelmaking companies to enhance their engagement with low-carbon innovations. Depending on their assets and locations, they pursued different transition pathways.

- TSUK, which operates two coal-fuelled blast furnaces at Port Talbot, stated in their evidence to the Parliamentary 'green steel' investigation that it had not yet committed to particular decarbonisation pathways [EAC, 2022d]. But since CCS is unsuitable, due to a lack of nearby offshore storage sites for CO_2 and an unhelpful configuration of their current plant [R23], TSUK is exploring conversion of the two blast furnaces into electric arc furnaces (EAFs) [Sweney, 2022], using either scrap metal or sponge-iron (produced by hydrogen direct reduction) as its feedstock. TSUK is considering starting this conversion, which is estimated to cost about £3bn, in 2025 [ibid].
- British Steel, which operates two coal-fuelled blast furnaces at Scunthorpe, is located in the Humber industrial cluster and therefore has the option to piggyback on the cluster-wide development of CCS and hydrogen. In their *Low-Carbon Roadmap*, British Steel [British Steel, 2021] advanced a vision for reducing 82% of its emissions by 2035 (and 100% by 2050), using a phased combination of: 1) further efficiency improvements, 2) replacing one blast furnace with EAF using scrap steel as its feedstock; 3) attaching CCS to their second blast furnace around 2030, 4) possible use of hydrogen direct reduction in the early 2030s. The first two steps are estimated to absorb most of Jingye's promised £1.2bn investment; costs for the last two have not been published.
- The four EAF steelmakers, which operate their assets using scrap steel feedstock, can further reduce emissions by using clean scrap steel supplies and decarbonised electricity.

This summary of company strategies indicates that steelmakers moved back to phase 3 of our conceptual model ('exploring radical alternatives'), while their future visions and roadmaps envisage further shifts to phase 4 and 5 (with the deployment of radical alternatives leading to 'diversification' and then 'full reorientation'). The problem for the two integrated steelworks is that deep decarbonisation is very expensive with R2 giving a plausible £6bn estimate. Raising the money for such large investments is difficult for both foreign-owned steelworks, because they have been loss making for several years, leading their owners to have doubts about long-term futures. Tata, which already tried to sell its UK assets in 2016, is hesitant about making long-term investments Port Talbot because the wider Tata conglomerate is focusing new investments on the rapidly growing Indian market, thus reversing its earlier globalisation strategy [Parkin et al, 2020; The Economist, 2022]. At the time of writing (November 2022), economic headwinds (such as skyrocketing energy and iron-ore prices, looming UK recession, high inflation) further erode the companies' willingness to invest in low-carbon transitions.

Political strategies, which are enacted in the Steel Council, the media, and bilateral discussions [R05, R06], focus on two main issues. First, steelmakers contest the feasibility of 'near-zero' emission targets by 2035, proposing lower targets instead. British Steel's roadmap, for instance, aims for 82% reduction by 2035. Second, the companies are asking for more financial support than the £250m proposed in the Clean Steel Fund. Tata reportedly requested £1.5bn and British Steel £500m [Raval et al, 2022; Pfeifer & Pickard, 2022]. Both companies warned that would have to close their steelworks without sufficient support. While UK policymakers see the steel industry as strategically important [Sweney, 2022], they are reluctant to provide too much "support to foreign-owned companies", as suggested by R21, especially considering the risk that the sites may prove unviable in the future. The current political 'game of chicken' may result in some negotiated financial support for decarbonising both steelworks in the coming years. But without sufficient support, it is also possible that Tata and/or Jingye will run down and close their assets [Raval & Pfeifer, 2022; Pfeifer & Pickard, 2022].

5.7. Pattern matching analysis

The case study addressed the first research question by describing longitudinal interactions between UK steel company strategies and changing economic and socio-political contexts in the last 34 years. As a further step towards assessing analytical patterns in this co-evolution process, we compare the empirical case study periods with the five phases in our conceptual model of industry reorientation. This model suggests that increasing external pressures can push firms to gradually reorient through five phases: 1) inaction due to misinterpretation or denial, 2) incremental change, 3) hedging and exploration of alternative technologies, 4) diversification to new technologies while continuing to operate existing assets), 5) full reorientation to new technologies, possibly complemented by changes in mission, identity, and mindset.

Throughout all case study periods, UK steelmakers encountered external pressures that invited both low-carbon and economic responses, so we discuss two reorientation processes for each period. With regard to *low-carbon* reorientation, the first period (1988-1997) resonates with phase 1, because British Steel PLC initially ignored climate change, and with phase 2, once they acknowledged the problem but only implemented incremental energy efficiency measures, while also using political strategies to resist climate policies. With regard to *economically-motivated* reorientation, the first period resonates with phase 2. Although the successful restructuring of the state-owned British Steel Corporation (BSC) between 1980 and 1985 generated a sense of optimism, subsequent economic pressures (recession, shrinking domestic markets in the early 1990s, increasing international competition) and moderate financial losses in the early

1990s led the privatised British Steel PLC to implement retrenchment strategies and incremental efficiency improvements to reduce costs and improve financial performance.

The second period (1997-2007) resonates with phase 3 for *low-carbon* reorientation because, after the 2003 CEO change, Corus acknowledged the climate change problem and the need for substantive action. It adopted a more constructive political strategy and supported both incremental technologies and more radical R&D activities for reducing CO_2 emissions. With regard to *economically-motivated* reorientation, the second period resonates with phase 2, because increasing economic pressures (stronger international competition, increasing import substitution), shrinking domestic and export markets, and substantial financial losses in the late 1990s and early 2000s led Corus to focus on cost-saving and downsizing strategies.

The third period (2007-2015) resonates with phase 2 for *low-carbon* reorientation, because Tata Steel UK (TSUK) decreased corporate actions on climate change. While its framing strategies acknowledged the importance of climate change, TSUK lost relevant capabilities by shrinking R&D activities on decarbonisation. With regard to *economically-motivated* reorientation, the third period again fits with phase 2, because major economic pressures (financial crisis, recession, increasing iron-ore and coal prices, increasing Chinese competition), shrinking domestic and export markets, and steep financial losses forced TSUK to implement relentless asset sales and cost-cutting strategies, including in R&D budgets.

The fourth period (2015-2022) resonates with phase 3 for *low-carbon* reorientation as rapidly increasing socio-political pressures stimulated TSUK and the newly created British Steel to seriously explore radical low-carbon technologies, while also developing visions and roadmaps for potential future deployment (which would resonate with phase 4 or 5). With regard to *economically-motivated* reorientation, the fourth period again fits with phase 2, because economic pressures (2015 steel crisis, declining international competitiveness, shrinking export markets, COVID-induced recession) and further losses led Tata to continue with divestment strategies and incremental asset improvements.

This pattern-matching analysis shows that low-carbon reorientation followed an oscillating pattern with steelmakers going back and forth between phase 2 and 3, whereas economically-motivated reorientation remained stuck in phase 2. The explanation for both patterns is that the UK steel industry continued to decline throughout all case study periods, because a succession of negative economic pressures forced companies to prioritise retrenchment strategies (through cost-cutting, divestment, mergers, shrinking, outsourcing, and incremental efficiency improvements). Whenever companies had implemented retrenchment strategies to accommodate pressures in a period, new pressures would appear in the next period that were perceived to require further retrenchment strategies. The continuous economic decline and retrenchment strategies hampered low-carbon reorientation because there were limited managerial attention and financial resources for investment in radical low-carbon alternatives. Particularly in the third period (2007-2015), very large economic pressures threatened company survival, leading to retrenchment strategies that pushed low-carbon reorientation strategies back to phase 2.

5.8. Conclusions

The UK steel industry reduced CO_2 emissions by 56% between 1990 and 2021. This reduction resulted from shrinking production rather than low-carbon reorientation. Our analysis shows that firm's low-carbon strategies throughout this period oscillated between phase 2 (incremental change) and phase 3 (exploration of more radical low-carbon technical alternatives) of our conceptual five-phase model, which do not represent substantive commitment. The reason for the oscillation pattern is that economic decline, financial problems, and repeated retrenchment strategies hampered low-carbon reorientation processes, because they reduced available resources and managerial attention. Although the industry started to explore low-carbon reorientation in the second period (1997-2007), moving to phase 3 in our conceptual model, struggles for economic survival in the third period (2007-2016) moved it back to phase 2. Rapidly increasing socio-political pressures in the fourth period (2015-2022), including economy-wide net-zero targets and industry-specific support policies, stimulated the principal steelmakers to move forward to phase 3 again and explore radical low-carbon alternatives. The two remaining integrated steelworks also made future plans for deploying these alternatives, which would move them to phase 4 or 5 in our conceptual model. However, they have not yet committed to implementing the plans, because the substantial financial investments required (around £6bn) are challenging for economically struggling companies and perceived as risky, especially in the recent context of increasing energy prices, high inflation, and looming recession. We therefore assess their current low-carbon reorientation strategies as *tentative* and *reluctant*, with future plans not conveying a high sense of urgency or speed. The companies say they are unable to implement low-carbon alternatives without more financial support, which has intensified political struggles as the foreign-owned steelmakers threaten to close their sites without sufficient support.

In terms of directionality, steelmakers are differentially exploring three of four possible decarbonisation pathways (scrap metal/EAF, HDRI/EAF, CCS). Scrap metal/EAF is well-known and less risky but has some drawbacks (scrap supply, steel quality). HDRI/EAF is less developed and more expensive, and companies do not perceive it as ready for large-scale deployment. CCS is only feasible for British Steel because of its location in the Humber industrial cluster, but not ready for deployment until the late 2020s. It would increase the cost of steelmaking. Companies have not yet committed to actually deploying specific options because of technical, economic and policy uncertainties.

Future low-carbon developments of the UK steel industry will strongly depend on public policies. Companies are unlikely to implement HDRI/EAF or CCS without support policies that mitigate negative effects on competitiveness. Political negotiations about emission targets and financial support are ongoing through multiple channels (Steel Council, bilateral discussions, public media). Policymakers recognise the strategic importance of keeping (some) steelmaking capability in the UK (to reduce security risks associated with import reliance and supply chain disruption), but they do not want to provide too much support or throw good money after bad (if some steelmakers turn out to be unviable in the future). Without sufficient support, however, it is possible that the foreign owners (Tata and Jingye) will decide to close their sites, because these have been loss-making for multiple years and may not warrant long-term investments. The outcome of these political negotiations is presently uncertain but will become clearer in the coming years. While it is likely that a compromise will be found, the instability, acrimony, and ideological fervour of the present UK political climate means that other outcomes are also possible.

6. Oil refining industry

6.1. Brief description of industry specifics

Petroleum refining (oil refining) is the third largest stationary source of global greenhouse gases (GHG), responsible for around 6% of all such industrial emissions [Jing et al, 2020]. Through the use of its products, the refining industry is also indirectly responsible for most of the 40% end-use GHG emissions arising from transport globally [IEA, 2022]. Global refining capacity has rapidly expanded since the early 2000s, propelled by seismic economic growth in China and India [IEA, 2021a]. As this is forecast to continue in the coming years [ibid], emissions from global refining will also increase without GHG mitigation measures. Low-carbon reorientation of the oil refining industry is therefore an important topic.

The oil refining process is a particular kind of manufacturing process that uses large amounts of heat to distil and chemically break ('crack') crude oil (and other feedstocks) into a number of different end-products that are more flexible in their energy release, e.g., gasoline, diesel, fuel oil, and kerosine [Griffiths et al, 2022; Speight, 2020]. The greater flexibility makes the constituent parts more valuable than the original crude-oil input. This increase in value is known as the 'crack-spread'.

There are different types of refineries that vary in their complexity and outputs [Griffiths et al, 2022; Speight, 2020]. ***Topping refineries*** use simple distillation units and light hydrocarbon recovery units to produce semi-finished products (such as naphtha) that are typically used to produce industrial fuels or feedstock for petrochemical plants. ***Hydroskimming refineries*** build upon the topping type by adding an atmospheric distillation unit, a naphtha reforming unit, and necessary blending units. It uses hydrogen (produced from reforming naphtha or natural gas) to make high-octane gasoline through hydrotreating. ***Conversion refineries*** augment the basic units of the first two types with residual oil conversion plants (such as catalytic cracking and hydrocracking) and olefin conversion plants (such as alkylation or polymerization units), which chemically break low-value oil residues into valuable ones. The most complex conversion refineries also have vacuum distillation and coker units, and apply very high temperatures in various processing steps.

Figure 2 provides a schematic overview of a conversion type refinery, which has come to dominate the industry because it maximises yields. It includes hydrogen as an output of steam methane reforming and input for hydrotreating and hydrocracking. Although refining contains many dispersed emission sources, some steps like fluid catalytic crackers and steam methane reforming typically produce concentrated CO_2 emissions. Refineries are designed and built to produce certain percentages of different outputs (gasoline/petrol, diesel, fuel oil, kerosine), based on expected market demand and crude oil characteristics. Once they are built, it is very expensive to reconfigure refineries to change the percentages of relative outputs [Griffiths et al, 2022; Speight, 2020] or to reduce greenhouse gas emissions.

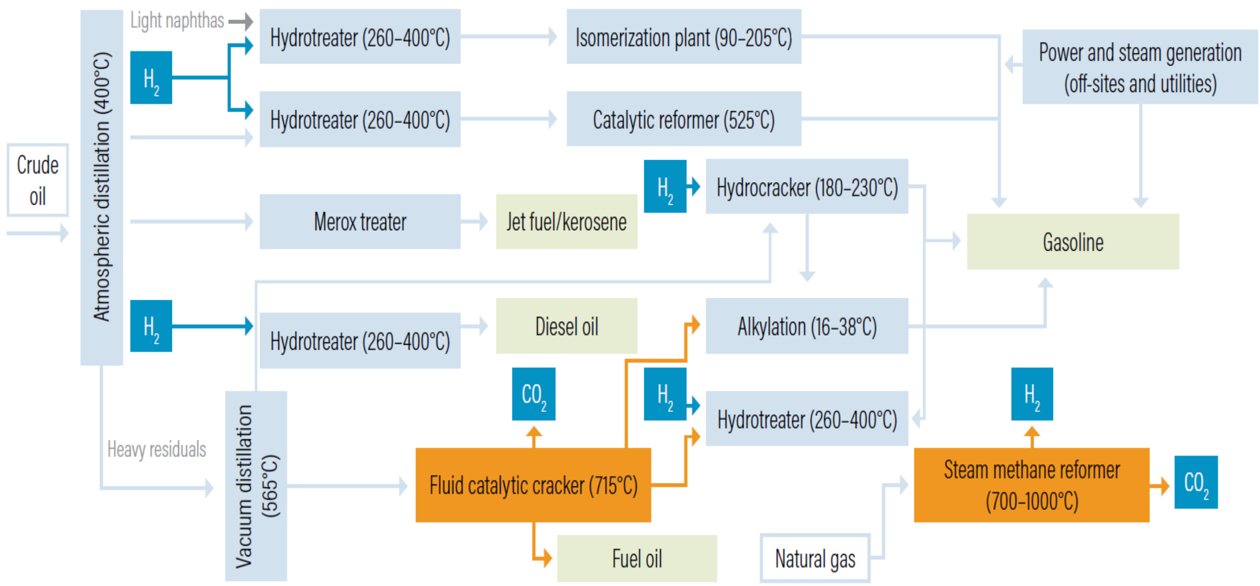

Figure 34. Representative flow diagram of a typical conversion refinery and its principal process steps and heat requirements; orange units delineate large process emission sources from other light blue units [Byrum et al, 2021: p3]

6.2. Pre-developments (1970-1990)

6.2.1. Economic pressures

Until the mid-1970s, the UK imported crude oil by sea from the Middle East (*Figure 35*). Refineries used this cheap oil to produce significant amounts of fuel-oil for use by the UK's growing electricity generation and industrial energy capacity (*Figure 36*).

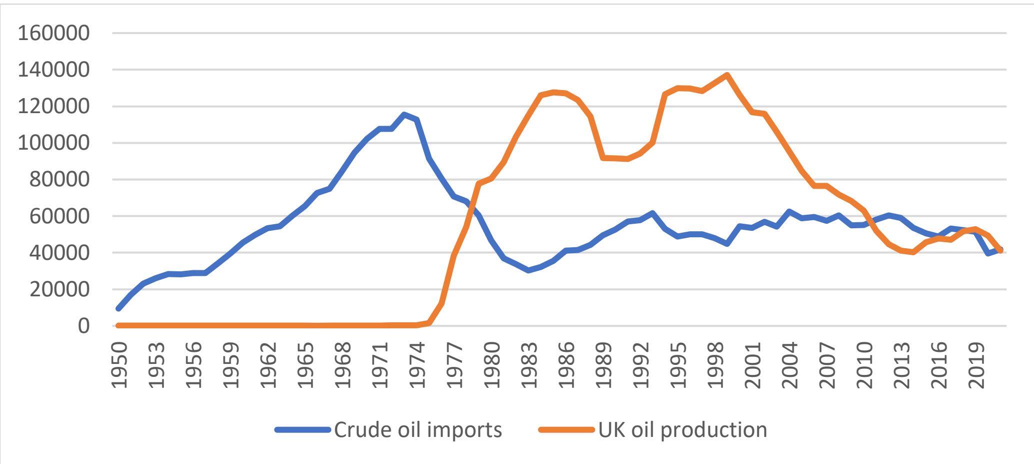

Figure 35: UK crude oil imports and domestic production (in thousand tonnes) (constructed using data from BEIS; Oil Statistics; Historical Time Series Data; Crude oil and petroleum products: production, imports, and exports 1890 to 2021)

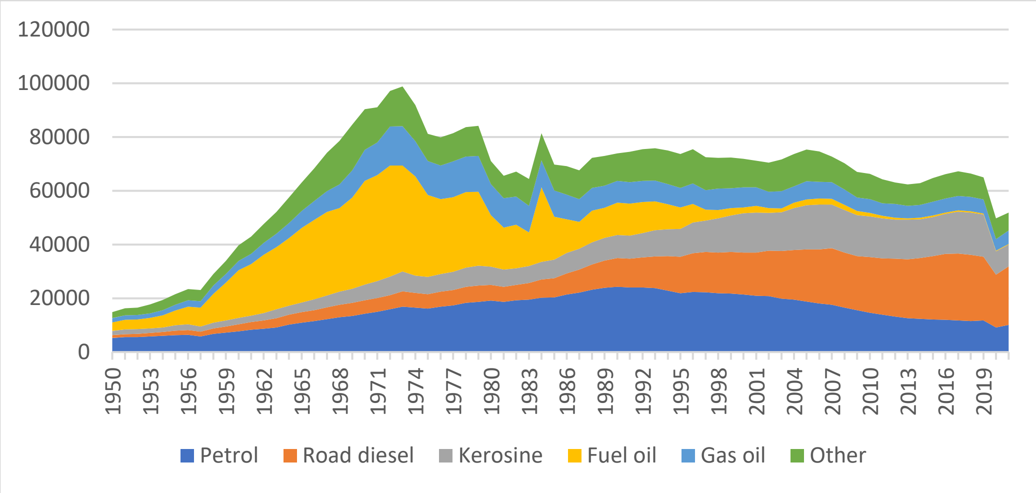

Figure 36: Domestic consumption of petroleum products (in thousand tonnes), 1950-2021 (constructed using data from BEIS Oil Statistics; Historical Time Series Data; Crude oil and petroleum products: production, imports, and exports 1890 to 2021)

The 1973 oil price shock created significant pressure on refineries because the petroleum product price rise induced recession, reducing demand for petroleum products generally and particularly reduced demand for fuel-oil from industrial users and electricity generators [UKPIA, 2013a]. The 1979 oil price shock further decreased economic activity and demand for fuel-oil (*Figure 36)*. The elevated international oil price also stimulated the UK to produce its own North Sea oil, which from the mid-1970s, rapidly replaced Middle Eastern crude as the principal feedstock for UK refiners (*Figure 35*). Declining North Sea oil production since the late 1990s did not significantly affect the UK refining industry since Brent crude prices are linked to global oil prices.

6.2.2. Socio-political pressures

The 1970s saw the rise of public concerns about environmental issues such as acid rain due to SO_2 emissions [Skea, 1998]. These emissions primarily arose from burning coal and fuel-oil for generating electricity, as the imported crude oil from the Middle East was high in sulphur. Environmental groups were very vocal on the issue throughout the 1970s and 1980s, which led to increasing policy pressure. Environmental regulations regarding SO_2 emissions contributed to declining fuel-oil use in both electricity generation and industry, which reduced the UK's emissions [ibid].

Environmental groups in the UK and Europe were also vocal about another issue: tetraethyllead (lead) in petrol [Ritson et al, 2018]. The EU responded in 1981 with a Directive that reduced lead levels in petrol to between 0.4 and 0.15 g/l [39]. In 1986, levels were reduced further in the UK (with EU direction), so 0.15g/l became the upper limit [Baek et al, 1992]. In 1988, the UK government also introduced a 10% tax differential to encourage consumer switching from leaded to unleaded petrol (which had become available for UK drivers at filling stations in 1986).

6.2.3. Company and industry responses

Although UK refineries had enjoyed healthy profit margins [R29, R36, R41], the oil shocks in the 1970s not only increased input costs but also decreased overall market demand for petroleum products (*Figure 36*), leading to the closure of seven of the nineteen UK refineries between 1975 and 1990, reducing total refining output until the early 1980s, after which it grew again (*Figure 7*).

Changes in specific market segments (especially declining fuel-oil and increasing petrol sales) also stimulated firms to either close simple hydroskimming refineries or convert these to more complex refining processes, including vacuum distillation and catalytic-cracking, to produce more valuable petrol outputs. These upgrades cost more than half a £billion investment in today's money for each plant [UKPIA, 2013a]. Because more complex refineries use very energy intensive processes, these upgrades and conversions increased relative energy use. While simple refineries consume 3-4% of the energy intake, complex refineries with multiple conversion units and product treatments increase this to 7-8% [Concawe, 2012].

To remove sulphur and other particulates from their emissions and products, UK refineries also adapted their processes with hydrotreating units [UKPIA, 2013a; Skea, 1998]. Regulations, supported by increasing consumer demand for unleaded petrol, also made refineries in the 1980s adapt their processes to improve octane levels in petrol without tetraethyllead [Ritson et al, 2018].

6.3. Incremental adjustments to increasing economic and decarbonisation pressures (1990-2000)

6.3.1. Economic pressures

At the macro-economic level, the 1990-1991 recession had limited effects on petroleum product demand (*Figure 36)*. The price of Brent Crude also traded in a fairly predictable range during the 1990s, except for the spike associated with the 1991-1992 Kuwait invasion (*Figure 37*). This accordingly kept the UK refining crack-spread stable during this period.

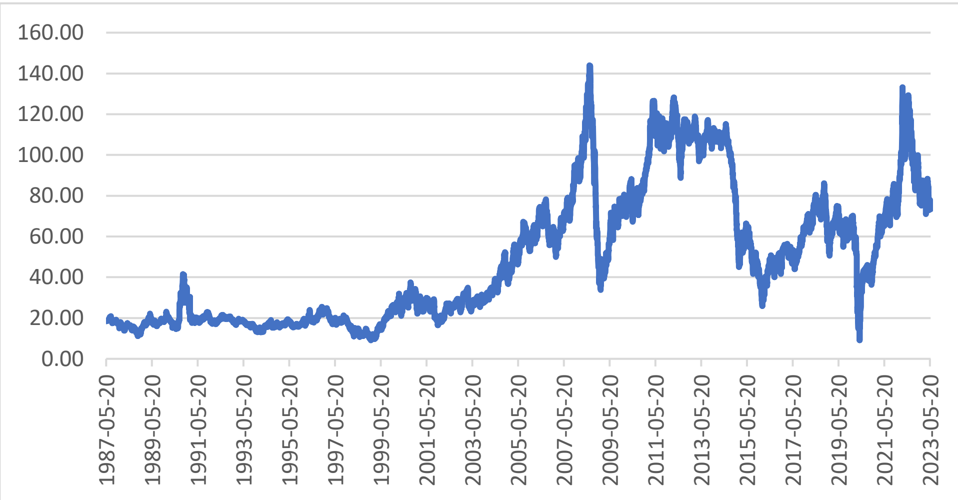

Figure 37: Daily Brent crude oil prices, 1987-2023 (dollars per barrel, daily, not seasonally adjusted) (constructed using data from Federal Reserve Economic Data)

Changes in product demand created more pressure on the refinery industry, which became progressively misconfigured. Specifically, petrol demand started decreasing from 1990 [Ritson et al, 2018], while demand for diesel and kerosene started to increase (*Figure 36*). Initially this was due to a switch to diesel cars for their better fuel consumption and because UK taxation policies affected relative prices of diesel and petrol [Ritson et al, 2018; Concawe, 2012; UKPIA, 2011a]; later, diesel demand accelerated further due an increase in light diesel-powered trucks [DUKES, 2018]. The increased demand for kerosene (*Figure 36*) was mostly due to the arrival of budget airlines from the late 1980s, which reduced the cost of air travel, stimulating demand [DUKES, 2000]. Fuel-oil demand from industry and electricity generation decreased significantly during the 1990s (*Figure 36*), further changing the composition of demand for refinery products. UK refineries struggled to adapt to this changing demand composition, which led to increased imports from 1997 and decreased output of UK refineries (*Figure 7*).

6.3.2. Socio-political pressures

Socio-political concerns about acid rain and lead continued into the 1990s. In 1990, the USA passed their Clean Air Amendment Act, which through its SO_2 regulations influenced the UK refining industry because seven of the twelve UK refineries operating in 1990 were US owned and managed. The 1992 United Nations Conference on Environment and Development also increased environmental issues on political agendas of both the EU and UK, particularly covering lead, sulphur, and climate change. In 1993, the UK also introduced a new UK Clean Air Act to update and consolidate the original 1956 Clean Air Act, and its 1968 revision [DEFRA, 2012]. This regulation had no particular application for the UK refining industry [ibid] because significant progress was being made with SO_2 emission levels.

Climate change also advanced up the political agenda through speeches by Margaret Thatcher; the creation of the United Nations Framework Convention on Climate Change in 1992, the agreement of the Kyoto Protocol in 1997, and the election of the Blair government (1997-2007).

6.3.3. Company and industry responses

The stable crack-spread during the 1990s delivered reliable but cyclical earnings for UK refineries, which had become healthier by the middle of the decade [McKinsey, 2015]. The changing composition of market demand created significant problems, however, because adjusting existing refineries (to produce less petrol and more diesel and kerosine) was considered unaffordable. UK refineries therefore experienced decreasing refining output after 1996, which, in turn, resulted in declining margins and profitability because of lower asset utilisation rates [Geels & Gregory, 2023].

Changing markets and declining profitability triggered two *economic repositioning strategies*. First, the major oil companies started to reappraise owning oil refining businesses in the late 1990s [BP, 1997; Shell, 1999]. Shell's group managing director for Oil Products, for instance, concluded in 2000: "The blunt fact is that most refining investments over the past twenty years have not delivered an adequate return" [Sluyterman, 2007: 202]. Oil companies therefore began to move out of the oil refining business by closing or selling refineries. Chevron's Milford Haven refinery shut in 1997 and Shell's Shell-Haven refinery followed in 1999. These closures temporality improved asset utilisation rates and profitability of the remaining refineries, until demand reduction increased economic pressures again.

Secondly, because it was reasoned unaffordable to reconfigure refineries to adjust to changing domestic market demand, firms started to engage more with overseas markets. As domestic demand for petrol stagnated, UK refineries began exporting more petrol to the USA, which was helped by US ownership of the three remaining refineries at the Southwestern point of Wales. And as domestic fuel-oil demand fell, they also increased fuel-oil exports to mainland Europe [DUKES, 2010; Deloitte, 2010]. The Humber refinery, which had the only coker unit in the UK, did not make fuel-oil and consequently enjoyed better profitability [R41]. Growing domestic kerosene and diesel demand also increased imports of both fuels [R43].

UK refineries also implemented *incremental innovation strategies* to reduce fuel and electricity expenses, which account for about 60% of operating costs [BEIS, 2017a:10]. They invested, for instance, in cogeneration of heat and power (CHP) units using refinery fuel gas (RFG)[18], which operated at higher energy conversion efficiencies (about 75%) than simpler thermal units previously burning fuel-oil (about 35% efficiency) [R26]. The side-effect of these economically-motivated investments was a gradual increase in energy efficiency performance (*Figure 38*).

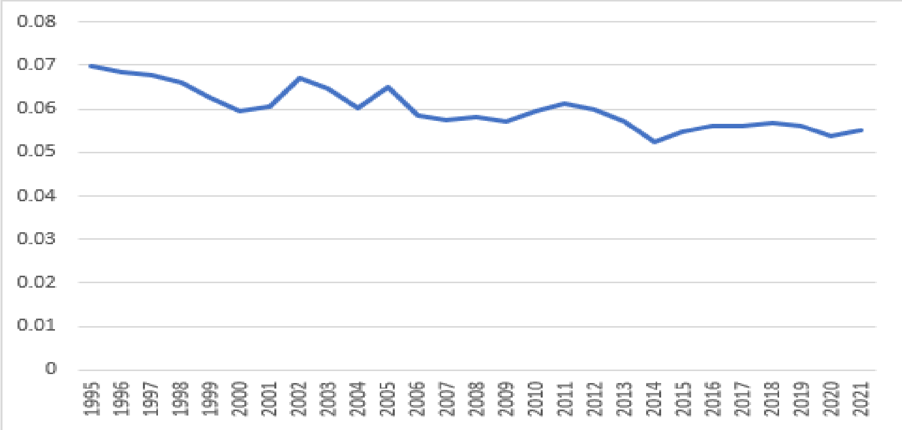

Figure 38: Energy efficiency, 1995-2021 (percentage of crude throughput used to power refineries) (constructed using data from Energy Trends, Table 3.12 'Refinery throughput and output')

With regard to climate-change, BP led the refining industry in acknowledging the problem. Under the leadership of John Browne (1995-2007), BP first recognised the issue in external communications and *framing strategies*. BP also started internally to price carbon on all of their projects [R31]. UK refineries initially focused on energy efficiency improvements to reduce CO_2 emissions (and fuel costs), as [R29] explained: "A 15% CO_2 emission reduction can generally be achieved in any energy driven process through energy efficiencies. (…) Plans for sequestering CO_2 came much later". Shell also recognised climate-change since their 1993 annual report [Shell, 1993]. However, both companies also emphasized the global economic demand for oil and refinery products and the industry's importance for economic welfare in their annual reports, which was accompanied by *political strategies* such as lobbying against regulations [BP, 1997; Shell, 1999]. This resonates with phase two of our low-carbon reorientation model.

6.4. Gradually worsening economic conditions and 'Big-oil' exit the UK refining business (2000-2008)

6.4.1. Economic pressures

Total demand for petroleum products steadily increased until 2005 (*Figure 36)* in line with macro-economic growth, enabling some recovery in the refining industry after the refinery closures of the late 1990s. Total demand then started decreasing because the oil price rapidly increased between 2005 and 2008, making oil products more expensive (*Figure 8)* [UKPIA, 2011a; Jefferson, 2020]. This created general downward pressure on the industry.

[18] Refinery fuel gas, or RFG, was formally an energy intensive emission, before being collected for use as a thermal source (which started in the 1980s) [R08]. It is often supplemented with methane, as there is not normally enough RFG produced within a refinery to meet total thermal needs [R41].

Continuing changes in specific market segments also created pressure on the UK refining industry (*Figure 7*). Domestic petrol demand continued to decrease, forcing refineries to shrink production or focus on more costly exports [DUKES, 2010; UKPIA, 2011b]. Demand for diesel and kerosine continued to increase but could not be met by UK refineries, which were still configured towards producing petrol. This thus led to more imports [UKPIA, 2013a] (*Figure 3*).

Asian economic growth in this period also meant that Asian refineries delivered buoyant earnings (*Figure 39*), which attracted considerable new investment into refining capacity in that region, sucking investment resources away from Europe [UKPIA, 2011a; BEIS, 2017a]. This created further pressure on UK refineries which are owned by multinational companies whose investment decisions are made on a global basis with long lead times and investment horizons.

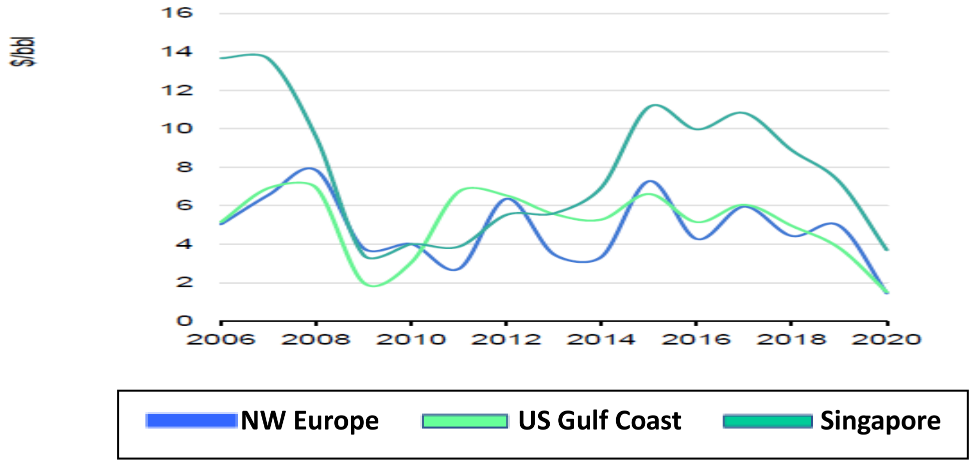

*Figure 39**:** Regional refinery margins* [IEA, 2021:94]

6.4.2. Socio-political pressures

Climate-oriented socio-political pressures increased somewhat in this period, especially with regard to biofuels. In 2003, the EU introduced the European Biofuels Directive, which mandated member-states to increase biofuel blends to 5.75% of transport fuel by 2010 [UKPA, 2013b]. In 2005, the UK introduced the Renewable Transport Fuel Obligation (RTFO), which imposed gradually increasing biofuel blending targets on large transport fuel suppliers (obligated suppliers): 2.5% in 2008/9, 3.75% in 2009/10 and 5% in 2010/11. The resulting increase in biofuel use (*Figure 40*) further reduced the consumption of hydrocarbons in the late 2000s.

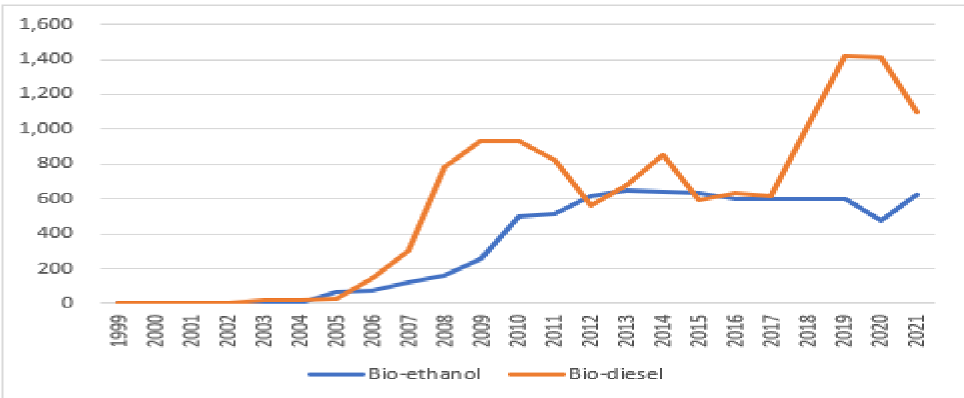

Figure 40: Biofuel use in UK transport, 1999-2021, in thousand tonnes (constructed using data from Energy Trends, Table 3.5 'Biofuel sales and sales through supermarkets'

General climate-change pressure also increased as the Kyoto protocol came into force in 2005. In 2005, the EU also commenced its Emission Trading System (EUETS), which aimed to reduce industrial GHG emissions by 21% by 2020 [Lukach, et al, 2015]. However, the impact of the EUETS on European refineries was not large during the first two phases (2005-2007, 2008-2012), due to a generous allocation of free emission allowances [ibid].

6.4.3. Company and industry responses

Following overall demand trends discussed above, refinery output increased in the early 2000s but started decreasing after 2004 (*Figure 36)*. The refinery utilisation rate consequently dropped (Figure 41), depressing profit margins that were already under pressure from the misconfiguration of refineries compared to specific market trends.

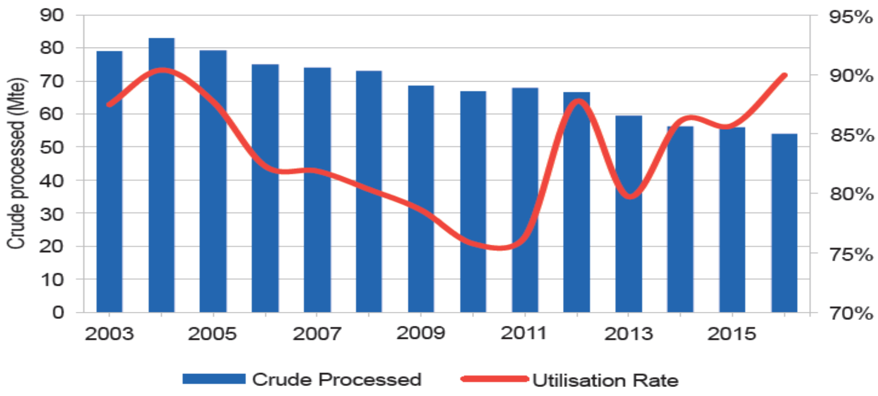

Figure 41: Output (blue and left axis) and utilisation rate (red line and right axis) of UK refineries, 2003-2016 [UKPIA, 2018:14]

In response to these continuing profitability challenges, companies implemented further *economic repositioning strategies*, with Big-Oil companies (excluding ExxonMobil) increasingly exiting the UK refining business: a) Phillips Petroleum and ICI sold the Teesside refinery to Petroplus (in 2000), b) Mobil sold its part ownership of Coryton to its joint venture partner BP in 2000, who then sold the combined equity to Petroplus in 2007, c) Total sold its 70% ownership of the Milford Haven refinery to its joint venture partner Murco Petroleum in 2007, d) BP sold Grangemouth to INEOS in 2005, e) Chevron bought Texaco in 2000 and thus acquired the Pembroke refinery.

By the end of 2008, nine UK refineries were still supplying 90% of the UK's oil-product demand [UKPIA, 2011b], and the UK was still a net-exporter of petroleum products. But the trade gap was closing, as growth in petrol exports to the US flattened after 2004 while imports of diesel and kerosene increased. As R26 explained (supported by R36 and R40), this pressured profit margins: "The more international trade is used to balance mismatched production with demand, the more the UK refining industry becomes impacted by overseas factors ... including pricing and margin pressures."

Poor margins continued to hamper the ability and willingness of refineries to invest in *innovation strategies*, including reconfiguration to address the growing product imbalance [UKPIA, 2013a, UKPIA, 2023b; UKPIA, 2011b]. To reconfigure production away from petrol (and increase diesel and kerosene output) would require the installation of major hydrocracking facilities and a reduction in catalytic cracking capacity, costing at least £700m per refinery [UKPIA, 2013a].

For climate-related pressures, refinery *innovation strategies* primarily continued to focus on incremental energy efficiency improvements [Lukach et al, 2015]. BP did, however, explore the more radical technology of carbon capture and storage (CCS) in relation to a power plant at Peterhead in Scotland. CCS was appealing to BP because it already had relevant capabilities, as R29 explained “The oil industry has significant experience in this area (...). We had been injecting rich CO2 streams into hydrocarbon reservoirs for some timed to enhance oil recovery from reservoirs”. Nevertheless, BP abandoned its CCS plans in 2007 when the Blair government delayed financial support for the Peterhead project [R29; R31].

In the absence of domestic production capacity, biofuels were initially imported to meet the government’s biofuel targets [R33, R40]. As R33 explained: “the RTFO makes no stipulation on national origin, so sourcing is very much driven by price”. The RTFO thus increased imports, including from new entrants who reformulated fuel blends to fulfil growing demand for greener products by supermarket petroleum retailers [R40, R43].

As the rising oil price made biofuels commercially more attractive [UKPIA, 2009], domestic production gradually developed after 2005, as new non-traditional refining entrants entered the market [Ecofys, 2014]. In 2006, Greenergy (which until the RTFO was a small independent importer) started building its first biodiesel production plant at Immingham on the Humber [Greenergy, 2006]. In 2007, Greenergy was supplying “over half of all biofuels sold in the UK”, selling to everyone [Greenergy, 2007:3]. For domestically produced diesel, blending occurred at the refinery [R08]; for imported diesel, blending happened at the import terminal [Greenergy, 2007]. For petrol, ethanol blending occurs at the final distribution terminals [R33]. Since blending did not require deep expertise, UK refineries only engaged in incremental biofuel innovation.

While reluctantly complying with the targets, UK refineries also used *framing and political strategies*, lobbying against biofuel regulations through UKPIA and arguing that these commercially disadvantaged them compared to the new Asian refineries, which did not experience environmental regulations [DECC & BIS, 2015;UKPIA, 2013a;UKPIA, 2011a]. For example, in their written evidence to an enquiry by the UK Parliament’s Energy and Climate Change committee, UKPIA claimed that various European environmental regulations “impose a £1 billion plus burden on the UK refining industry that does not apply to non-EU refineries” – [UKPIA, 2011b:4].

6.5. Major economic shock and pressures causing decline and retrenchment (2008-2015)

6.5.1. Economic pressures

The 2008 financial crisis and subsequent recession were a major shock that reduced UK demand for petroleum products by 11% between 2008 and 2013 (*Figure 36*), causing significant pressure on UK refineries. Past trends such as shrinking petrol and expanding diesel and kerosine markets continued (*Figure 36*), further increasing misconfiguration pressures through increasing imports (*Figure 3*), and lowering refinery utilisation rates (*Figure 41*) [UKPIA, 2011a; DUKES, 2010; DECC, 2014]. By 2012, 44% of diesel and 64% of aviation fuel was imported [DECC, 2014]. By 2013, the UK became a net-importer of petroleum products, and the imbalance grew the following year (*Figure 42*) [UKPIA, 2016].

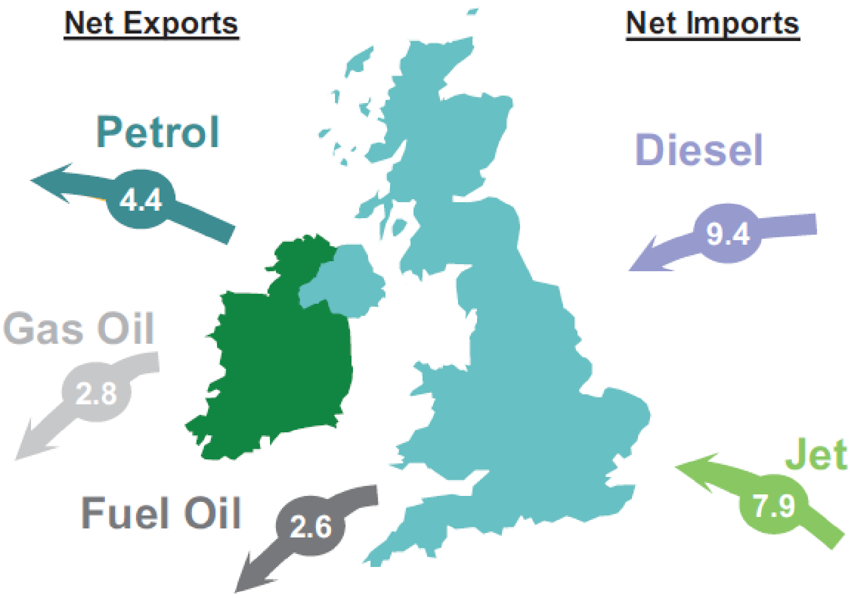

Figure 42: UK net petroleum product flows in 2014 (Source [UKPIA, 2015]: *using* [DUKES, 2014] *production statistics. Measured in million tonnes energy equivalent).*

UK petrol exports experienced pressure from the US shale gas revolution, which tripled the US production of tight-oil between 2009 and 2014. This ended its structural gasoline shortage and eroded the principal market for UK surplus refined petrol [BEIS, 2017a; DECC, 2014], pressuring UK petrol exports (*Figure 7*).

6.5.2. Socio-political pressures

Increasing civil-society demand for climate-related action culminated in the UK's 2008 Climate Change Act [Lockwood, 2013], which set an ambitious GHG-reduction target of 80% by 2050. Subsequent policies, however, had limited focus on energy-intensive industries, which were seen as the 'hard-to-decarbonise' remaining 20%. In 2012, the coalition government (2010-15) launched a £20m funding competition for the development of innovations in Carbon Capture and Storage (CCS) technology. Despite choosing two candidates, follow-through funding never materialised, undermining industry's belief in the government's commitment [R32, R37]. As R32 explained: "In 2014, at the eleventh hour and fifty-ninth minute, George Osborne decided that he needed the billion pounds that was being earmarked for CCS, for something else, and closed down the very final-stage discussions". Further, the government's 2014 *Review of the Refining and Fuel Import Sectors in the UK* [DECC, 2014] was more focussed on the resilience of fuel supply to the public than on GHG emission reduction, which meant that climate-related policy pressure on refining was relatively low in this period.

Vocal environmental NGO protests over the indirect effects of first-generation biofuels (including CO_2 emissions from indirect land-use change and competition with food production) led policymakers to launch the Gallagher Review in 2008, which recommended a precautionary approach through a pulling back from original targets and focussing on better environmental sustainability (such as using waste products) [Harvey & Pilgrim, 2013]. The government accepted the recommendations and in 2009 scaled-down the RTFO-targets to 3.25% for 2009/10, 3.5% for 2010/11, 4% for 2011/12, 4.5% for 2012/13 and 4.75% for 2013.

The biofuel controversy also affected EU policies. The 2009 European Renewable Energy Directive not only set new targets for 10% renewable transport fuels by 2020, but also introduced stronger sustainability criteria (such as an increase of life-cycle CO_2 savings from 35% in 2011 to 50% in 2017) and stimulated a shift from first to second generation biofuels by allowing double counting of more sustainable biofuels such as wastes and residues. This led to further amendments in the UK's RTFO, which came to apply to non-road-mobile machinery from 2013 [UKPIA, 2013b] and increased biofuel targets to 7.25% in 2018, 8.5% in 2019, 10% in 2020. Phase 3 of the EUETS (2013-2020) reduced the number of free allocations and introduced an auctioned component. Because refineries could initially 'bank' allowances from earlier phases, pressure at first remained limited [Lukach, 2015].

6.5.3. Company and industry responses

The financial crisis and subsequent recession and increasing imports caused UK refinery output to collapse by 19% between 2008 and 2013 (*Figure 7*), followed by a further downward slide. Refinery utilisation rates consequently fell until 2011, and then remained volatile (*Figure 39*), causing further downward pressures on profit margins (*Figure 43*). Reported 2014 refinery profits (for 2013 performance) turned negative for UK refineries due to a further dip in utilisation rate in 2013 (*Figure 41*). The average return on capital between 2010-2015 was circa 2%, compared to 8% for manufacturing and 16% for upstream oil [UKPIA, 2017: 10].

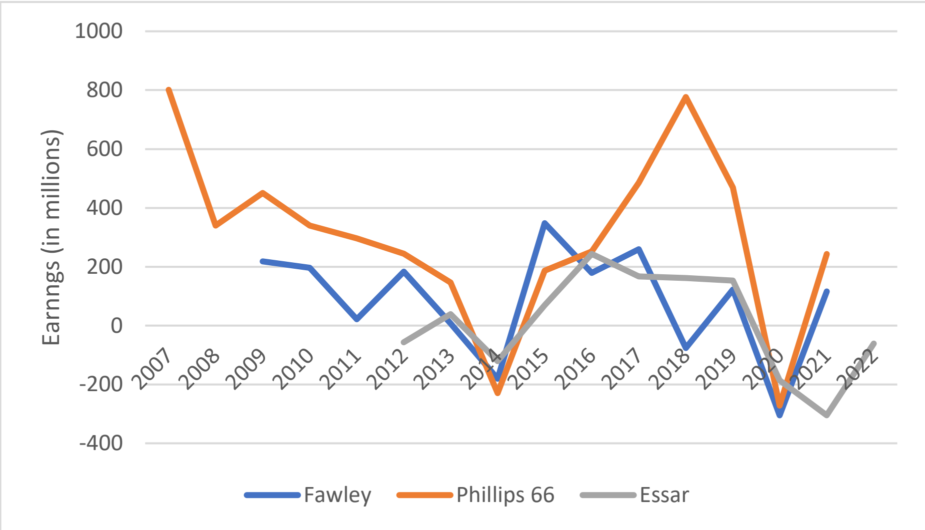

Figure 43: Earnings (in millions) for three UK refineries (Fawley in UK pounds and Essar and Phillips 66 in US dollars) (constructed using financial data from successive annual reports)

The financial problems caused further *economic repositioning* such as the closure of three further refineries: Teesside in 2009, Coryton in 2012 (both owned by Petroplus, which went bankrupt in 2012), and Murco's Milford Haven in 2014. These closures helped the remaining refineries improve their utilisation rates from 2011 (with a notable dip in 2013), despite declining industry output (*Figure 41*). Nevertheless, Big-Oil companies continued to exit UK refining: Chevron sold the Pembroke refinery to Valero in 2011 and Shell sold Stanlow to Indian-owned Essar in 2011. ExxonMobil also reduced processing capacity at Fawley in 2012, with the permanent closure of a crude distillation unit [UKPIA, 2013a] to adjust to shrinking demand. Fawley's capacity reduction and Coryton's closure worsened the refineries' petroleum product imbalance [ibid], which rapidly increased the imports of diesel and kerosine between 2010 and 2016 (*Figure 7*).

Regarding biofuels, the UK refineries met, or slightly exceeded, the RTFO targets in this period [UKPIA, 2015]. However, collapsing margins and profitability problems made refineries reluctant to engage in biofuel *innovation and manufacturing strategies*. Instead, they purchased biofuels from domestic and international biofuel suppliers, and blended this with traditional products [R37, R40, R41, R43]. Although domestic biofuel production increased, imports also remained significant [R33, R40, R43].

In terms of *framing strategies*, the refining industry's trade body UKPIA was active on a number of fronts. It was keen to emphasise the industry's positive contributions to the UK economy through petroleum products importance for economic growth and its contribution to direct jobs, tax raising, and supporting transport and other petroleum-enabled industrial activities [UKPIA, 2011a; 2011b; 2013a; 2013b; 2013c; 2015]. It also bemoaned the burden of regulation, which increased compliance costs [UKPIA, 2011b; 2013b; 2013c; 2015]. It also emphasised the industry's positive contributions to climate mitigation, referring mostly to incremental innovations. "Emissions of CO_2 from road transport have reduced significantly when compared to the overall increasing mileage. In 2015, the average CO_2 emissions of new cars was around 36% lower compared to 17 years ago, reflecting improvements in vehicle efficiency enabled in part by cleaner fuels" [UKPIA, 2016a:39].

6.6. Accelerating socio-political pressures and mixed responses for low-carbon reorientation (2015-2019)

6.6.1. Economic pressures

Macro-economic growth led to a 6.4% increase in the demand for petroleum products between 2013 and 2018 (*Figure 36*). As the misalignment of production with demand remained, much of this growth was captured by imports of diesel and kerosene (*Figure 7*), whilst petrol still needed to be exported [DUKES, 2021]. Nevertheless, economic pressure on the industry diminished in this period, as refinery output somewhat stabilised, after collapsing earlier in the decade (*Figure 7*).

6.6.2. Socio-political pressures

Socio-political decarbonisation pressures started to accelerate from 2015. Internationally through the 2015 Paris agreement; and domestically through the industrial decarbonisation roadmaps, which investigated how the oil refining industry "could decarbonise and increase energy efficiency whilst remaining competitive" [DECC & BIS:1]. The 2017 *Clean Growth Strategy* further stressed the importance of radical innovations to move energy intensive industries "beyond energy efficiency" solutions. These more radical innovations included fuel switching and technologies such as CCS [BEIS, 2017a: 64]. By 2017, the rising cost of carbon (through the EUETS and the Carbon Floor Price[19]) also started to influence refinery attitudes towards decarbonisation. As R37 pointed out (supported by R40 and R41): climate was finally appreciated as a problem when firms were "notified that they were going to be hit with a potential multimillion pound bill each for the CO_2 that they emit into the atmosphere (...) as it became a balance sheet problem".

Following the 2015 Dieselgate scandal, which revealed widespread emission test cheating by automakers and caused public outrage, the UK government in 2017 announced plans to phase out petrol and diesel cars by 2040. In February 2020, the phase-out date was brought forward to 2035, and in November 2020 to 2030. Because this would create mass markets for electric vehicles and decrease demand for petrol and diesel fuel, this policy further increased decarbonisation pressure on the refining industry.

In 2018, the government introduced a *CCS Action plan*, which supported an industrial cluster approach with targets of a first CCUS facility by the mid-2020s and full-scale deployment by the 2030s [Sovacool, et al,

[19] The Carbon Floor Price is a UK policy instrument that facilitates the EUETS.

2022]. To support this, a £170m Industrial Strategy Challenge Fund (ISCF) was launched in 2018 to support industrial firms to work on front-end engineering and design (FEED) solutions for low-carbon technologies.

6.6.3. Company and industry responses

Reduced economic pressures enabled UK refineries to recover financially during this period (*Figure 43*), despite output still showing a small decline (*Figure 7*). Refinery utilisation rates increased to healthy levels after 2013, remaining high until 2019 (*Figure 41)* [UKPIA, 2020:11]. Earnings and profits were positive until 2020, although they started declining after 2018 (*Figure 43*) [UKPIA, 2020]. Consequently, there were no further refinery closures in this period, and no significant *economic repositioning strategies*.

In terms of *innovation strategies*, the Humber refinery in 2017 started to co-process waste cooking oil as a crude feedstock, after management identified this as offering additional revenue, derived from the RTFO design[20]. As R41 explained: "The UK's refining industry has been in decline since the 1970s, and some of the remaining refineries will have to close as demand will continue to fall for our products due to climate-change. Some refineries will also survive, as there will still be demand for some refinery products for some time – I believe for many decades. For Humber to be one of them, we needed to maximise any revenue streams we could identify." This strategy subsequently evolved to include global sourcing and trading of used cooking oil, as well as trading the refined product and monetising their excess RTFO created certificates [R41]. The Humber refinery thus became a sustainable technology leader, which partly related to its legacy refining processes that lend themselves for easier reconfiguration for refining biocrudes [R41].

In response to the stronger socio-political decarbonisation pressures, the industry started to accept the need for radical innovation. It participated, for instance, in developing the Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan for oil refining [BEIS, 2017a], which emphasised both incremental efficiency innovations and radical innovations such as CCS. The Director General of UKPIA did, however, in his foreword to the Action Plan emphasise that the deployment of more radical innovations would require a suitable "policy framework to create the right market conditions" [BEIS, 2017a:6]. This suggests the industry was entering phase 3 of our conceptual model, in which firms still focus on incremental innovations but also begin to explore more radical options, while refraining from actual deployment.

Some refineries (especially and Stanlow in Merseyside and Phillips 66 in the Humber) participated in net-zero innovation initiatives (focused on CCS and hydrogen) that emerged in response to the government's CCS Action Plan and ISCF-funding, although they were not initiators [R32, R44, R45, R46, R49]. The Zero Carbon Humber initiative was started by Equinor, Drax, and National Grid Ventures, which then subsequently approached other firms in the Humber cluster, including Phillips 66 [Geels et al, 2023]. The consultancy Progressive Energy was a lead actor in the HyNet initiative, which then subsequently approached other firms in the Merseyside cluster, including the Stanlow refinery [Sovacool et al, 2023]. As R46 (echoed by R44, for a different cluster) explained for HyNet: "the successful development of clusters requires a systems approach beyond any one industry, and needs to appreciate connectivity (pipelines), financing, engineering design, and both CO_2 and hydrogen storage." Once lead actors initiated these

[20] Under the RTFO, certificates are issued to renewable fuel producers for each litre of eligible renewable transport fuel they produce. These certificates serve as evidence that the fuel meets the sustainability and greenhouse gas emissions criteria set by the RTFO regulations. Fuel suppliers can buy these certificates from renewable fuel producers to offset their obligations [UKPIA, 2009].

industrial cluster projects, refineries embraced them as the benefits from being involved became compelling [R31, R32, R37, R44, R45, R46, R49]. As a first step, the refineries participated in developing cluster-wide proposals for ISCF funding, which were submitted in 2020.

In terms of *socio-political framing strategies*, UKPIA remained active on behalf of its members, emphasising in reports and statements both the need for low-carbon transitions [BEIS, 2017a; UKPIA, 2018; 2019a; 2019b], whilst also advancing defensive framings used in the previous period such as stressing the importance of hydrocarbons for future economic activity, highlighting the refining industry's positive contributions to the UK economy, and bemoaning regulatory burdens [UKPIA, 2018; 2016a; 2016b; 2016c; 2017; 2019; Oxford Economics, 2019]. But the industry also started to pivot towards emphasising the importance of the UK refining industry for successfully achieving net-zero for the UK, while also calling for government support to do so [BEIS, 2017a; 2019b; Oxford Economics, 2019]. This hedging mix of defensive and more pro-active strategies further confirms that the industry was entering phase 3 in this period.

6.7. Moving towards decarbonisation despite major external shocks (2019-2023)

6.7.1. Economic pressures

In 2020, the COVID-19 shock led to global lockdowns, global supply chain disruptions, and a slump in economic activity, which reduced global refining activity by 10% that year [IEA, 2021:93]. Demand for petroleum products in the UK fell by 23% (*Figure 36*), whilst UK refinery output decreased by 18% (*Figure 7*). As lockdown restrictions were lifted later in 2020, demand recovered significantly for diesel and petrol (for road vehicles), but remained depressed for kerosene (*Figure 36)*, as aviation was slower to recover due to ongoing international travel restrictions. Russia's invasion of Ukraine in 2022 was another major shock. This had a positive effect on the UK crack-spread because much of the diesel imported into the UK was sourced from Russia [R41]. Sanctions on Russian products consequently lowered competitive pricing pressures, increasing the industry's margins and profits [R41, R49], even though output remained significantly lower than in 2019 (*Figure 7*).

6.7.2. Socio-political pressures

UK socio-political decarbonisation pressures further increased in this period, as the government adopted an economy-wide net-zero target in 2019, which meant that climate legislation also applied to 'hard-to-decarbonise' sectors like oil refining. Whilst net-zero policy set the overall direction, a raft of implementation-oriented instruments were introduced to assist energy-intensive industries with their reorientation. ISCF funding calls in 2019 and 2020 enabled firms to make feasibility and FEED studies of CCS and hydrogen technologies. The 2020 *Ten Point Plan for a Green Industrial Revolution* [BEIS, 2020a] stated the ambition to deploy CCS in two industrial clusters by 2025 (Track-1) and two more by 2030 (Track-2), while also aiming for the production and use of 5GW low-carbon hydrogen by 2030 (mostly 'blue' hydrogen, produced through steam reformation of methane with CO_2 captured). In 2020, the government also introduced the £1 billion CCS Infrastructure Fund (CIF), which in 2021 was implemented through a cluster sequencing approach that distinguished each Track between a phase-1 competition for two CCS clusters, which can be operational by the mid-2020s, and a phase-2 competition for plant-specific CO_2 capture projects that can feasibly connect to the Transport and Storage (T&S) infrastructure by 2027 [BEIS, 2021].

By July 2021, five cluster-based CCS partnerships had submitted phase-1 funding applications: East Coast Cluster, HyNet, V Net Zero, the Scottish Cluster, and DelpHYnus. In October 2021, the government selected the East Coast Cluster (encapsulating Humberside and Teesside) and HyNet (Merseyside). By January 2022, 36 proposals were submitted for the phase-2 competition for plant specific projects in both the HyNet and East Coast Clusters. In August 2022, the government shortlisted 20 projects to proceed to the due diligence stage, which included three refinery projects (by Essar Oil, Phillips 66, and Prax Lindsey). In March 2023, the government selected 8 projects for further negotiation, which included the Essar Oil project [DESNZ, 2023a]. And in July 2023, policymakers selected the Scottish cluster and V Net Zero cluster (renamed Viking) as the successful Track-2 T&S systems [DESNZ, 2023b].

To support the deployment of low-carbon technologies, the government also introduced other funding facilities such as the £165m Advanced Fuels Fund (AFF) and the £289m Industrial Energy Transformation Fund (IETF), which between 2021-2025 provides capital grants for the deployment of energy efficiency technologies (Strand 1) and deeper decarbonisation options, including fuel switching (Strand 2). Three refinery companies (Essar Oil, Phillips 66, and Prax Lindsey) received grants from this Fund [DESNZ, 2023c]. In 2021, the government also introduced the £240 million Net Zero Hydrogen Fund (NZHF), which from mid-2022 provides capital grants (and some FEED grants) to support the at-scale deployment of low-carbon hydrogen production during the 2020s. This raft of policies and support instruments stimulated low-carbon reorientation at some refineries, as part of cluster-wide initiatives, despite firms being buffeted by major external shocks.

One complication is that the US government passed the Inflation Reduction Act (IRA) in 2022, which offers significant investment tax-breaks for climate action investments in the USA. Many interviewees were concerned that this would make the UK refinery industry less attractive as a low-carbon investment destination compared to the US [R29, R35, R36, R37, R38, R41, R44, R46, R48, R49].

6.7.3. Company and industry responses[21]

The COVID-induced 18% fall in output in 2020 caused refinery capacity utilisation rates to fall below 80%, pushing UK refineries into losses (*Figure 43*). Profitability rebounded in 2021 and increased further in 2022 and 2023, after sanctions against Russia increased the value of the industry's crack-spread [R41, R49]. In response to the UK increased socio-political decarbonisation pressures, UK refineries embarked on low-carbon *innovation and reorientation strategies*, although with significant variation in their degree of commitment.

Stanlow (Essar). Essar and its Stanlow refinery are fundamental to the HyNet project in the Merseyside cluster [86], which the government in 2021 selected as one of two Track 1 CCS cluster project. The HyNet project provides new technologies and infrastructure for capturing, transporting, and storing industrially-produced CO_2 in exhausted gas wells in the Liverpool Bay, and new technologies and infrastructure for producing, transporting, storing, and using low-CO_2 hydrogen (*Figure 44*). *Vertex Hydrogen*, a joint venture between Essar Oil UK (90%) and Progressive Energy (10%), will build and operate the hydrogen production plant, which will produce 'blue hydrogen' [R49]. Essar plans to invest £1 billion over five years into *Vertex*

[21] The information in this section varies in depth and length for each refinery, reflecting different levels of low-carbon reorientation activity by each refinery.

Hydrogen and play a central part in HyNet [Essar, 2022]. R49 explained the rationale behind this strategic reorientation as follows: ”Particularly after the shock of COVID, we realised that the cost of carbon was going to {overwhelm} the profit of the company. So, we had to be proactive towards hydrogen and the HyNet infrastructure”.

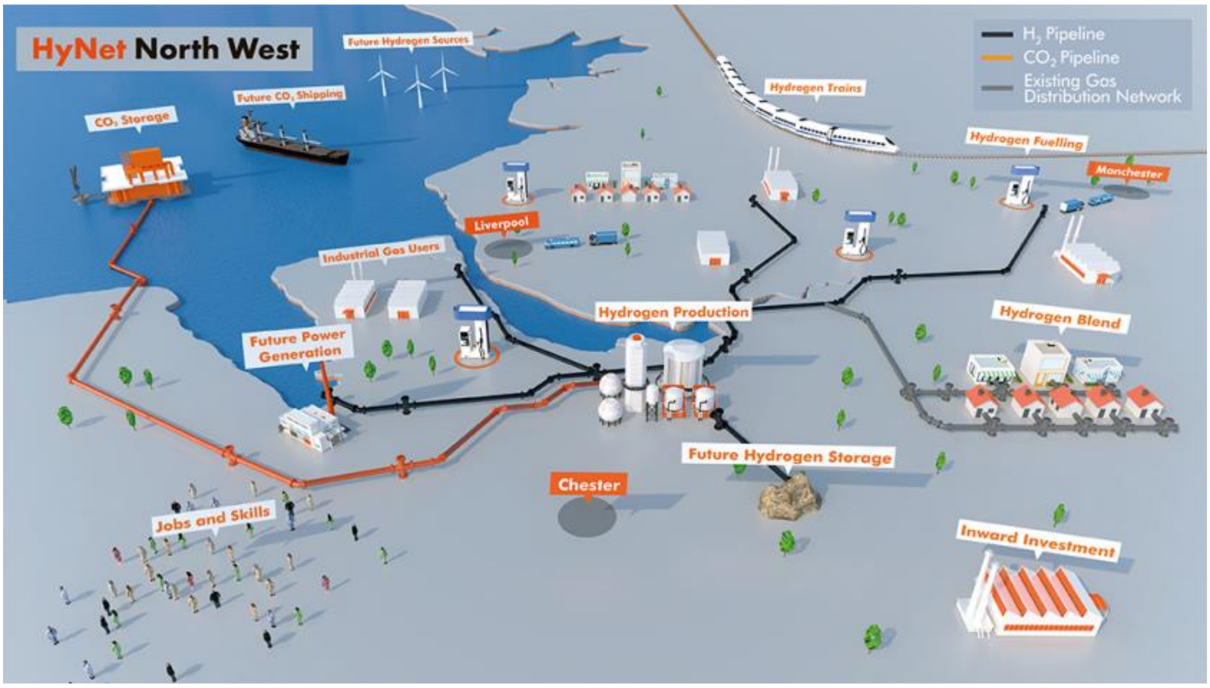

Figure 44: Visualisation of the HyNet project in the Merseyside industrial cluster [HyNet, 2023]

To produce 1 GW hydrogen per year by 2026, Vertex will build two hydrogen production plants, which process Stanlow’s refinery flue gas into hydrogen using steam reformation and CCS technology [R49]. Construction of the first hydrogen plant will start in 2024, when ongoing negotiations between the government and Essar, under the low-carbon hydrogen business model, are expected to conclude. Construction of the second plant, which will be twice the size, is currently envisaged to start in 2025. This sequencing strategy enables *learning-by-doing* [Gregory, 2020]. The first two offtakers of Vertex’s blue hydrogen will be Encirc (a glassmaker), and Essar Oil, with substantial interest being shown by other industrial customers throughout the Northwest cluster [R46, R49].

Essar Oil is also evaluating a separate ‘green hydrogen’ strategy (using green electricity to electrolyse water). Its Indian parent intends to leverage a recent Indian government policy (March/April 2023) for green hydrogen, which would enable it to ship ‘green ammonia’ from India to the UK, for conversion into green hydrogen at Stanlow [R49].

Essar will also use hydrogen as its principal heat source for standard refining needs. The refinery therefore bought a £45m hydrogen furnace, which was delivered in 2022 (Figure 45) [Essar, 2022], and is to be installed in September 2023; the furnace can also burn methane until the hydrogen becomes available [R49]. To decarbonise other parts of the refinery, Essar will also install established (solvent-based) carbon technology on its catalytic cracker and send the captured CO_2 to the Liverpool Bay. A further element of Essar’s low-carbon reorientation strategy is the development of sustainable aviation fuel (SAF) together with Fulcrum Bioenergy. This project was awarded a £16m grant from the Advanced Fuels Fund in late

2022, to develop the Front-End Engineering Design (FEED) package which will enable it to reach a Final Investment Decision.

Figure 45. A ten-story hydrogen ready furnace being transported to the crude distillation unit at the Essar Refinery ((Chester and Cheshire News, 14 August 2022; https://www.cheshire-live.co.uk/news/chester-cheshire-news/giant-hydrogen-furnace-makes-way-24752714)

Humber (Phillips 66). The Phillips 66 and the Prax Lindsey oil refineries are both located in Immingham in the Humber industrial cluster (*Figure 46*), which the government in 2021 also selected as a Track-1 CCS cluster project, in combination with the Teesside industrial cluster and the Northern Endurance Partnership, which plans to build and operate the offshore CO_2 pipelines and subsea storage [ECC, 2023].

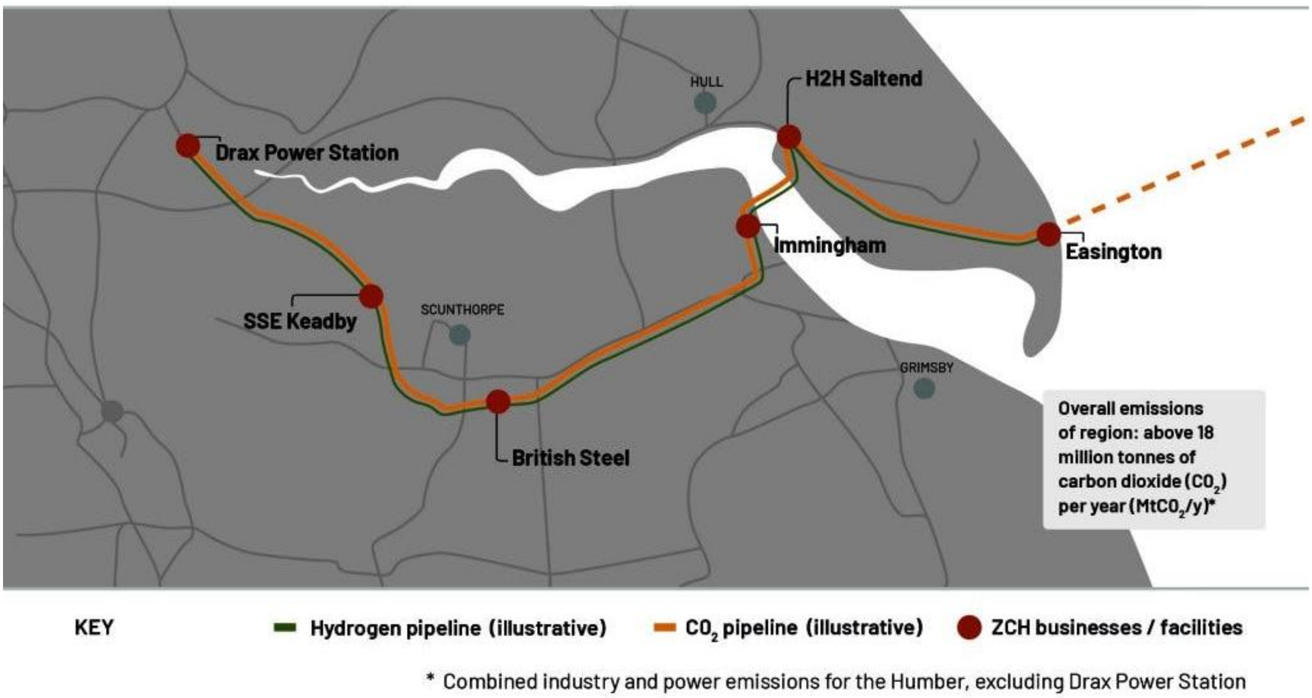

Figure 46: Envisaged hydrogen and CO_2 pipelines in the Zero Carbon Humber project [ZCH, 2020]

Although Phillips 66 was initially part of the *Zero Carbon Humber Partnership*, it left this consortium in 2020 (due to concerns over its interest being sidelined) and launched the *Humber Zero* project with VPI Immingham (an adjacent electricity producer that supplies steam to the refinery) [Geels, et al, 2023]. This £1.2bn project aims to build a carbon capture facility that will capture CO_2 emissions from VPI's combined heat and power plant and the oil refinery's catalytic cracker. In March 2021, this project received £12.5 million ISCF-funding, which enabled it to further develop technical and economic designs. VPI and Phillips 66 also aligned themselves with Harbour Energy's *V Net Zero cluster*, which had developed to connect industrial emitters in Immingham to the offshore Viking field to store CO_2 emissions [R35, R41, R44, R48]. When the *V Net Zero cluster* was not selected in 2021, VPI and Phillips 66 pivoted back to the Zero Carbon Humber Partnership, submitting their Humber Zero project (as two bids) in January 2022 for the Track-1 phase-2 competition [ibid]. Although the Phillips 66 bid was shortlisted in August 2022 (the VPI bid was not), it was not selected in March 2023 for further negotiation, which was a major disappointment. This setback did, however, not derail Phillips 66's low-carbon reorientation plans as it hopes that its CCS project (and possibly the wider *V Net Zero cluster* plans, which have been relabelled *Viking CCS*) will qualify for future government funding schemes [R35, R41, R48]. The government's selection of the Viking cluster in July 2023 (in the Track 2 phase 1 competition) means that the Phillips 66 project indeed has a good chance for a future Track 2 phase 2 competition.

The Phillips 66 refinery is also still engaging with other low-carbon technologies as part of Phillips 66 global decarbonisation strategy [R35, R41]. Its Humber refinery is part of the Gigastack project (a joint venture with Ørsted, ITM Power, and Element Energy), which produces green hydrogen using electrolysers and renewable electricity from offshore wind-parks. Phillips 66 intends to use this green hydrogen as their main thermal heat source for the refinery [R35, R41]. Building on its experience with co-processing and marketing of used vegetable oils, Phillips 66 also intends to produce a broader range of renewable fuels such as bio-propane, bio-gasoline, and SAF [Phillips 66, 2023]. The refinery has also increased its engagement with the growing market of lithium batteries, using its global leadership in providing speciality graphite coke, which is a key input in lithium-ion battery anodes [R35, R41]. As R10 pointed out: "Humber is the only refinery in Europe that produces such suitable graphite coke". This could in the coming years also be relevant for creating a successful battery Gigafactory and electric car manufacturing industry in the UK.

Immingham (Prax Lindsey). In recent years, this refinery has decreased its output by 25% as a consequence of ownership uncertainty [R30]. Prax only completed the purchase of the Immingham refinery from Total in March 2021, which at the time had no material decarbonisation strategy [Laister, 2023]. Although Prax was therefore not part of the *Zero Carbon Humber Partnership*, it did develop plans for a £300m carbon capture project, which was initially linked to the *V Net Zero cluster* to transport and store the captured CO_2. In January 2022, it submitted a bid for the Track-1 phase-2 competition, which was shortlisted in August 2022 but not selected in March 2023 for further negotiation. They are currently in discussions to buy off-the-shelf Amine CCS technology for retrofitting to emission points with the expectation of disposing the captured carbon through the recently selected Viking CCS cluster project [R48].

Grangemouth (Petroineos). In response to the COVID-induced recession, the Petroineos refinery closed its catalytic converter unit and one of two energy-intensive crude distillation units, which reduced emissions by 37% and was framed by the company as positive climate action [R30, R47, R48]. To reduce CO_2 emissions further, the refinery joined the Scottish Acorn CCS project, which has plans for repurposing existing onshore and offshore gas pipelines to transport CO_2 from Grangemouth to St Fergus gas terminal and from there to North Sea storage sites (*Figure 47*). Longer-term plans include the possibility that the St Fergus terminal could process natural gas into 'blue hydrogen' (using the same CCS infrastructure) and transport that to Grangemouth, where the Petroineos refinery (and INEOS petrochemical plant) could use it for thermal needs [R27, R47]. This Scottish cluster project was not selected in the 2021 Track-1 phase-1 competition, qualifying instead as 'reserve cluster'. In July 2023, however, Acorn was chosen as a Track-2 CO_2 transport and storage system, which opens the way for progressing the refinery's decarbonisation plans.

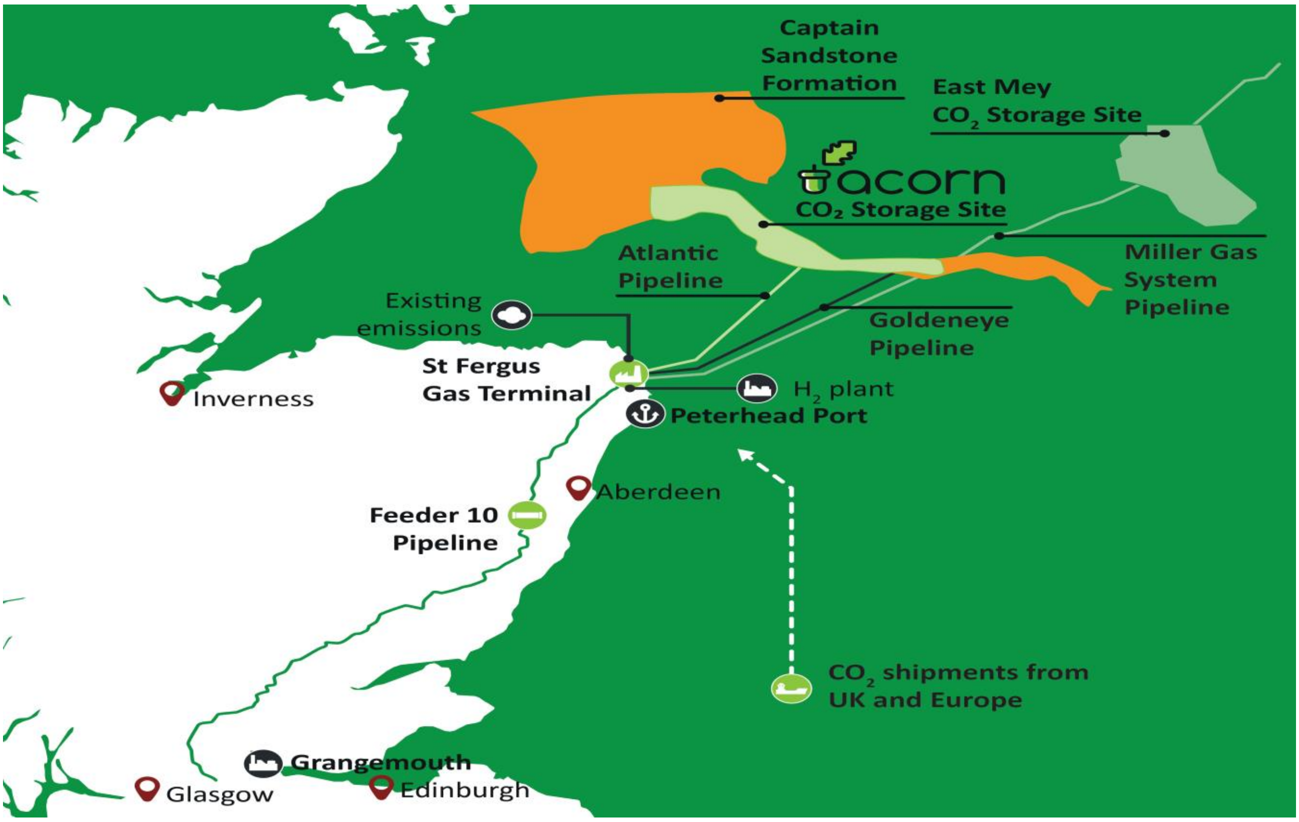

Figure 47: Schematic representation of the Acorn CCS project linking Grangemouth, St Fergus gas terminal, and North Sea storage sites (from: https://theacornproject.uk/; accessed July 2023)

There are uncertainties, however, about the future of the (relatively old) Grangemouth refinery, because PetroChina (which co-owns the refinery with INEOS on a 50:50 basis) is reportedly keen to sell its equity-stake [Lawson, 2022]. Because PetroChina is responsible for most of the refinery's financing requirements, this has caused concern with trade unions and government about management's willingness to invest in future decarbonisation [ibid].

Fawley (ExxonMobil). Decarbonisation of the Fawley refinery is disadvantaged by its location on the Solent on the south coast, firstly because there are no nearby exhausted gas fields for CO_2 storage (which complicate CCS solutions) and, secondly, because the Solent industrial cluster does not have a large industrial base where firms can share decarbonisation costs or buy (green or blue) hydrogen from a possible producer. Although ExxonMobil has started to explore hydrogen and CCS options with SGN (a British gas distribution company) and Macquarie's Green Investment Group, they have not committed to deployment [ExxonMobil, 2023].

Pembroke (Valero). Decarbonisation of the Pembroke refinery is also challenging because it has no suitable nearby CO_2 storage sites, and is even more isolated industrially than Fawley, which removes the ability to share decarbonisation infrastructure costs with other industries. Valero therefore has no advanced plans for deep decarbonisation, but has incrementally reduced emissions by investing in a new CHP plant [Welsh Government, 2023].

6.8. Pattern matching analysis

Our first descriptive research question has been answered by our 33-year longitudinal study, which identified the main contextual developments and business strategies in the oil refining industry. To assess further patterns in this longitudinal process, we compare each analytical period with the five phases in our conceptual model of industry reorientation, focussing on their low-carbon implications. As described in section 2, this model suggests that increasing external pressures push firms to gradually reorient through five phases: 1) inaction due to misinterpretation or denial, 2) incremental change, 3) hedging and exploration of alternative technologies, 4) deployment of new technologies while continuing to operate existing assets, 5) full reorientation to new technologies, possibly complemented by changes in mission, identity, and mindset.

The case-study clearly showed that climate-change was not the only important external pressure that UK refineries experienced throughout the five analytical periods. They also encountered significant economic pressures, which reduced their output by 45% between 1990 and 2021 (*Figure 7*) and reduced the number of refineries from 13 to 6. The industry also experienced socio-political pressures related to sulphur and lead in fuels, which were initially seen as more significant environmental problems than climate change. Because these other pressures also required corporate attention and responses, it is unsurprising that low-carbon reorientation by UK refineries was a protracted and non-linear process that only accelerated in the last two periods, as we will show.

In the first period (1990–2000), when climate-change rose on national and international socio-political agendas, refining industry actors mostly ignored the issue or the need to respond, which resonates with phase-1 in our model. By the mid-1990s, some industry actors (mostly BP and Shell) moved to phase-2 by starting to acknowledge the climate-change problem and proposing incremental responses (such as energy efficiency and reducing methane leakage), which also had positive economic value. Refineries in this period paid more attention to other pressures such sulphur and other particulate emissions, and changes in specific market segments (such as declining petrol and fuel oil demand and increasing diesel and kerosene demand), which caused increasing mismatches between refinery configuration and market demand, leading to more imports.

In the second period (2000–2008), when climate-change became embedded in international treaties and national and EU policies (including biofuel policies), refinery actors continued to focus on incremental energy efficiency improvements, but also started to engage with new technologies such as biofuels and CCS (although the latter was only done by BP). While this to some extent resonates with phase-3 for low-carbon reorientation, UK refineries mostly embraced biofuel blending, which is a relatively incremental change that resonates more with phase-2. The incumbent refineries did not choose to manufacture biofuels, but instead purchased biofuels from importers and domestic new entrants such as Greenergy. This period thus has elements of phase-2 and phase-3. Shrinking and changing market demand after 2005 continued to be of greater importance for managers, because declining refinery margins challenged profitability, leading *Big-Oil* companies to leave the refinery business, selling or closing particular plants.

In the third period (2008–2015), when the ground-breaking 2008 Climate Change Act set ambitious long-term targets, UK refineries reverted back towards phase-2, focusing primarily on incremental innovations and defensively bemoaning regulatory burdens (for biofuels). One important reason was that the 2008 financial crisis and subsequent recession exerted major economic pressures due to shrinking overall demand, which further diminished operating margins, causing financial losses and several closures. The refining industry thus focused on survival and retrenchment rather than low-carbon reorientation. Another reason is that climate policies in this period hardly focused on energy-intensive industries, which were assumed to be part of the remaining 20% of hard-to-decarbonise sectors. Refineries thus experienced limited decarbonisation policy pressure apart from biofuel policies that were strengthened (and continued to be met through blending).

In the fourth period (2015–2019), when UK policymakers started to focus more on industrial decarbonisation, highlighting the importance of more radical technologies like CCS and introducing funding schemes for FEED studies, UK refineries moved to phase-3 in which they continued to emphasise incremental innovations and advance defensive framings, but also acknowledged the possible need for more radical solutions. Their framing strategies also stressed, however, that the government would have to create the right financial conditions for them to deploy such technologies. Some companies also began to position themselves as frontrunners, with Phillips 66 for example moving into biofuel co-refining. Several refineries also participated in cluster-wide net-zero initiatives (especially in Merseyside and Humberside), which began to develop ambitious decarbonisation plans. Reduced economic pressures in this period also enabled refineries to recover financially, despite output still showing a small decline.

In the final period (2019-2023), after UK policymakers adopted a net-zero target for 2050 and introduced a raft of plans and instruments for industrial cluster decarbonisation, Essar Oil and Phillips 66 refineries in Merseyside and East Coast clusters moved to phase-4 for climate reorientation. Both started to prepare for radical technology changes (such as fuel switching and carbon capture), participating in cluster-wide net-zero initiatives. Even Prax Lindsey, whose management only recently arrived after ownership changed in 2021 and are not as financially well-resourced as the two leaders, are still tentatively embracing phase-4 change through their region's advanced cluster infrastructure, when compared to refineries in clusters that do not have defined CCS solutions. Petroineos aligned itself with the Acorn CCS project but uncertainties about future ownership and investment decisions mean that their commitment is ambiguous, which is why their reorientation has elements of phase-3 and phase-4. Valero and ExxonMobil are more tentative, as they are still evaluating their options, due to their locational disadvantages. The different geographies of industrial clusters has thus led to mixed responses by UK refineries.

This pattern-matching analysis thus shows that low-carbon reorientation followed an oscillating pattern with refineries going back and forth between phase-2 and 3 in the first four periods, only moving to phase-4 in the last period (at least some refineries). This oscillation pattern is, at least partly, due to the 2008 financial crisis, which pushed the industry into survival mode in the third period, leading to less interest in low-carbon reorientation.

Although economic decline in output continued in the fourth and fifth period, this did not prevent UK refineries to increasingly engage with low-carbon technologies, moving towards deployment in the last period. Because this differs from the UK steel industry, where economic decline did hamper low-carbon reorientation [15], we provide three reasons for this. One reason is that UK refineries were mostly profitable after 2015 (with a dip in 2020), which means they had some scope for decarbonisation investments, which they perceive as necessary to ensure long-term survival. The UK steel industry, in contrast, experienced significant financial losses (£5.8bn) between 2009 and 2021[15]. Secondly, while the UK steel industry was long under single ownership, the multiple UK refineries competed with each other, which meant that the closure of one or more refineries could have positive effects on the performance of the remaining ones (increasing their operating and profit margins). A third reason is that four UK refineries are in clusters that have the ability to develop CCS-systems (and blue hydrogen) using nearby offshore storage sites, which is not the case for Tata's main steelworks in Port Talbot. These three differences help explain why the UK oil refining industry has been able to move towards phase-4 in recent years and the UK steel industry not, despite both industries experiencing prolonged decline.

6.9. Conclusions

Although the UK oil refining industry reduced its CO_2 emissions by 46% between 1996 and 2021, this was mostly due to refinery closures and incremental efficiency improvements rather than deeper low-carbon reorientation. Our longitudinal analysis shows that the industry only limitedly engaged with climate change for most of the case study period, oscillating between phase-2 (incremental change) and phase-3 (exploration of radical alternatives) in our conceptual model. Since about 2019, however, the industry's low-carbon reorientation markedly accelerated as most UK refineries have moved towards the deployment of low-carbon alternatives (phase-4). Although full implementation of these alternatives, notably CCS, hydrogen (mostly 'blue' with some 'green') and bio-crudes, will happen the coming years, refineries have developed detailed plans and committed significant financial resources, including to purchasing low-carbon technologies.

This commitment happened despite the refining industry being in long-term decline, which normally reduces the willingness of firms to embark on deeper forms of low-carbon reorientation [Geels & Gregory, 2023]. We identified several reasons that explain why (most) UK refineries nevertheless engaged in deeper reorientation: 1) in general, remaining firms in declining industries can be profitable if the closure of unprofitable firms increases market share and operating margins of surviving firms; specifically in the case, UK refineries had restored profitability by the mid-2010s and thus had resources for investment, 2) four refineries could piggyback on wider industrial cluster decarbonisation initiatives, 3) legally-enshrined net-zero targets increased general decarbonisation pressures, 4) multiple government subsidy schemes (for CCS systems, blue and green hydrogen, and carbon capture) lowered cost thresholds for technology deployment, 5) some refineries perceived new economic opportunities (e.g., biofuel markets, selling blue hydrogen to other firms).

Because of these reasons, (most) UK refineries were willing to strategically reorient in low-carbon directions, which had long been seen as very difficult (because refineries have capital intensive, non-standard, complex configurations of technology that are difficult and costly to reconfigure). In terms of directionality, the four refineries that can piggyback on wider cluster initiatives all use carbon capture technologies. Of these four, Essar (and possibly Petroineos in the future) will also make and use blue hydrogen, while Phillips 66 intends to use green hydrogen. Essar and Phillips 66 are also moving into biocrude processing. The two refineries without nearby offshore storage sites (in Fawley and Pembroke) have less developed decarbonisation plans and focus mostly on incremental changes.

An important future uncertainty is that the intended ban on new petrol and diesel car sales, which was recently (in September 2023) delayed from 2030 to 2035, is likely to significantly reduce the demand for oil products in the UK. It is thus quite possible that some of the six remaining oil refineries will (have to) close in the medium term. Because of the long-lived nature of capital-intensive refinery assets, this prospect will likely shape future investment decisions of some refinery managers. Some refineries may thus delay significant investments, run-down their assets for as long as they remain profitable and abandon them when they start to make losses. Investment in low-carbon reorientation thus also reflects the degree of confidence that owners and investors have in the long-term future of particular refineries. The flippancy of policymakers (as with the recently delayed petrol and diesel car sales ban) further increases investment uncertainty, making it more difficult for companies to develop long-term strategies. Although it is difficult to predict how many refineries will survive 10-15 years from now, these considerations imply that the unfolding low-carbon transition will not only affect the industry's future carbon performance, but also its future size and shape.

We suggest that our general findings about the drivers and barriers of oil refinery decarbonisation have wider applicability beyond the UK case. Specifically, we expect that refinery decarbonisation in other countries will also be a protracted process, in which firms slowly and reluctantly move through different phases. The shift to phase 4 (deployment and diversification) will likely require significant policy support because firms balk at the significant capital expenditures involved. Also, the more specific findings with regard to decline and decarbonisation are likely relevant for oil refining industries in many countries, as the diffusion of electric vehicles will likely reduce the demand for petrol and diesel in the coming decade, leading to reduced output. While the types of factors and mechanisms will likely show similarities between countries, the precise way in which socio-political and economic context pressures interact with company responses will probably vary between countries, possibly affecting the speed and patterns of low-carbon reorientation.

Conceptually, we conclude that the Triple Embeddedness Framework (TEF) is a useful analytical framework for analysing industrial decarbonisation because it acknowledges that low-carbon reorientation is a multi-phase process, that firms-in-industries face multiple pressures besides climate mitigation, that increases in other pressures may delay or partly reverse low-carbon reorientation, and that firms can accelerate decarbonisation activities if they see economic opportunities and/or are sufficiently supported and incentivised. One limitation is that the TEF does not explicitly accommodate geographical dimensions, which in the UK case were clearly important (through varied availability of offshore CO_2 storage sites and varied net-zero activities in regional clusters). Future conceptual work could fruitfully elaborate the TEF's geographical dimension.

Future transitions research could also fruitfully investigate and compare oil refining decarbonisation in other countries, analyse decarbonisation in other declining industries like steel (in many countries), or apply the TEF to decarbonisation in other industries. More generally, we hope that this article will inspire more future research that builds on but goes beyond techno-economic analyses of industrial decarbonisation to provide deeper real-world understandings of the multiple contextual pressures and strategic considerations that shape low-carbon technology deployment by industrial firms.

7. Comparative analysis, conclusions, and policy advice

The three separate, longitudinal industry case studies presented in Chapters 4, 5 and 6, showed that oil refiners have moved from phase 3 to phase 4 since 2019, but that steelmakers and petrochemical firms are still in phase 3. This Chapter's comparative analysis now explains why there were these differences focusing on five factors: a) varying effects of policy support, b) the degree of foreign competition, c) financial health and economic feasibility, d) technical and practical feasibility, e) wider corporate strategies and mindsets. It will then offer lessons and policy advice.

Before analysing these factors, we note that all three UK industries significantly reduced their (scope-1) greenhouse gas emissions in recent decades: steelmakers by 56% between 1990 and 2021, oil refining by 46% between 1996 and 2021, and petrochemicals by 88% between 1990 and 2019. These reductions, however, did not result from significant low-carbon reorientation, but instead arose from: a) incremental (energy efficiency) innovations related to cost-reduction, b) reduced emissions of two very strong climate-forcing gases (N_2O and HCFC-22) in petrochemicals, and c) industrial decline, leading to plant closures. This decline has been especially marked in the steel industry (Chapter 5) and oil refining industry (Chapter 6). UK petrochemical production output increased steadily in the 1990s and early 2000s, but decreased by 32% between 2008 and 2010, followed by oscillating output in subsequent years (Chapter 4).

7.1. Varying effects of policy support

The first important *external* pressure is the varying degree of policy support for industrial decarbonisation, which in recent years has increasingly focused on six industrial clusters (Figure 48) [Sovacool et al., 2022], which account for 53% of industrial greenhouse gas emissions [HM Government, 2021: 17]. This cluster focus stems from the government's preference for carbon-capture-and-storage (CCS) and hydrogen fuel switching as the core industrial decarbonisation options, which was first articulated in the 2017 *Clean Growth Strategy*, elaborated in the government's 2018 *CCS Action Plan*, and anchored in the 2020 *Ten Point Plan for a Green Industrial Revolution*, which aimed for CCS deployment in two industrial clusters by 2025 and in four clusters by 2030, capturing up to 10 $MtCO_2$ per year. This Plan also aimed for the production and use of 5GW low-carbon hydrogen by 2030 (mostly 'blue' hydrogen produced from natural gas and CCS). Because CCS and hydrogen require expensive infrastructures they can only be developed and deployed in industrial clusters where co-located firms can share costs and technical capabilities [Sovacool et al., 2022].

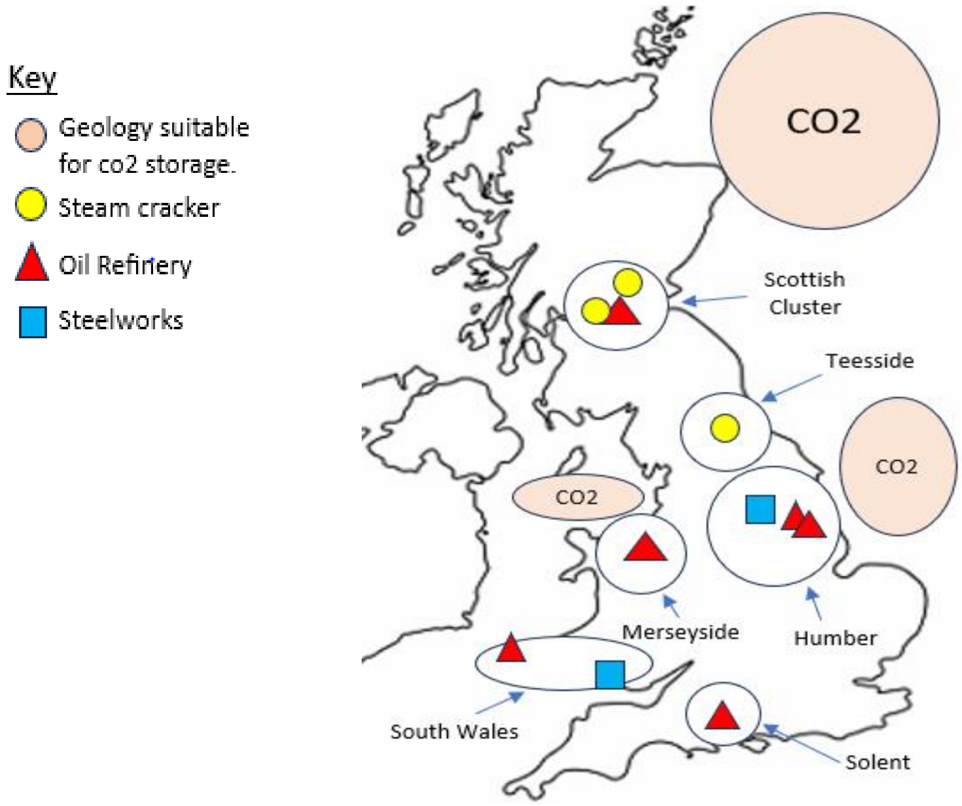

Figure 48: The six principal UK cluster locations, with emitting assets and usable CCS geology highlighted

The government's goals and general strategies were increasingly complemented by a raft of implementation-oriented instruments and funds, including the Industrial Strategy Challenge Fund (which allocates £170m to Clean Growth and Transforming Construction, matched by £250m of private sector investment, to enable firms to make feasibility and Front-End-Engineering-Design studies of CCS and hydrogen), the £315mn Industrial Energy Transformation Fund (to provide capital grants for the deployment of low-carbon technologies such as hydrogen fuel switching), the £240m Net Zero Hydrogen Fund (to support at-scale deployment of low-carbon hydrogen production during the 2020s), a £140m Industrial Decarbonisation and Hydrogen Revenue Support Scheme to support the deployment of carbon capture technologies and hydrogen fuel switching in industrial firms), and a £1bn CCS Infrastructure Fund (to support capital expenditure on CO2 transport & storage infrastructure (T&S)).

Additionally, policymakers created specific business models to create financial support for different parts of CCS and hydrogen systems, including Dispatchable Power Agreements (for electricity plants with CCS), Industrial Carbon Capture business models (for the deployment of carbon capture technology by industrial users), Low Carbon Hydrogen Agreements (for low-carbon hydrogen producers), and a Regulated Asset Base model (to support the *operation* of CO_2 T&S infrastructures). In tandem, the government further increased its commitment to CCS and hydrogen, as its 2021 *Net Zero Strategy* raised CCS targets for 2030 to 20-30 $MtCO_2$ per year, while the 2022 *British Energy Security Strategy* doubled low-carbon hydrogen ambitions to 10 GW by 2030, with at least half coming from electrolytic (or 'green') hydrogen. The government's 2023 Spring Budget also earmarked £20 billion to scaling up CCS projects across UK clusters in the coming years.

Implementation of various funds has proceeded through the government's cluster sequencing approach, which distinguishes Track-1 (for two operational low-carbon clusters by 2027) and Track-2 (for two more operational low-carbon clusters by 2030). Both tracks have a phase-1 competition (focused on creating CO2 T&S infrastructures) and a phase-2 competition (for firm-level projects that can connect to T&S infrastructures). In October 2021, the government selected the East Coast Cluster (which encapsulates both Humberside and Teesside) and HyNet (in Merseyside) as Track-1 phase-1 winners. In July 2023, policymakers also selected the Acorn T&S project (linked to Grangemouth) and the V Net Zero (renamed 'Viking') T&S project (linked to Humberside) as Track-2 winners.

The reason that these policy support schemes differentially affect the speed of low-carbon reorientation in our three focal industries is that these industries have varying degrees of presence in the selected clusters (Figure 49). The two integrated steelworks are only in two clusters, and one of them (TSUK in South Wales) is not in the government's selected clusters, which helps explain its low reorientation speed, as it does not benefit from the above-mentioned policies and funds. The other one (British Steel in Humberside) could have piggybacked on the Zero Carbon Humber Initiative by submitting a Track-1 phase-2 bid but did not do so (because the take-over in 2020 by Jingye Group of China misaligned with the timeframes).

The UK's six remaining oil refineries are spread across five clusters (with two in Humberside). The two refineries (Valero and ExxonMobil) in the non-selected clusters (South Wales and Solent) have limited access to policy support, which hampers their low-carbon reorientation – and it should not be assumed that either refinery will prefer low-carbon reorientation over withdrawing from the UK, particularly as both companies are American owned and managed, and the policy support for net-zero related investments within the USA is significantly greater. Of the three refineries in Track-1 clusters (Essar Oil, Phillips 66, Prax Lindsay) submitted Track-1 phase-2 funding bids in January 2022. Although only Essar's bid was selected in March 2023, the other two refinery projects are very well-placed for future Track-2 phase 2 funding bids, because the refineries are closely linked to the V Net Zero cluster (recently renamed 'Viking'). The Petroineos refinery in Grangemouth, despite the recent creation of a forward trajectory by the Acorn project being recently selected as Track-2, is now set to close [citation].

The biggest chemical and petrochemical firms are in Grangemouth (INEOS, ExxonMobil), Teesside (SABIC, CF Fertilisers, INEOS), and Merseyside (CF Fertilisers), which are selected Track-1 and Track-2 clusters. Although these firms could thus benefit from policy support, they have not yet significantly committed to deploying low-carbon technologies, despite making future-oriented plans and statements [Feltrin et al., 2022; Geels, 2022; Mah, 2023]. This means that other factors, which we discuss below, are at play.

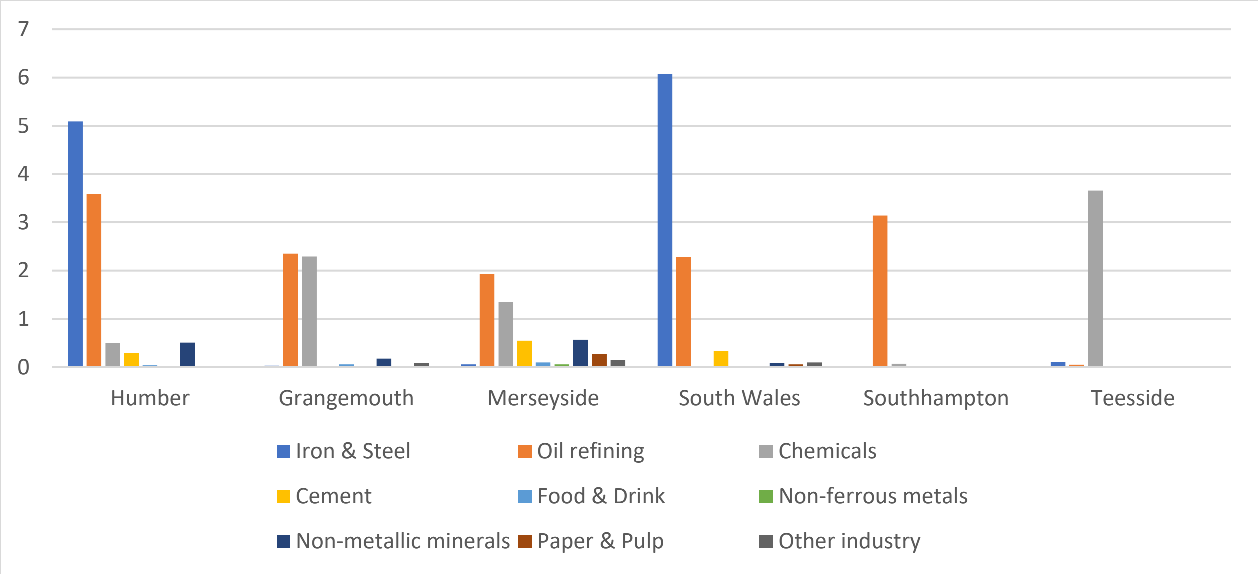

Figure 49: CO_2 emissions (in Mt) from different industrial sectors (excluding power generation) in 2018 in six UK clusters (constructed using data from HM Government, 2021 121)

Another (technological) dimension of selectivity is that the government's focus on CCS and fuel switching led to less policy support the steel industry, where other decarbonisation pathways are also important, including Electric Arc Furnaces (EAFs) and hydrogen direct reduction of iron ore (HDRI) [Kim et al., 2022; UK Steel, 2022]. Initially, the government's only direct support for steelmakers was the £250m Green Steel Fund, which policymakers consulted on in 2019. But since deep decarbonisation of Port Talbot and Scunthorpe steelworks with an iron-ore feedstock, is estimated to cost around £6bn [Geels and Gregory, 2023], both TSUK and British Steel said this was too little funding, leading them to raise the prospect of closure. After years of difficult negotiations, the owners of the two integrated steelworks have recently (Autumn 2023) made deals with the government to reorient towards Electric Arc Furnaces (EAFs), each receiving £500m policy support, which they will match with about £750m funding [Sweeney, 2023; Jolly, 2023]. Although this has the potential to transform UK steelmakers from the (comparatively) slowest to the fastest low-carbon reorienting industry, there are practical hurdles that may cause delays – which will be discussed further in section 7.4 (Technical and practical feasibility).

7.2. Degree of foreign competition

Another relevant *external* pressure is the varying degree of foreign competition, which shapes to what extent additional costs for low-carbon technologies may affect competitiveness. Steelmaking has the greatest product homogeneity and has been mostly impacted by international competition in both international and UK markets, first by cheap steel from former Soviet countries and then by steel from China, which by 2021 produced 53% of the world's crude steel. This negatively affected both the exports of UK steel products and the sale of UK steel products in the UK, where foreign imports steadily replaced it (Figure 7). This not only contributed to the steady decline of the UK steel industry (Figure 2), but also limited its ability to pass additional decarbonisation costs on to consumers, which helps explain its slow speed of low-carbon reorientation.

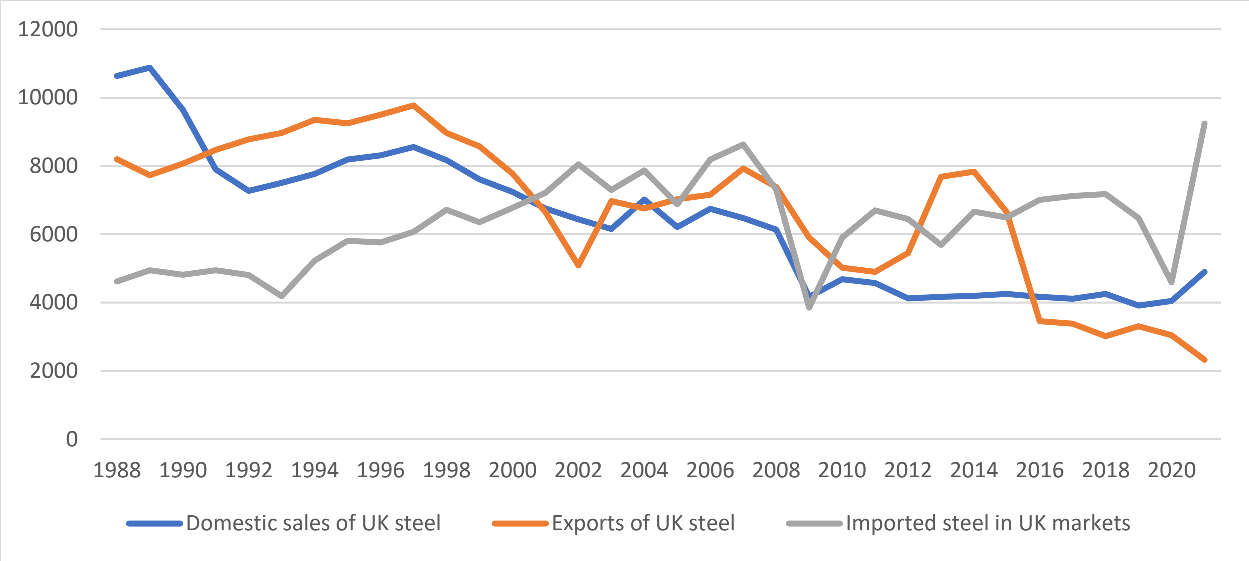

Figure 50: Sales volumes (in kilotonnes) of UK steel products in domestic and export markets and imported steel into UK markets, 1988-2021 (constructed using purchased data from the International Steel Statistics Bureau)

The UK petrochemical industry also faced increasing international competition in the past few decades, especially in the bulk chemicals segment, where producers from Asia and the Middle East (with cheap feedstocks) entered world markets. This created overcapacity in Europe, leading to plant closures and declining operating margins [Galambos et al., 2007]. While some petrochemical firms diversified towards the more profitable specialty chemicals segments, others continued to produce primary chemicals. Petrochemical firms expanded output until the 2007/8 financial crisis (Figure 4), taking advantage of growing market demand. Stagnating production and sales after 2008 increased the petrochemical industry's concern that decarbonisation costs would reduce its international competitiveness. Using this argument, the industry has long resisted climate policies and low-carbon reorientation [Mah, 2023], for example through statements by the Chemical Industries Association (CIA, 2019) and public letters by INEOS [Pooler, 2019]. UK oil refineries have comparatively been least impacted by international competition because they mostly compete with each other in the UK market. Foreign imports did increase since the 1990s (Figure 50), but this was because existing UK refineries, which were configured to mostly produce gasoline, were unable to meet changing market demand for more kerosine (due to increased aviation) and more diesel and less gasoline (due changes in the car market). The increasing imports of diesel and kerosine thus met unfulfilled demand rather than competing with UK refineries. The imports also remained smaller than domestic production (Figure 7), which differs from the steel sector where imports overtook domestic sales of UK steel products (Figure 50). This lesser degree of international competition means that additional costs for low-carbon reorientation do not significantly affect competitiveness, since they affect all UK refineries.

In sum, while concerns about international competitiveness hampered and delayed low-carbon reorientation in steel and petrochemical industries, this factor was less important in oil refining.

7.3. Financial health and economic feasibility

One important *endogenous* consideration are decarbonisation costs, which are high in all three industries. Deep decarbonisation of the two integrated steelworks is about £6bn, so roughly £3bn per plant [Geels and Gregory, 2023]. The two biggest petrochemical firms, INEOS and SABIC, announced that their future decarbonisation plans and roadmaps, which would entail CCS, hydrogen fuel switching and some degree of equipment electrification, would respectively cost more than £1bn for the Grangemouth site (which is shared with the Petroineos refinery) and about £850m for the Teesside cracker complex (INEOS, 2021; Jasi, 2021). For oil refinery decarbonisation, Essar Oil (2023) estimates decarbonisation costs (for CCS, hydrogen fuel switching, and hydrogen production) at around $1.2bn dollars, while Phillips 66 estimates the first phase of its large carbon capture project with VPI Immingham power plant (to capture 3.8 $MtCO_2$ per year by 2027) at £1.2bn and the second phase (to capture 8 $MtCO_2$ per year by 2030) at over £2bn [Geels et al., 2023].

Although the government provides significant subsidies, as discussed in section 7.1, the economic feasibility of these expensive low-carbon options strongly depends on the financial health of firms, which varies significantly across industries. Financial health is lowest in the steel industry, where TSUK experienced $5.8bn losses between 2009 and 2021 (Figure 51) because of declining sales and utilisation rates.[22] In 2016, TSUK tried to sell all its assets, but could not find a buyer. It did, however, sell the Scunthorpe steelworks in 2016 to Greybull Capital for £1. The renamed company, British Steel, went bankrupt in 2019 but was bought in 2020 for £24.1m by Jingye Group of China [Geels and Gregory, 2023]. Because of these financial problems (and continued doubts about future viability), it is understandable that steelmakers balked at the high decarbonisation costs, which slowed their reorientation speed.

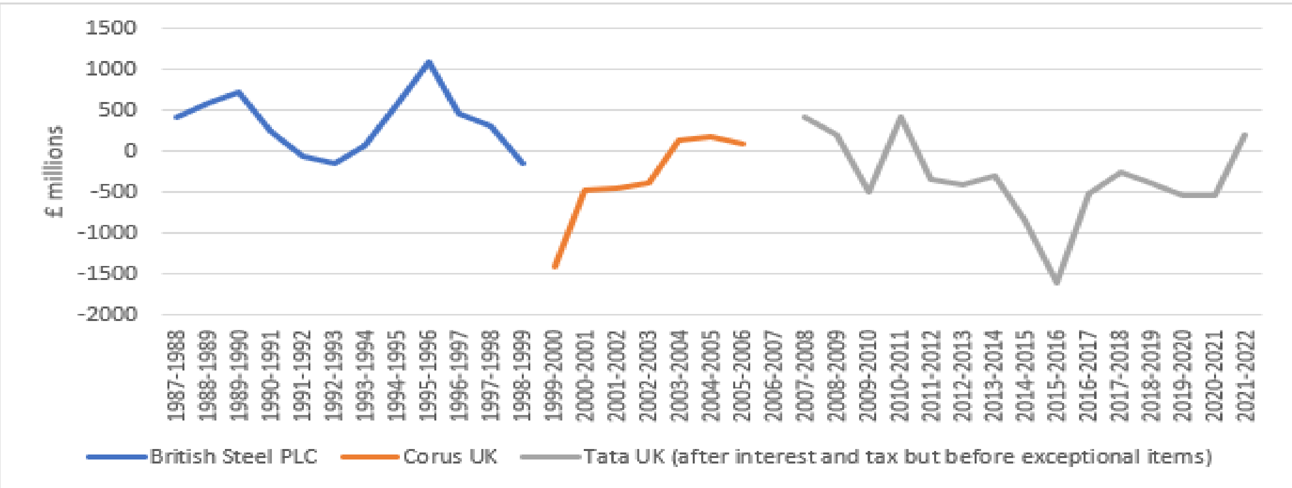

Figure 51: Annual consolidated financial earnings (in £ millions) before tax of successive owners of UK steel industry assets (constructed using annual report and accounts of British Steel PLC, Corus UK, Tata Steel UK.

Compared to steelmakers, oil refining firms are financially healthier (Figure 52). The surviving refineries have mostly been profitable in the past 15 years, although two external shocks (the financial crisis and COVID-pandemic) caused problems. The 19% decrease in refinery output between 2008 and 2013 (Figure 3) worsened industry-wide utilisation rates (Figure 53), causing downward pressure on profits (Figure 9). This resulted in three refinery closures in Teesside (2009), Coryton (2012) and Milford Haven (2014). These closures enabled the remaining refineries to improve their utilisation rates, with a notable dip in 2013 (which caused financial loses that were reported in 2014 annual reports). Improved utilisation rates enabled the

[22] To stay profitable, capital-intensive industries need to produce above certain utilisation rates margins (often around 75-80% of total capacity) to spread fixed costs over many output units. When they operate below these rates (due to declining demand and sales), these industries can quickly make large losses. Their profitability therefore often has a cyclical character.

surviving refineries to restore profitability[23] until the COVID-induced slump in economic activity reduced refinery output (Figure 3), utilisation rates, and profits in 2020 (Figure 52& 53). The financial dip was short-lived, and most refineries soon turned profitable again. Because of their stronger financial performance, the economic feasibility of low-carbon option is greater for refineries than for steel and petrochemicals, which helps to further explain their higher reorientation speed.

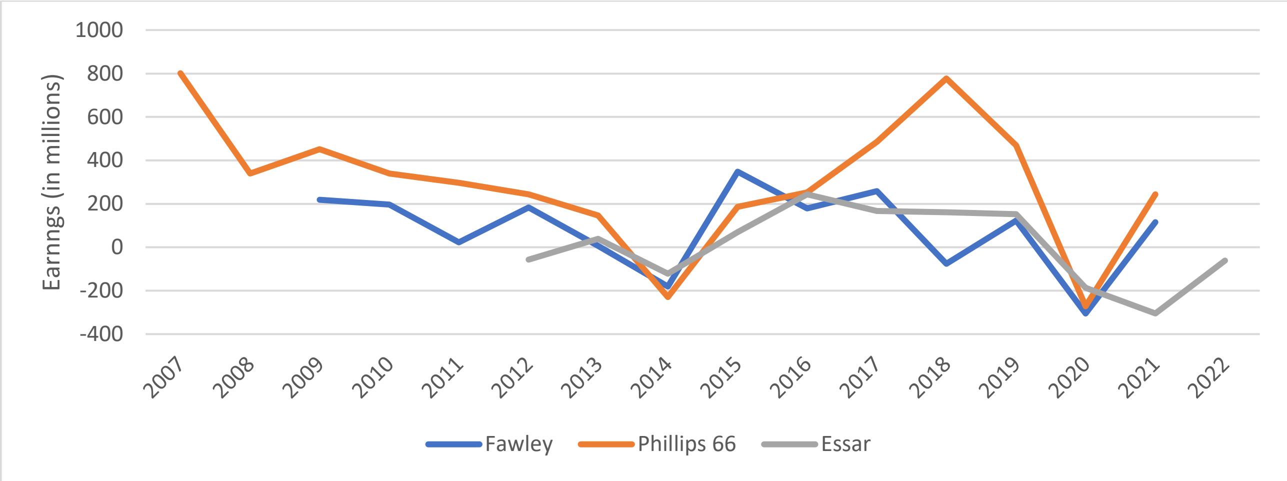

Figure 52: Earnings (in millions) for three UK refineries (Fawley in UK pounds and Essar and Phillips 66 in US dollars) (constructed using financial data from successive annual reports; we did not include information from Petroineos, Valero, and Prax because their financial data had frequently changing parameters and sometimes obscure reporting)

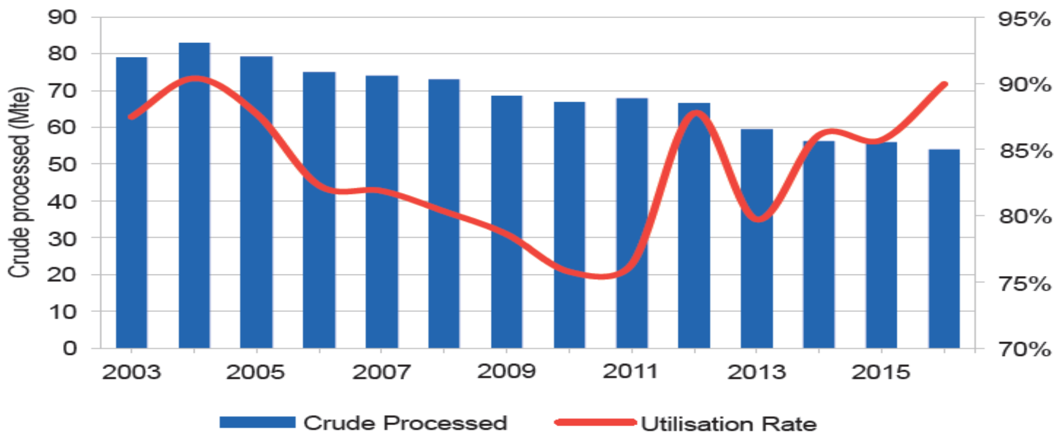

Figure 53: Output (blue and left axis) and utilisation rate (red line and right axis) of UK refineries, 2003-2016 (UKPIA, 2018: 14)

The financial performance of petrochemical firms (Figure 54) was better than steelmakers but worse than oil refineries. Decreasing production after the 2007/8 financial crisis worsened utilisation rates, leading to losses in 2013/14 [Geels, 2022]. Since then, SABIC and INEOS have both made profits, but since these have been relatively small, it is challenging for both firms to raise the large sums needed for decarbonisation, which helps explain why both firms have reoriented rather slowly.

[23] This effect points to an important industry structure difference between oil refining and steelmaking. Because oil refining is an oligopoly with multiple competing firms, the significant decline in industry output (Figure 3) led to the demise of weaker firms but enabled surviving firms to remain profitable. This contrasts with UK steelmaking, which for a long time was a single entity (British Steel PLC, Corus UK, Tata Steel UK). Without the possibility of weaker firms absorbing losses, declining output, closures, and asset write-offs therefore directly affected profitability of the entity.

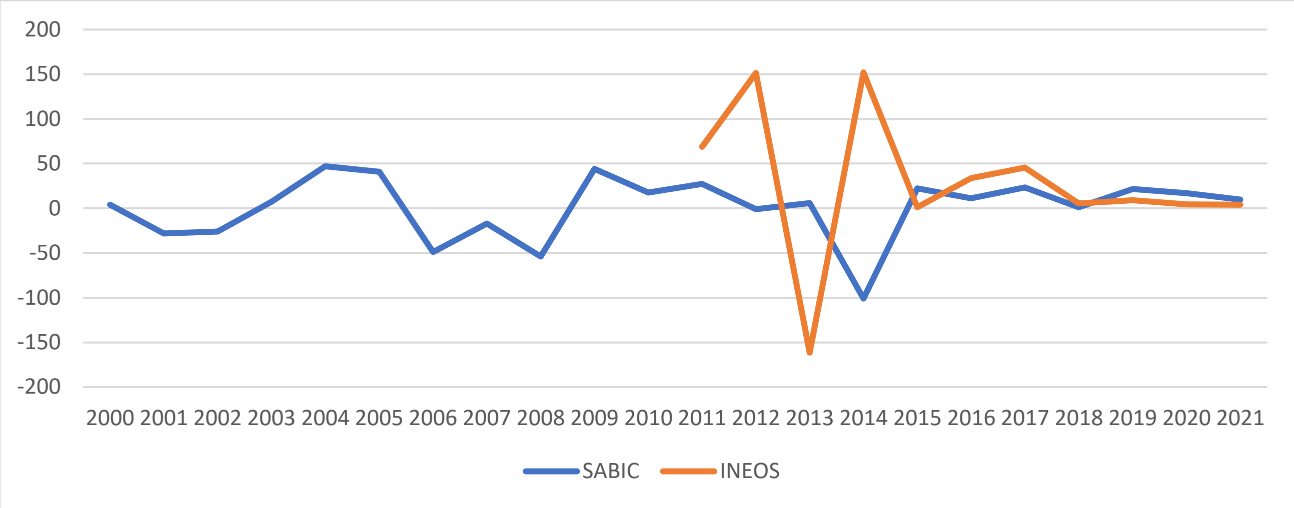

Figure 54: Earnings (in £millions) for INEOS and SABIC petrochemical firms (constructed using financial data from successive annual reports – which included Huntsman Petrochemical data from 2000 - 2005)

7.4. Technical and practical feasibility

Another important *endogenous* consideration are technical feasibility, disruptiveness, and other practical considerations of low-carbon options, which vary considerably across the three industries. CCS and hydrogen fuel switching are technologically feasible and not overly disruptive for both oil refineries and petrochemical plants [Geels, 2022; Gregory and Geels, 2023]. Carbon capture is not technically challenging, because it uses acid-gas absorption and regeneration process capabilities that firms in both industries have familiarity with. The main practical challenge is that the technical kit is bulky because of the large amounts of CO_2 that need to be captured (sometimes from exhaust streams with low CO_2 concentrations). Because carbon capture technologies require a lot of space, it may be practically challenging to fit them onto existing sites.

Hydrogen fuel switching is also not technically complicated for refineries, which already use hydrogen as part of their operational processes such as hydrotreating and hydrocracking [Gregory and Geels, 2023]. Petrochemical plants also have deep capabilities with regard to processing various gases, which enable them to implement hydrogen fuel switching [Geels, 2022]. This switch will require some adjustments in burners and furnaces (because hydrogen burns differently), but these changes are mostly incremental.

The strong appeal of CCS and hydrogen fuel switching for refineries and petrochemical plants is that they can be retrofitted onto existing plants (at the back-end or front-end) without requiring significant changes in core operational processes. A crucial practical challenge is that only the Teesside, Humberside, Merseyside, and Grangemouth clusters have nearby offshore CO_2 storage sites. The geographical morphology near South Wales and Solent does not provide suitable offshore storage sites, which means that CCS and blue hydrogen are not practically feasible for two refineries (Valero, and ExxonMobil), which hampers their low-carbon reorientation.

The technical and practical feasibility of low-carbon options are lower for steelmakers. CCS (and blue hydrogen) is not feasible for Port Talbot in South Wales (because of lacking offshore storage sites). It is feasible for the Scunthorpe site, which could piggyback on the Humberside's wider net-zero cluster development, but British Steel has decided not to take this route.

Hydrogen direct reduction of iron ore is still in early development stages with uncertain cost, and therefore less attractive for steelmakers. EAFs are a proven technology, but shifting the integrated steelworks to EAFs, which both firms recently agreed with policymakers, will likely encounter practical feasibility challenges: 1) electricity grids will struggle to provide the large amounts of power required (and grid upgrades are slow), 2) the required large amounts of high-quality scrap metal are not yet available, 3) recycled steel (from scrap metal smelting) has lower quality and cannot be used for all purposes, 4) high UK electricity prices may hamper international competitiveness (see figure below), 5) there will also be a significant loss of high-earning skilled employment, when the blast furnace closes, as EAF technologies are far less labour intensive than blast furnace technology, and this is likely to create considerable political turbulence in the region. It remains to be seen if these hurdles can be overcome, or if the shift to EAFs will further reduce the UK's steel output.

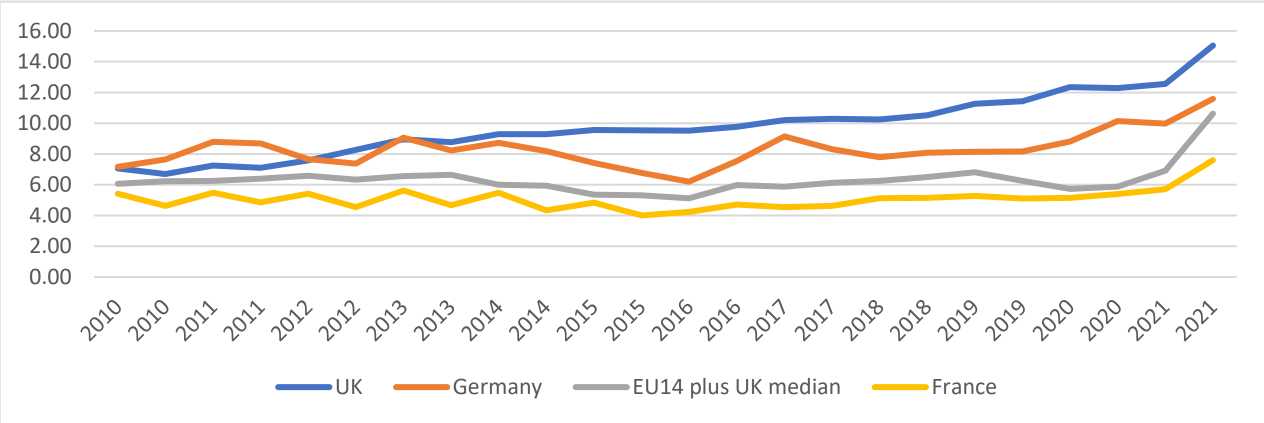

Figure 55: Industrial electricity prices in pence/kWh (for January and July of each year) in selected European countries for extra-large electricity consumers including taxes (excluding VAT and other recoverable taxes and levies) (constructed using data from BEIS, 2022)

Inputs for EAFs could also come from hydrogen direct reduction of iron ore (HDRI), which produces

More generally, since both the South Wales and the Solent clusters are disadvantaged structurally by their location's geology, lack of industrial density and soon to be lack of CCS and blue hydrogen infrastructure, both these regions will remain handicapped in the future, in their ability to attract the 'green' businesses of the future. The politically discussed net-zero levelling up will not be open to them. This thus requires additional policy attention.

The above considerations imply that the steel industry faces larger technical and practical feasibility problems than the refining and petrochemical industries, which helps explain why its low-carbon reorientation is the slowest. These considerations do not explain, however, why petrochemical firms have not yet moved to phase-4 of low-carbon reorientation. We suggest that corporate strategies and mindset are important in that regard.

7.5. Wider corporate strategies and mindset

A third *endogenous* consideration is the degree to which low-carbon reorientation aligns with wider corporate strategies and mindsets. This alignment is low in the steel industry, where the 61% decline between 1997 and 2021 (Figure 2) led corporate strategy to focus primarily on retrenchment through cost-cutting, divestment, asset closure, outsourcing, and incremental efficiency improvements [Geels and

Gregory, 2023]. The 2008-2015 period was particularly challenging, as escalating financial losses (Figure 51) threatened the survival of steelmakers and led to the closure of the Redcar integrated steelworks in 2015. Steelmakers thus mostly perceived decarbonisation as imposing cost that reduces profitability and international competitiveness, which helps explain their slow reorientation speed.

The alignment is also low in the petrochemical industry because corporate strategies of the main firms have deepened their fossil fuel-oriented trajectories in the past decade [Geels, 2022; Mah, 2023]. INEOS, for example, invested £1.5bn in securing cheap ethane from the United States (constructing pipelines from US shale gas fields to the coast, building deep-water port terminals, purchasing 8 new gas-carrier ships, and securing 15-year gas supply contracts starting in 2016). In 2017, INEOS purchased the entire North Sea exploration and production business from DONG Energy (for $1.05bn) and the Forties pipeline system from BP for £200m, which it aims to upgrade to “ensure it operates into the 2040s” (Dickie, 2019). SABIC (Saudi Arabia's Basic Industries Corporation), which purchased the massive Olefin 6 cracker in Teesside in 2006, also secured cheap US ethane imports in the late 2010s. In 2020, Saudi Aramco increased its ownership share of SABIC to 70 %, deepening the integration of oil and petrochemical industries.

Because of these wider corporate strategies, petrochemical firms not only perceived low-carbon reorientation as externally-imposed cost that reduces international competitiveness (discussed in section 3.2), but also as a potential threat to their new assets and wider strategy. The industry has therefore long resisted low-carbon reorientation, with INEOS acting as particularly combative firm that has underreported CO_2 emissions, lobbied for UK shale gas and green tax exemptions, opposed climate policies, and threatened to offshore its plants [Feltrin et al., 2022; Mah, 2023]. This strategy and mindset are a significant factor in explaining the relatively limited speed of the industry’s low-carbon reorientation, despite the high technical feasibility and potential access to policy support, discussed above. Although the industry has, in recent years, made future low-carbon roadmaps and plans, increased its exploration activities, and floated possible large expenditures, its commitment to real-world deployment and spending is still limited.

While oil refineries have also long opposed and delayed significant low-carbon reorientation, some of them have, since 2019, changed their strategies and mindset as they started to see economic opportunities [Gregory and Geels, 2023]. Essar Oil, for example, has actively participated in the HyNet cluster initiative, where it will become the main (blue) hydrogen supplier that can sell to other firms in the cluster (to enable fuel switching). Phillips 6 has similarly moved into new economic areas such as biofuel co-refining, green hydrogen production (through participating in the Gigastack project), and the production of speciality graphite coke, which is a key input in lithium-ion battery anodes. More broadly, the low-carbon frontrunners aim to position themselves as leaders for the longer-term future, for which they expect decreasing demand for oil refining products (because of electric vehicles) and a further reduction in the number of UK refineries [Gregory and Geels, 2023].

The varying mindsets and corporate strategies thus help to further explain why low-carbon reorientation is presently progressing faster in oil refining than in steel and petrochemicals.

7.6. Conclusions

Having unpacked the five factors that explain the varying speed of low-carbon reorientation in UK steel, petrochemical and oil refining industries, despite all facing similar regulatory net-zero obligations and sharing many characteristics (such as plants being capital-intensive, technologically complex, and expensive to reconfigure), we can also rank and summarise their impact. Table 1 shows that the UK steel industry scores low on all factors, so it is understandable why steelmakers have been slow to reorient. The industry receives comparatively limited policy support, faces stiff international competition, has poor financial health, has focused mostly on survival (through retrenchment), and experiences practical and technical feasibility problems for all of its low-carbon options.

Table 8 also shows that UK oil refining scores comparatively well on all five factors, which explains why it is reorienting fastest. It benefits significantly from support funds, mostly competes nationally (and thus has fewer concerns about negative effects on international competitiveness), is in decent financial health (and thus has money to spend), has technically feasible low-carbon options, and changed its strategy and mindset (focusing on economic opportunities and long-term strategic positioning).

The relatively slow reorientation in the UK petrochemical industry is more puzzling, because its low-carbon options are technically feasible, and the industry could access significant policy support (but has only limitedly done so). Strong international competition (and associated concerns about additional costs) and limited financial profitability in recent years are part of the explanation. But the main reason, we suggest, is that the industry's corporate strategy has deepened its fossil fuel commitments in the past decade, which it wants to protect by delaying its low-carbon reorientation.

	Steel	**Petrochemicals**	**Oil refining**
EXTERNAL PRESSURES			
1) Potential access to policy support	Weak	Strong	Strong
2) International competition (with strong competition decreasing decarbonisation ambitions)	Strong	Strong	Weak
FACTORS SHAPING STRATEGIC RESPONSES			
3) Financial health and economic feasibility	Weak	Moderate	Strong
4) Technical and practical feasibility	Low	High	High
5) Wider corporate strategy and mindset	Weak	Weak	Strong

Table 8*: Assessment of the relative importance of different factors in accelerating low-carbon reorientation*

The wider contribution of our project to the industrial decarbonisation literature is that it highlights the importance of making multi-dimensional analyses of industries, which acknowledge both external pressures and firm-level strategic considerations. While techno-economic analyses of low-carbon options, which dominate the literature, remain important, the paper shows the relevance of also addressing national, regional, and international contexts and varying firm-specific factors (in location, mindset, strategy, and financial performance). It also highlights the importance of complementing the manifold future-oriented investigations with analyses of historical developments up to the present, because these help to better understand the current speed and commitment of firms to low-carbon reorientation.

Although recent U-turns in UK climate change polices have increased uncertainties about the future, our forward outlook is that it will be very challenging for the UK steel industry to engage in low-carbon reorientation. Despite the recent £500m deal with the government [Sweney, 2023; Jolly, 2023], we doubt that Tata will actually proceed with a shift towards EAFs (for reasons of cost, practical feasibility, and higher possible returns on investment elsewhere). For oil refining, we expect that Essar and Phillips 66 will continue their low-carbon reorientation, while Valero and ExxonMobil (in South Wales and Southampton) face a dire future as the industry will further contract in the coming years (because electric vehicles will reduce demand for petrol and diesel). It remains to be seen to what degree Prax Lindsay and Petroineos will reorient and survive by 2030. For petrochemicals, we expect that major firms will engage in low-carbon reorientation, but do this as slow as possible to protect fossil fuel assets and to extract further government support. INEOS, in particular, may first want to empty its recently purchased North Sea oil and gas fields and then offer these for CO_2 storage services, which would enable it to financially benefit twice from these assets.

Industrial decarbonisation will thus likely remain an important and interesting research topic in the coming years, both in the UK and elsewhere. Understanding the drivers, barriers, trade-offs, and dilemmas requires a multi-dimensional analysis of technological, economic, political, strategic, and geographical considerations, which will likely vary between industries and countries. ERSS readers will hopefully contribute to this interesting research agenda, which clearly requires an interdisciplinary energy social science approach.

7.7. Policy advice and lessons

Industrial decarbonisation is a challenging and expensive process, which is shaped by multiple factors. UK refineries are presently reorienting faster than petrochemical and steel industries, although the latter two have also increased their low-carbon activities. Based on our in-depth longitudinal case studies we offer the following policy lessons and advice.:

1) The strengthening and expanding policy mix since 2019 has increased low-carbon reorientation activities in industrial firms.
2) The policy focus on CCS and low-carbon hydrogen suits oil refining and petrochemical industries better than steelmakers. Other important decarbonisation pathways such as electrification, feedstock substitution, or demand reduction receive less attention than they should.
3) The policy focus on four clusters disadvantages firms in the two other clusters, including a steelmaker and two refineries.
4) Recent government deals with two steelmakers partly alleviate these biases, but the intended shift to Electric Arc Furnaces faces practical obstacles, including: a) insufficient UK supply of high-quality scrap steel, b) grid challenges in supplying sufficient electricity, c) internationally high electricity prices, d) social acceptance problems because of layoffs.
5) As the cost of industrial reorientation may be £billions, past profitability of firms is important in shaping speed and commitment.
6) Industrial decarbonisation policies need broadening to address other technologies, practical barriers, and social acceptance.
7) The South Wales and Solent clusters will require further structural policy support if they are not to be disadvantaged in a future net-zero industrial environment.

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