A Review of the UK Offshore Wind Supply Chain: Reconciling Economic Impact and Policy Action

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Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Date: 18th September 2025

Abstract

Throughout the 21st century to date, there has been significant emphasis on reducing greenhouse gas (GHG) emissions, with the electricity sector identified as a particular focus. In the UK, offshore wind has been highlighted as a key technology in the transition away from fossil fuel generation and to help meet the goal of net zero emissions by 2050. Recent years have seen the focus of policy change from solely targeting increased installations of offshore wind farms, to the desire to maximise the economic benefit that could be gained through the growth of the sector.

The main route to capitalise on this opportunity is through developing the offshore wind supply chain in the UK, with a target of increasing local content in new projects to 60% by 2030. Following a holistic approach, this thesis aims to improve the understanding of the offshore wind supply chain in the UK by examining the interrelated considerations of GHG emission reductions, policy actions, and economic impact.

In Chapter 4, the main driving factors behind the reductions in UK GHG production emissions between 2010 and 2018 are investigated, to quantify the specific contribution of the electricity sector. A structural decomposition analysis is performed to determine how this manifests at a sectoral level due to changes in the supply chain, in the first study to employ the technique in an energy context using national economic tables for the UK. Isolating the electricity sector and decomposing the specific contribution of different fuel types further demonstrate the impact of transitioning the sector from fossil fuels to renewable energy generation.

Chapter 5 presents the first comprehensive review in the literature assessing how the offshore wind supply chain is encapsulated within UK legislation. The key mechanisms for supply chain planning in UK offshore wind developments are assessed, to improve the understanding of how policy actions can contribute to raising levels of local content. The chapter concludes with a novel, high-level assessment of the supply chain development statements of the twenty ScotWind projects, exploring how the level of

local content differs across the proposals and investigating the parameters which may drive the variation.

Chapter 6 examines the potential economic impact of the UK investment expected from the ScotWind offshore wind leasing round, and marks the first academic analysis of the economic impact of these projects. Employing Input-Output modelling, the expenditure outlined in the supply chain development statements of the projects is used to capture the economic impacts across the supply chain for offshore wind in the UK, and in addition examine the potential economy-wide consequences of delaying investments.

Through the combination of qualitative assessment of policy actions, and both ex-post and ex-ante economic analysis, this thesis demonstrates where progress has been made in developing the UK offshore wind supply chain to date — and highlights where emphasis should be placed to reach the future ambitious goals for the sector.

Acknowledgements

First and foremost, I would like to express my gratitude to my supervisors Dr Grant Allan and Dr David McMillan. A huge thank you for all of your guidance and assistance throughout this PhD. Your knowledge and expertise shaped the path of this work, and I greatly appreciate the boundless help you gave me over these past years. Economics and supply chain policy are a world away from my previous work, and the completion of this PhD is a testament to your teaching while I learned an entirely new field.

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Finally, to Luna, thank you for being my constant work from home companion.

Contents

Acronyms

A

AR allocation round

ASP Administrative Strike Price

B

BEIS Department for Business, Energy & Industrial Strategy

BIS Department for Business, Innovation & Skills

C

CAPEX capital expenditure

CCC Committee on Climate Change

CCUS carbon capture, utilisation and storage

CfD Contracts for Difference

CGE Computable General Equilibrium

CIB Clean Industry Bonus

CO_2 carbon dioxide

CO_2e carbon dioxide equivalent

COP Conference of the Parties

CPS Contracted Position Statement

D

DECC Department of Energy & Climate Change

DECEX decommissioning expenditure

DESNZ Department for Energy Security & Net Zero

DEVEX development expenditure

DTI Department of Trade and Industry

E

EMR Electricity Market Reform

EPCI Engineering, Procurement, Construction and Installation

ESO Electricity System Operator

EU European Union

EU ETS EU Emissions Trading System

F

FTE full-time equivalent

G

GHG greenhouse gas

GVA Gross Value Added

GW gigawatt

I

IAS international aviation and shipping

IDA Index Decomposition Analysis

IEA International Energy Agency

INTOG Innovation and Targeted Oil and Gas

IO Input-Output

IPCC Intergovernmental Panel on Climate Change

K

kWh Kilowatt hour

L

LCOE Levelised cost of energy

M

MRIO multi-regional Input-Output

$MtCO_2e$ megatonnes of CO_2 equivalent

MW megawatt

MWh megawatt hour

N

NDC Nationally Determined Contributions

NESO National Energy System Operator

NIC National Infrastructure Commission

O

O&M operations and maintenance

OEM original equipment manufacturers

ONS Office for National Statistics

OPEX operational expenditure

OWIC Offshore Wind Industry Council

OWIG Offshore Wind Industry Group

R

RO Renewables Obligation

ROC Renewables Obligation Certificate

rUK Rest of UK

S

SAM Social Accounting Matrix

SCDS Supply Chain Development Statement

SCP Supply Chain Plan

SDA Structural Decomposition Analysis

SIC Standard Industrial Classification

solar PV solar photovoltaic

SOWEC Scottish Offshore Wind Energy Council

U

UK United Kingdom

UNFCCC United Nations Framework Convention on Climate Change

W

WIOD World Input-Output Database

WTO World Trade Organization

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Chapter 1

Introduction

Through the early years of the 21st century there has been a growing emphasis globally on the need to transition away from using fossil fuels for energy, due to their effects on the climate. The UK Climate Change Act (2008) was the first framework in the world to set a national pathway for emissions reductions, and its implementation set in motion a transformation within the energy sector towards clean energy sources. The generation of electricity has historically been one of the most polluting sectors within the economy, burning fuels like coal and natural gas to power industries and bring energy to our homes. The push to reduce our usage of fossil fuels has led to a growth in generation from renewable energy sources, increasing from a share of less than 7% of total generated power in 2010 to a 46% share in 2023[1] (DESNZ 2024c).

Key within this progress has been the development of wind energy, with offshore wind farms increasingly playing a significant role. Much importance has been placed on offshore wind as a crucial technology for the future UK energy system, and with a capacity target of 50GW installed capacity by 2030 the sector is only set to grow in the coming years (BEIS 2022a). In the nascent days of UK offshore wind, policy related to its development was focused almost exclusively on growing the capacity and

[1] The latest year where annual figures are available. In Q1 – Q3 of 2024, renewable sources generated more than 50% of UK electricity.

demonstrating the usefulness of the technology as a strong contributor to the future energy system. While there were challenges, by the end of the 2010s the UK had the largest installed capacity of offshore wind in the world, and the sector was firmly positioned to be the backbone of the energy system in the transition to meet the new ‘Net Zero’ CO_2 emissions target by 2050 (Climate Change Act 2008 (2050 Target Amendment) Order 2019; BEIS 2019c).

Although the aim to continue increasing the installed capacity of offshore wind in the UK was still a priority, much of the focus at this point shifted towards a desire to maximise the economic benefits delivered from this growth. The Offshore Wind Sector Deal, published in 2019, identified that developing the domestic supply chain was crucial in capturing the opportunity available within the sector (BEIS 2019c). The Deal also set a target of 60% local content in new projects by 2030, with increases in the capital expenditure stage highlighted as a focus. Rising from an estimate of 50% local content in offshore wind farms commissioning at the time, the pertinent question remained — how can the UK capitalise on the strong delivery of capacity and grow its domestic supply chain, delivering on the key government goals of low-carbon energy, increased jobs, and clean growth?

Throughout the following chapters, this thesis looks to contribute to the understanding of the economic impacts of the offshore wind sector, with a focus on how supply chain considerations can affect the level of local content in a project and, ultimately, the benefit generated within the UK. The remainder of this section is presented as follows: firstly, a high-level overview of offshore wind as a technology, and some background detail to place the UK sector in context, are provided in Section 1.1, supporting the subsequent work; the main objectives of the chapters contained within this thesis are then outlined in Section 1.2, with the structure and contributions of each chapter detailed in Section 1.3.

1.1 Background

To place the work in the following chapters of this thesis in context, this section provides some background to the UK offshore wind sector and supply chain. Firstly, Section 1.1.1 explains offshore wind as a power generation technology, detailing some of the key constituent parts of an offshore wind farm along with an explanation on the differences between fixed and floating wind technology. Section 1.1.2 then delves into a high-level review of what is meant by the supply chain of offshore wind, and the type of companies that may be included. The discussion is finalised in Section 1.1.3, where the relative market size of the UK compared to the global potential is outlined.

1.1.1 Offshore Wind Fundamentals

While large-scale electricity generation from wind turbines has played a part in the UK power system since the 1990s, it was not until the early 2000s that wind power began to be installed offshore (BEIS 2023; National Grid 2025). The core technology remains the same as in an onshore project, with a turbine powered by the flow of the wind, though there are additional considerations required offshore (Ren et al. 2021). These could be elements such as transport to site for installation and maintenance purposes, where boats are typically the vessel of choice, and a more challenging environment than for construction of a project on land as sea conditions have to be taken into account (Halvorsen-Weare et al. 2013). However, the benefits to constructing offshore include a generally stronger wind resource, leading to higher capacity factors and power generation; the potential for lower public opposition due to noise or visual impact (though there are significant environmental factors to consider); scope to use larger turbines; and the opportunity for more space as onshore locations with the best resource become filled (Poulsen and Lema 2017; Diaz and Guedes Soares 2020).

Regarding the constituent parts of an offshore wind farm, simply put, an offshore wind farm comprises an array of turbines, which are typically connected to an offshore substation (BVG Associates 2019). Electrical cables installed subsea transfer power generated by the individual turbines to the substation, and from there back to shore where the power is converted to grid voltage at an onshore substation and exported to the grid. Key parts of the turbines themselves are the blades, the nacelle which houses components such as the generator and gearbox, and the tower which supports and elevates the mechanics of the turbine; allowing energy to be captured at heights where the wind speed is greater than at ground level.

Generally, offshore wind turbines sit on foundations which extend to the seabed, classed as 'fixed-bottom' wind. These foundations can take multiple forms, though most commonly installed are the monopile and jacket (BVG Associates 2019). The monopile is essentially a hollow steel tube which is driven directly into the seabed, while a jacket foundation takes the form of a steel, lattice framework (X. Wu et al. 2019). A simple visualisation is shown in diagrams (a) and (b) of Figure 1.1. Water depth, ground conditions at the project site, and the size of the turbine can be driving factors in the selection of a particular foundation type — with monopiles more likely in shallower areas, and jackets in regions with particularly soft or hard ground conditions (BVG Associates 2019). However, there are limits to the water depth where a fixed-bottom turbine can be sited — generally about 60m (Scottish Government 2019). Around much of the UK coast, only waters close to shore exhibit depths in this range and, at a European level, it is estimated that up to 80% of the potential offshore wind resource is located in waters beyond 60m depth (Scottish Government 2019; WindEurope 2017b). Thus, if the plentiful wind resource further out to sea is to be capitalised upon, different technology must be deployed.

For these locations, 'floating offshore wind' is the most attractive, or in some cases only, option. In floating wind, instead of the turbine being placed on a base which is fixed to the seabed, it is supported by a platform which floats on the water surface and is anchored to the seabed by mooring lines (Empire Engineering 2021). A visualisation of this is shown in diagram (c) of Figure 1.1 As floating wind is a nascent technology, there remain multiple designs for the turbine foundation — and the optimum may

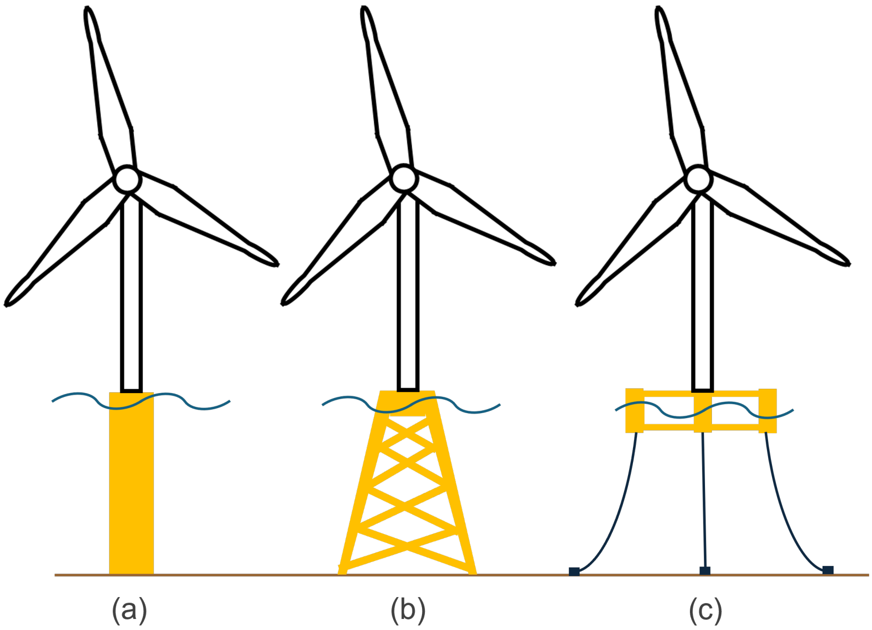

Figure 1.1: Example wind turbine foundations (a) monopile (b) jacket (c) floating

depend on the characteristics of the specific project site. However, in the majority of floating offshore wind farms and proposals to date, a semi-submersible foundation has been the design of choice (Hong et al. 2024). One benefit of this form is that the platform itself does not extend very far below the water line, increasing the ease of being able to combine the foundation and turbine in port or close to shore, before towing the assembly to the project site. For deep water or far from shore locations, this is a clear advantage and could minimise the complexity and cost of offshore installation (Hannon et al. 2019).

1.1.2 What is the Offshore Wind Supply Chain?

The construction and operation of an offshore wind farm is a complex endeavour, with many aspects coming together to create the final project. All of these disparate aspects are typically provided by different companies, all of whom have their own areas of expertise, and together comprise the supply chain of the sector. An offshore wind farm is like any other large engineering project, with much work in the way of management and logistics required. Typically, the main companies carrying out these stages are the project developers, with some of the largest stakeholders to date in the UK including Ørsted, SSE, and RWE (The Crown Estate 2023b). While these companies will handle much of the project management of their wind farm, they may contract out for different stages of work, such as environmental impact assessments, surveys, or vessel hire (BVG Associates 2019). Collectively, these service-based businesses may typify much of the supply chain in the development and operational stages of a project.

Considering the construction and procurement phases of an offshore wind farm, sectors in the manufacturing and engineering areas of the economy are the key elements of the supply chain. First, for the wind turbine itself, two companies account for the majority of installations in Europe to date, namely Vestas and Siemens Gamesa (Diaz and Guedes Soares 2020). Taking a wider view, manufacturers such as Ming Yang and Goldwind, both from China, are increasingly ranking within the top 10 of global wind turbine manufacturers as offshore wind scales up in Asian markets, but they are yet to gain much of a foothold in supplying UK or European projects (Rystad Energy 2023). Wind turbine suppliers will provide the overall turbine assembly, and are also the manufacturer of crucial components such as the rotor and blades. In the UK, both Siemens Gamesa and Vestas have long-established factories for the manufacture of offshore wind turbine blades (RenewableUK 2024). Beyond this, many elements within the rest of the turbine are sourced from dedicated suppliers. These range from specialists in complex manufacturing of mechanical or electrical components like gearboxes and generators, to more generic engineering of materials such as fabricated steel (BVG Associates 2019).

For large heavy-engineering components of an offshore wind farm, namely the on and offshore substations and foundations, aspects such as the structure and electrical systems will be completed by dedicated manufacturers and combined into the overall asset (BVG Associates 2019). The key remaining feature is the cabling, with subsea electrical cables transmitting the power generated by the turbines to connect with the grid. These are mainly split into two categories, array cables and export cables. Array cables connect the individual turbines to the offshore substation, while export cables transfer power from the offshore substation to the onshore substation back on land. Key suppliers with factories within the UK include JDR Cables and Sumitomo Electric (RenewableUK 2024).

Overall, there could be many hundreds of discrete suppliers who combine in the development and operation of an offshore wind farm. Collectively they constitute the supply chain of the sector, and are the type of businesses where the employment and potential economic growth of the expansion of offshore wind could be delivered.

1.1.3 How does the UK fit in globally?

The UK has ambitious installation goals for offshore wind, with up to 50GW of installed capacity targeted by the year 2030 (BEIS 2022a). The development of these targets will be discussed in more detail throughout the chapters of this thesis but, with a cumulative 14GW of offshore wind operational in the UK in 2024, they represent a significant scaling of installations in a short timeframe (GWEC 2023). Looking forward, the Climate Change Committee (CCC), in their modelling of potential scenarios which could allow the UK to meet its net zero goals by 2050, suggest that offshore wind will be the “backbone” of the future electricity sector (CCC 2020b, p27). In the central scenario, 95GW of offshore wind would be expected to be installed by 2050, with capacity increasing to 140GW on the grid in the scenario with the greatest level of electrification. Meanwhile, in their Future Energy Scenarios modelling, the electricity system operator in Great Britain estimated 116GW of installed capacity by 2050 in their most ambitious scenario (National Grid ESO 2023). It is clear that regardless of the trajectory followed, offshore wind technology is expected to be widespread in the future UK energy system, and a key contributor in the transition away from fossil fuel generation. In this scaling up of capacity, though there is inherent risk in meeting the governmental targets and longer term aims, there is also substantial opportunity for the UK economy and supply chain to capitalise on the growth.

However, the UK does not stand in isolation. Looking further afield, many other

Table 1.1: Summary of UK, EU and Global offshore wind capacity, with 2030 and 2050 targets for net zero trajectory

	2024 (actual) [GW]	2030 (target) [GW]	2050 (target) [GW]
UK	14	50	95
EU	19	83	300
Global	75	380	2,000

regions are also scaling up or targeting an increase in their offshore wind capacity. Considering the European Union (EU), there is an estimate of 83GW of installed capacity by 2030, a substantial increase from around 19GW installed by the start of 2024 (WindEurope 2024b). However, to meet the EU net zero goals, the target is for offshore wind to reach 300GW of installations by 2050 (European Commission 2020). On the global scale, it has been estimated that for a trajectory to meet net zero by 2050 there would need to be 380GW of offshore wind capacity installed globally, and 2,000GW by 2050 (GWEC 2024). As with both the UK and EU targets for the same years, this represents a significant increase on the installed capacity in 2024, when around 75GW of offshore wind was operational. A summary of the installed capacity postulated for each region for 2030 and 2050, on the way to a net zero energy system, is presented in Table 1.1 to demonstrate the scale of installations required, and where the UK fits in to the wider global picture.

While UK projects are likely to source some components in their supply chain from foreign markets, there could also be scope for UK companies to export and fulfil orders for projects in other countries. If a fully competitive domestic supply chain can be developed as the market scales up to meet the 2030 and 2050 goals, then the international opportunity available could be substantial. However, it should be noted that the consideration of exports as an avenue for increased economic benefit is not explicitly explored within this thesis, and has been viewed as outwith the scope of the objectives which are detailed in Section 1.2.

1.2 Aim and Objectives

This thesis aims to bridge the gap between different facets of the offshore wind sector, following a holistic approach to improve the overall understanding of the supply chain in the UK. By reconciling considerations of policy actions and both ex-post and ex-ante economic impact analysis, the work is informative to policymakers and industry stakeholders on what has driven the progress that has been made to date within the sector and possible trajectories for the future to meet the governmental goals on installed capacity and levels of local content.

The main aspects under examination are the issues of GHG emissions, economic growth, and policy. On the first, the desire to reduce emissions was the initial driving force behind the energy transition in the UK, and ultimately the instigator for the growth of the offshore wind sector. Economic growth represents the other overriding focus of government, to not only reach our climate change goals but to maximise the benefit to the UK through doing so. The final aspect, policy, is what needs to be put in place at a national level to facilitate the former two considerations.

These prevailing topics are covered by three main objectives, which are addressed throughout the chapters of this thesis. These can be summarised as follows:

(i) Quantify the contribution of the electricity sector in decarbonisation by applying structural decomposition analysis to investigate the main economic drivers in observed reductions in UK GHG emissions, with a focus on how this manifests at a sectoral level due to changes in the supply chain.

(ii) Review how supply chain planning for offshore wind has been encapsulated within UK policy to date, and identify the key mechanisms employed to develop the domestic supply chain and levels of local content. Assess published examples of supply chain statements from the UK ScotWind projects in detail, to gain an understanding of how industry view the capability of the UK supply chain, and propose recommendations for policy action to improve levels of local content.

(iii) Analyse the potential macroeconomic impact of investment into the UK supply chain, using the planned expenditure of the ScotWind projects to represent the capacity increase required to meet UK installation targets, and assess the possible effects of delaying project investment on delivering economic growth.

1.3 Thesis Structure and Novel Contributions

The work in this thesis is presented across seven chapters, including this introductory first chapter. It starts with a comprehensive study of the evolution of renewable energy policy in Chapter 2, before leading into a review of the salient economic literature and models in Chapter 3. Then follow the three distinct quantitative chapters, in Chapters 4 to 6, while Chapter 7 concludes. Each of these chapters is outlined in turn through the remainder of this section. A visual overview of the contribution of each chapter, and how they are linked together under the overriding narrative of the supply chain of the offshore wind sector in the UK, is presented in Figure 1.2.

To place the work in the following chapters of this thesis into the wider context of the energy transition, Chapter 2 provides a chronological overview of progress in renewable energy and decarbonisation in the UK since the Kyoto Protocol in 1997. A discussion on policy interventions to promote action on climate change at both an EU and UK level in the early years of the 21st century is presented, covering the pivotal Paris Agreement in 2015 and the change in focus to reaching Net Zero emissions by 2050. Progress on offshore wind deployment is spotlighted throughout, demonstrating how the technology has developed in the UK from its first installation in 2004 to almost 15GW of installed capacity in 2024 (DESNZ 2025b).

Chapter 3 presents a review of existing literature in the realm of the economics of offshore wind. The salient research on the economic impacts of renewable energy developments is first examined — focusing on the application of two key modelling

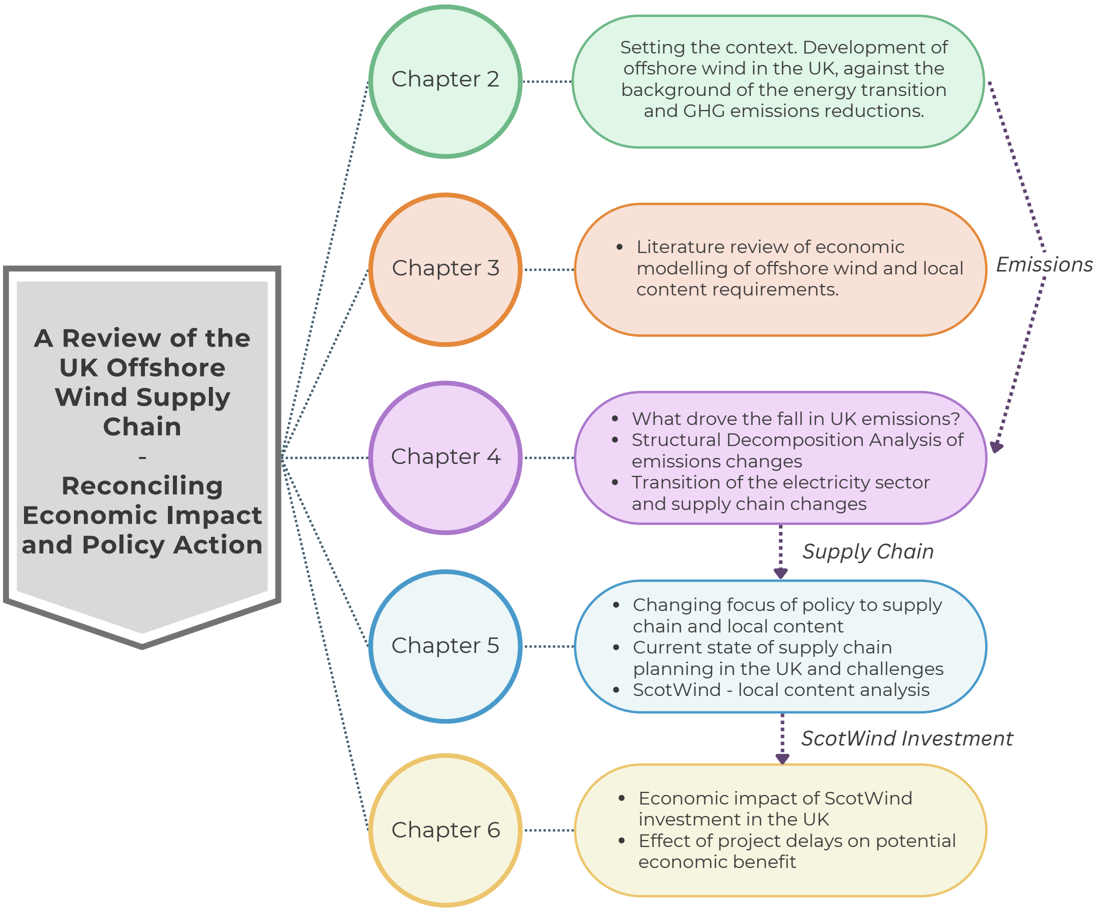

Figure 1.2: Thesis structure and chapter highlights

techniques, Input-Output (IO) and Computable General Equilibrium (CGE), before narrowing to the specific field of the offshore wind sector. This is followed by an overview of research into the costs of offshore wind development; and a final subsection which focuses on the topic of supply chain and local content, with particular attention paid to the implementation of local content requirements.

Given the focus globally on reducing greenhouse gas (GHG) emissions, and the progress made in the UK following the Kyoto Protocol and the Paris Agreement, it is important to understand what has been driving the change in emissions thus far — to better inform decisions to support future progress. Chapter 4 presents a Structural Decomposition Analysis (SDA) which, through the use of an environmentally-extended IO table, assesses the specific contribution of the electricity sector to UK decarbonisation between 2010 and 2018. Beyond representing one of the first SDA studies focused on UK emissions in the literature, this work demonstrates two novel extensions to the standard SDA method. Firstly, the impact on emissions due to changes in the production technology of the electricity sector is separated from changes in the rest of the economy, allowing for the contribution of power generation to decarbonisation to be more clearly observed. Second, the results of performing an SDA on the impact of specific fuel types are presented — specifically demonstrating the difference in emissions due to coal and natural gas use in the UK respectively.

Chapter 5 narrows the focus of the thesis to understanding the policy landscape in the UK relating to the supply chain of offshore wind, and the desire to increase local content in new projects. The intensifying focus on developing the UK supply chain is scrutinised, evaluating how the goals for the progression of the sector have evolved over time — from the earlier emphasis on offshore wind as a tool for decarbonisation, as outlined in Chapter 2, to the growing priority of maximising economic benefit. A detailed discussion of the current capability of the offshore wind supply chain, and the challenges facing the sector globally, leads into an assessment of one of the key mechanisms for supply chain planning currently implemented in the UK. The ScotWind Leasing Round, completed in 2022, required developers to provide a Supply

Chain Development Statement (SCDS) detailing the planned expenditure of their projects, with the submissions from the successful applicants made public. This chapter is concluded by a thorough analysis of the data provided in these SCDS, investigating how the proposed investment varies across the projects and providing an insight into how well current supply chain planning is supporting the local content goals of the UK. Chapter 5 represents the first comprehensive review of the development of supply chain planning and related policy actions for the UK, as well as the novel contribution of a detailed assessment of the ScotWind projects and their local content commitments.

Leading on from the high-level assessment of the key features of the ScotWind projects, Chapter 6 presents the results of a case study analysing the potential economic impact of the overall ScotWind investment in the UK. Employing IO modelling, the GVA and employment impacts of the expenditure are calculated, with direct and indirect effects across the entire UK economy considered. Representing the first detailed economic study of the ScotWind investment in the academic literature, to the author's knowledge, the analysis utilises the real, planned project expenditure from the ScotWind SCDS to inform an economic shock that is introduced into the economy as contained within a UK IO table. The availability of such monetary data is not typical, with most previous studies relying on observed investment from a previous project or estimates from industry publications, with the utilisation of the committed expenditure for the ScotWind projects a departure from the existing body of literature. The final novel contribution of this chapter is the consideration of the possible impact of project delays on the economic benefit generated by offshore wind investment — with the results of key interest to policymakers, signalling the importance of developing projects sooner and minimising delays to maximise the gain to the UK economy.

This thesis is concluded by Chapter 7, which provides a summary of the key findings of each facet of the work presented here. While each chapter presents a novel contribution to the literature and answers the research questions set out in this introduction, Chapter 7 is finalised with some ideas for possible extensions to the analysis contained within the thesis.

Chapter 2

Renewable Energy — How Did We Get Here?

In 2020, renewable energy overtook fossil fuels as the largest contributor to UK electricity generation for the first time (BEIS 2021c). Across the year, 43% of the UK's electricity mix was produced by renewable power sources, with 13% of the total electricity generated from offshore wind (The Crown Estate 2021). This made the technology the joint third largest contributor of any energy source, providing enough electricity to power 39% of UK homes. Offshore wind capacity has grown year-on-year, from a base of zero in the year 2000 to 10.4GW installed by December 2020 and almost 15GW by 2024 (DESNZ 2025b). This capacity is set to increase, with the UK Government targeting 50GW by 2030 — a significant increase in less than 10 years (BEIS 2022a). To fully understand the scale of this challenge, it is important to consider how we got to this position, and what lessons can be learned from the growth to date to fully realise the desired capacity and the benefits to the UK economy that this could bring. This chapter presents a comprehensive appraisal of the development of policy related to clean energy in the UK in the first two decades of the 21st century, with a focus on its impact upon the offshore wind sector.

This discussion is broken down as follows: Section 2.1 outlines the development of renewable energy across the UK and wider European Union (EU) after the signing of the Kyoto Protocol and up to 2015, while Section 2.1.1 focuses on the development of offshore wind in the UK over the same period. Section 2.2 details the signing of the Paris Agreement in 2015, with Section 2.3 dealing with the development of renewable energy in the time since the Paris Agreement was ratified, with focuses on: the energy trilemma (Section 2.3.1); Net Zero (Section 2.3.2); offshore wind progress in particular (Section 2.3.3); and finally a summary up to the year 2021, in Section 2.4. A summary of offshore wind milestones in the UK and key policy developments for both the UK and EU discussed through this section are shown in Figure 2.1.

2.1 Kyoto to Paris: 1997 – 2015

With the 1997 signing of the Kyoto Protocol, the EU made a commitment to reduce greenhouse gas (GHG) emissions by 8% over the period 2008 – 2012 in comparison to their levels in 1990 (Commission of the European Communities 2000). As a member of the EU15, the UK committed to a 12.5% reduction under the Burden Sharing Agreement, which was put in place to ensure that the EU as a whole could reach an 8% reduction while each country would have an individual target based on their respective circumstances (Marklund and Samakovlis 2007).

There then followed a period of increased focus in the early years of the 21st century, as the EU introduced policies such as the Monitoring Mechanism Regulation (The European Parliament and the Council of the European Union 2004) and the EU Emissions Trading System (EU ETS) (Delbeke et al. 2015). Over the subsequent years, the goal of transitioning to a greener energy system less reliant on fossil fuels gathered momentum. The EU-wide commitments were updated in 2007 with legally binding targets for a minimum of 20% reduction in GHG emissions by 2020, and a 20% share of renewable sources in EU energy consumption by 2020 (Commission of the European Communities 2008). In 2010, the *Energy 2020* strategy was enacted, further strength-

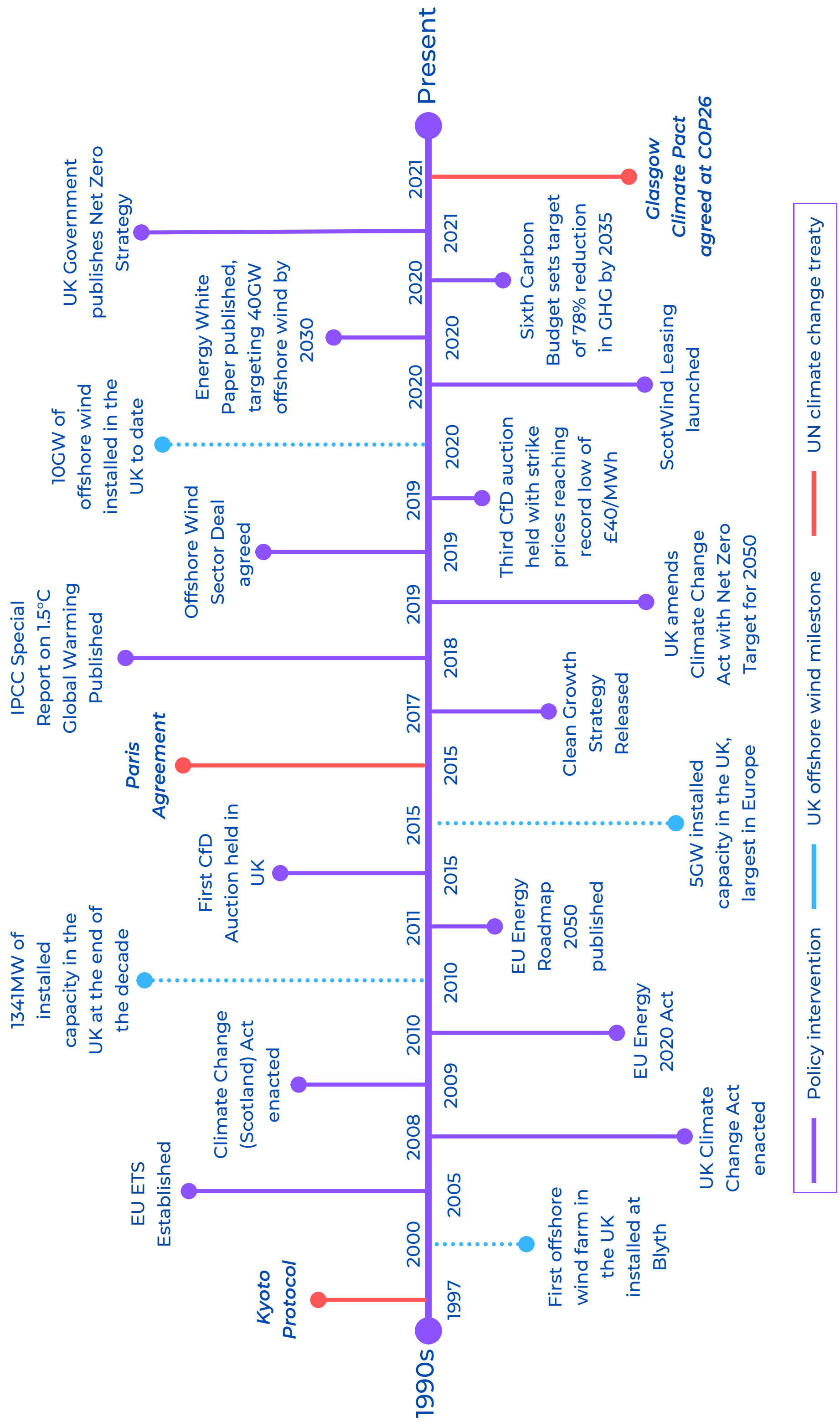

Figure 2.1: Timeline of UK and EU climate change and renewable energy developments

ening these objectives (European Commission 2010).

Alongside these EU-wide measures, the UK adopted policies which went further towards tackling GHG emissions, starting with the *Climate Change Act 2008* (henceforth 'Climate Change Act'). This was the world's first legally binding policy for the reduction of GHG emissions (Lockwood 2013), and set out that the "net UK carbon account for the year 2050 [must be] at least 80% lower than the 1990 baseline" (Climate Change Act 2008, p1). When the Act was passed into law, the *Committee on Climate Change* (CCC) was established as an independent, non-governmental body to advise the targets that the UK Government should set for emissions reductions and carbon budgets (McGregor et al. 2012). Additionally, the CCC are tasked each year with producing a report assessing the progress towards the existing GHG targets, with views on the actions taken by the Government in the year and on whether or not the budgets for the period have been met (CCC 2010).

These carbon budgets detail the levels of GHG emissions that are permissible by the UK over a five year period, to keep on track with, originally, the goals of the Climate Change Act. The first three carbon budgets covered the time periods 2008 – 2012, 2013 – 2017 and 2018 – 2022 respectively. Within the Climate Change Act, the only legally binding level which needed to be included within the carbon budgets (other than the 2050 target) was that the 2018 – 2022 budget must be at least 26% below the 1990 baseline (Climate Change Act 2008). These carbon budgets were intended to give interim targets for GHG reductions towards the ultimate 2050 goal, which ideally would provide more urgency and an improved roadmap for reductions versus one long-term target which could feel distant and intangible. The first three carbon budgets were implemented via the *Carbon Budgets Order 2009*, with a targeted reduction in GHG emissions of 25% and 31% below 1990 levels for the first two budgets respectively, and a 37% reduction by 2020 within the third budget (Priestly 2019).

In the years following enactment of the Energy 2020 strategy and the UK adoption of the Climate Change Act, at the European Union level the *Energy Roadmap 2050* was published in 2011 with a target of reducing GHG emissions by 80 – 95% of 1990 levels by 2050 (European Commission 2011b). To achieve this ambitious target, fundamental changes to the EU energy system were necessary, with a significant shift away from a reliance on fossil fuel use to a greener energy mix. This required new objectives to be set regarding the share of low-carbon energy — with the electricity sector in particular targeted as an area which could almost entirely remove GHG emissions by 2050, whilst also contributing to the replacement of fossil fuels and decarbonisation within other sectors such as heating and transportation (European Commission 2011a). An interim target for 2030 was set for a 45% share of renewable energy within the electricity sector across the EU, while for the energy sector as a whole at least a 27% share was proposed (European Commission 2014). Alongside, a target for a GHG emission reduction of 40% relative to 1990 levels by the same year was also set out.

This transformation of the energy sector was required across the entire European Union, with an acknowledgement that individual member states may follow different paths based on their respective circumstances (European Commission 2014). Focusing within the UK, between 1990 and 2000 significant progress had already been made in reducing the reliance of coal power in power generation — more than halving from 65% of the total in 1990 to 32% in 2000 (IEA Data and Statistics 2021b), as illustrated in Figure 2.2. However, this was mostly replaced with generation by gas which increased from 2% to 41% of the total power generated in the UK over the same period, showing that for the period which we could reasonably class as ‘pre-Kyoto Protocol’ there was limited improvement in the share of non-fossil fuel energy sources in UK power generation. Indeed, renewable energy sources only improved their share from 2% to 3% over the same timeframe, while nuclear generation remained constant. At this point in the year 2000, wind, solar photovoltaic (solar PV) and tidal electricity combined only accounted for 0.25% of total electricity generation in the UK, with the majority of renewable power consisting of hydroelectric (IEA Data and Statistics 2021a).

Given all this, it is then interesting to view the progress over the following years after the efforts to reduce GHG emissions gathered steam following the Kyoto Protocol

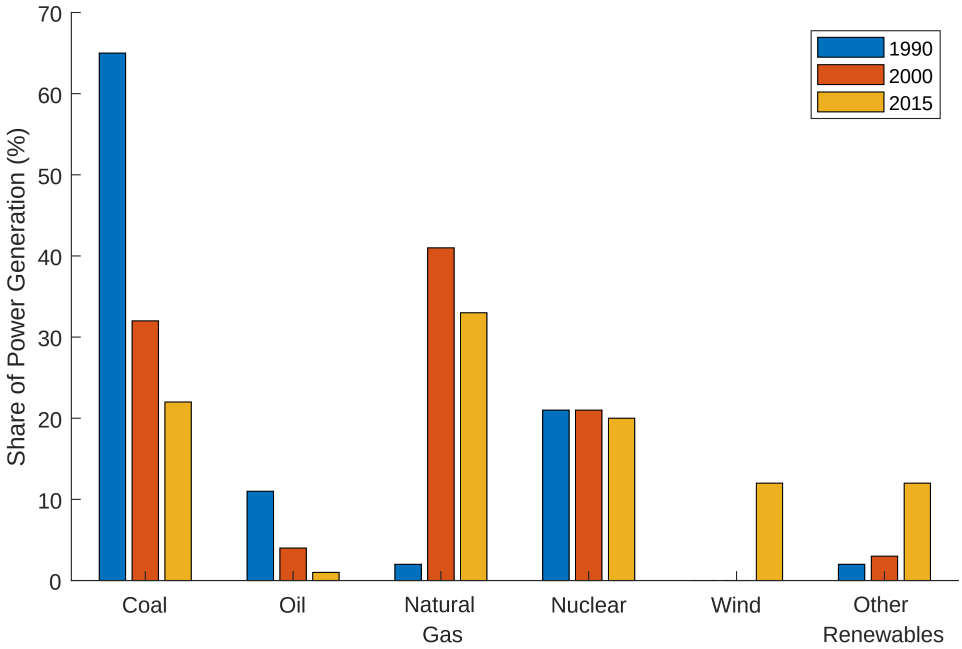

Figure 2.2: Share of UK power generation by source – 1990 to 2015 (Adapted from IEA Data and Statistics (2021a) and IEA Data and Statistics (2021b))

and subsequent measures such as the Climate Change Act. By 2015, coal had dropped to a 22% share of power generation, while oil had plummeted to only 1%, which is again evidenced by Figure 2.2. Contrasting this, wind energy increased from less than 1% of production in 2000 to contributing 12% of the total electricity generated in the UK by 2015 — the same percentage produced by all other renewable sources combined (IEA Data and Statistics 2021a). At this point, onshore wind produced more energy than its offshore counterpart, with contributions of 7% and 5% of total electricity generation respectively for 2015 (BEIS 2020d). This represents a relatively small difference in the generation shares of the two technologies when their respective technological maturity is taken into account — the first commercial scale farm onshore was completed in 1991 while the first demonstration wind farm located offshore in the UK wasn't installed until December 2000 (BVG Associates 2021d; BEIS 2020d). This demonstrates the faster growth in renewable technologies in the 21st century, as funding mechanisms began to be put in place to counter the higher costs of renewable energy.

Until 2015, funding for large-scale renewable energy in the UK was delivered under the Renewables Obligation (RO) scheme, which was the main support mechanism from 2002 onwards (DECC 2013a; G. Wood and Dow 2011). Under RO, renewable energy generators received Renewables Obligation Certificates (ROCs) for each MWh of energy they produced, which could then be traded on a market. RO imposed an obligation upon electricity suppliers to source a given proportion of their energy from renewable sources each year or face a fine, with the required percentage share of renewables increasing year-on-year (Woodman and Mitchell 2011). However, given that ROCs could be traded in the market, there was a downside that suppliers or generators could skirt their obligated renewable targets and simply purchase ROCs if that were cheaper than paying the fine (Gürkan and Langestraat 2014). RO ostensibly worked well to promote the deployment of renewable energy in the UK in the early years of the 21st century, given the demonstrated increase in capacity through this time (Shao et al. 2022).

However, limitations of the RO system were well documented. Firstly, in the earlier years of the RO scheme, the Government took the decision that all technologies would receive the same number of ROCs per MWh as they did not wish to impose levels of importance to different generating types, preferring the market to choose the best option (G. Wood and Dow 2011). This led to less developed technologies such as wave and tidal generation being passed over for funding while cheaper and more established technologies like onshore wind were successful under RO. To address this issue, the RO was reformed in 2009 with the introduction of banding, where technologies received different levels of ROCs per MWh depending on their level of technological readiness (Allan et al. 2011). The intention behind the reform of the system was to incentivise investment in 'emerging' technologies such as offshore wind, wave, and tidal energy by awarding them a higher level of support (G. Wood and Dow 2011).

An additional issue identified both in the original and reformed RO was that by merit of being a market-based mechanism, the financial risk for projects was placed upon developers (Grubb and Newbery 2018). This arose as renewable technologies are typically found to have high capital costs compared with conventional generation, and the price which a generator would receive for their ROCs was not fixed. The combination of these factors meant that there was a high level of financial risk associated with renewable energy projects under the RO scheme, which in turn both priced out smaller companies from the market and passed higher costs onto consumers through their energy bills (G. Wood and Dow 2011; Shao et al. 2022). Thus, though evident that some technologies and projects found success through the RO scheme, there were inherent problems in its formulation that did not allow for the maximum deployment of renewable energy at the lowest cost to consumers.

As a remedy to the concerns around RO, the UK Electricity Market Reform programme (EMR) was announced in 2013, which introduced Contracts for Difference (CfD) as the new primary mechanism for incentivising renewable energy generation (DECC 2013b). Through CfD, generators are paid a guaranteed price for each unit of electricity produced, the 'strike price' agreed in the contract between the generator and the Low-carbon Contracts Company, a public sector company owned by BEIS[1] (National Audit Office 2016). If the market price is below the strike price, the generator receives a top-up to the strike price. If the market price is above the strike price, the generator pays back the difference. The aim of this was to reduce financial risk for investors by providing a guaranteed price and thus keeping financing costs low, which in turn passes lower costs for low-carbon electricity onto consumers. After delivery of the EMR, RO began to be phased out in favour of CfD, with funding under the former closing to new capacity in 2017 (DECC 2014).

2.1.1 Offshore Wind Energy — Growth to 2015

Against the backdrop of intensifying focus on climate change, and the recognition of renewable energy as a tool for reducing reliance on fossil fuels discussed thus far, offshore wind was increasingly acknowledged as a key technology in helping the UK to meet its emissions targets. This section discusses the expansion of the offshore wind sector in

[1]Now Department for Energy Security & Net Zero (DESNZ), since 2023.

the UK from its earliest days at the dawn of the 21st century, up to the signing of the Paris Agreement in 2015.

In December 2000, the first offshore wind farm in the UK was installed off the coast of Blyth, in North-East England. This demonstration project consisted of two turbines with a total generating capacity of 4MW (BVG Associates 2021d). The completion of this project was followed in 2001 by the launch of the 'Offshore Wind Capital Grants Scheme' by the UK Department of Trade and Industry (DTI), which assisted in funding the first round of projects gaining seabed leasing approval from the Crown Estate[2]. Leading on from this investment, the first commercial offshore wind farm in the UK, North Hoyle, was fully operational by July 2004 (Y. Feng et al. 2010). The farm consisted of thirty 2MW turbines, for a total installed capacity of 60MW. In round 1 of leasing, twelve projects were granted consents (the last of these coming online at Ormonde in 2012) with a total capacity of 1,191MW (Higgins and Foley 2014). Round 2 leasing was completed in 2003, when fifteen wind farm proposals were granted seabed rights, for a total capacity of 7.2GW (7,200MW) — a six-fold increase on the results from round 1 (BVG Associates 2021d). This growth in successful projects demonstrates the appetite for offshore wind that was apparent in the UK market even in the early 2000s, catalysed by the nascent climate change legislation at both EU and UK level.

By the end of the decade, 2,946MW of offshore wind was installed across the EU, consisting of 45 wind farms with over one thousand wind turbines (EWEA 2011). The UK was the market leader in offshore wind installations, contributing 1,341MW across thirteen farms, with 300MW added by the Thanet project which at the time was the offshore wind farm with the largest operational capacity in the world. It was also in 2010 that the third round of UK seabed leasing was completed, with over 32GW of capacity awarded across nine offshore wind zones (EWEA 2011). This installed and consented capacity shows the trajectory and the promise of the sector at this point in time. Considering the financial crash in the late 2000s, the continued growth of offshore

[2]The Crown Estate manage the assets of the Crown and the seabed in England, Wales, and Northern Ireland. Until 2017, Scottish assets and seabed were also included, prior to the establishment of Crown Estate Scotland (HM Treasury 2023).

wind is indicative of the potential identified within the technology, and how it could be used to contribute to the transition of the energy system away from fossil fuels.

To this end, the National Renewable Energy Action Plan for the United Kingdom estimated that, by 2020, offshore wind would be the second largest renewable energy contributor in the UK with almost 13GW predicted to be online — surpassed only by onshore wind with a capacity estimate of 14.9GW[3] (DECC 2010). However, by the release of the EMR Delivery Plan in 2013, this capacity estimate was downgraded to 10GW due to changes in modelling with the introduction of CfD (DECC 2013a). Nevertheless, even at this lower estimate, offshore wind was still predicted to be second only to its onshore counterpart in contribution by 2020 — a significant goal when comparing the maturity of the two technologies. Alongside the push for decarbonisation through more installed capacity, there was also growing recognition at the time that a growth in offshore wind could bring positive economic impacts to the UK. Following the financial crash in 2008, there was additional emphasis on wanting to create lasting, high quality jobs and offshore wind was increasingly identified as a crucial sector to deliver upon this desire (Bird 2009).

In 2010, the Scottish Government published an Offshore Wind Route Map for 2020 via the recently established Offshore Wind Industry Group (OWIG), with the aim of "setting out the opportunities, challenges and the priority recommendations for action for the sector to realise Scotland's full potential in offshore wind" (OWIG 2010, p iii). At the time of publication in 2010, Scotland had a target of 80% of electricity consumption coming from renewable energy sources by 2020, and offshore wind was identified as a key industry to meet these goals. Four scenarios for the development of the sector were modelled in the route map using forecasts to the year 2025, to assess the potential economic benefits that could be brought to Scotland. This study predicted employment effects in the range of 1,000 – 28,000 FTE jobs created by 2020, depending on the degree of penetration of Scottish offshore wind in the market, and a potential

[3] In reality, by 2020 offshore wind had the third largest cumulative installed capacity of any renewable energy technology (10.3GW), behind onshore wind (14.1GW) and solar PV (13.5GW) (DESNZ 2025b).

cumulative GVA of £224m – £7.1bn across the four scenarios.

The highest of these estimates, from Scenario A, were to be realised if the full 10.6GW of offshore wind capacity in Scottish waters proposed at the time were to be developed. This included a potential capacity of 5.8GW from the Scottish Territorial Waters leasing, across nine wind farm sites, and 4.8GW over two sites in Scotland's Renewable Energy Zone which were granted in Round 3 of the UK Crown Estate auction (OWIG 2010). However, this ambitious scenario required a concerted effort across the wider energy sector for these benefits to be attained. It was identified that, to fulfil the full potential of this scenario, a complete development of a Scottish supply chain for all stages of a project's lifecycle would be required; along with a reduction in project costs and a cheaper, interconnected grid with the rest of the UK and Europe to allow for export of energy, to name but a few of the possible barriers to deployment.

A similar study at UK level was reported in 2013, within the Offshore Wind Industrial Strategy, which estimated over 30,000 FTE jobs and £7bn GVA delivered to the UK economy by 2020 (DECC & BIS 2013). These results were based on 16GW of installed capacity, though the GVA estimate excluded any income from exporting excess power generated by offshore wind in the UK to markets overseas. It should be noted that this capacity estimate is in direct contradiction to the 10GW of installed capacity expected by 2020 that was set out in the EMR Delivery Plan in December of the same year (DECC 2013a).

Nonetheless, it is interesting to compare with the Scottish estimations from 2010 (as shown in Figure 2.3), where it becomes apparent that there was a discrepancy in the potential economic benefit predicted from the UK development of the offshore wind industry. Both studies pertain to be the possibility with the sector maximised to its full potential, but with a 28,000 job estimate for Scotland and a 30,000 estimate for the UK as a whole, one could consider that the Scottish predictions for Scenario A were either excessively optimistic, or the UK study was not optimistic enough. Potentially, the UK study did not account for the full maximisation of the sector within Scottish

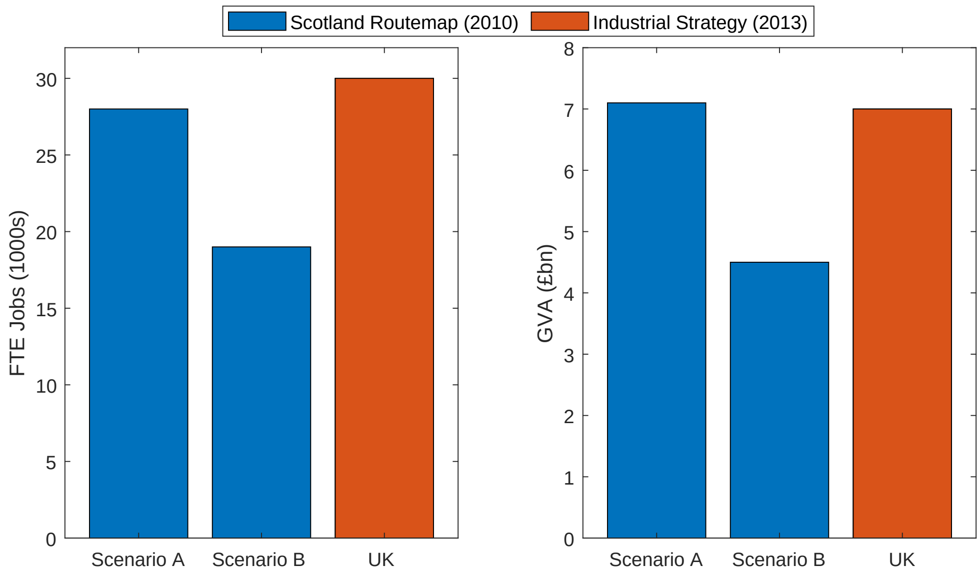

Figure 2.3: Estimated employment and GVA from offshore wind in Scotland and UK by 2020 (Source: OWIG (2010) and DECC & BIS (2013))

waters, as it only considered 16GW of capacity in the UK as a whole, versus 10.6GW in Scottish waters in the OWIG route map. However, with only summaries of the model results available, these assumptions are purely speculative and the operational wind farms comprising the potential 16GW of UK capacity were not provided to allow for further comparisons.

Recalling that Scenario A of the Scottish study assumed capability of energy export, while this was excluded from the UK study, this inconsistency could be a reason for the discrepancy in the employment figures detailed here. Scenario B of Scotland's Offshore Wind Route Map is perhaps more consistent with the UK study: though no details on specific capacity assumptions were provided, this scenario assumed a less than full delivery of Scottish capacity and did not include export capability. In this case, an estimate of 19,000 FTE jobs and a cumulative GVA of £4.5bn by 2020 were given (OWIG 2010). Nevertheless, this amount of direct jobs still seems high when compared to the 30,000 estimate for the UK, so it is obvious that there is a mismatch between the modelling of the two studies.

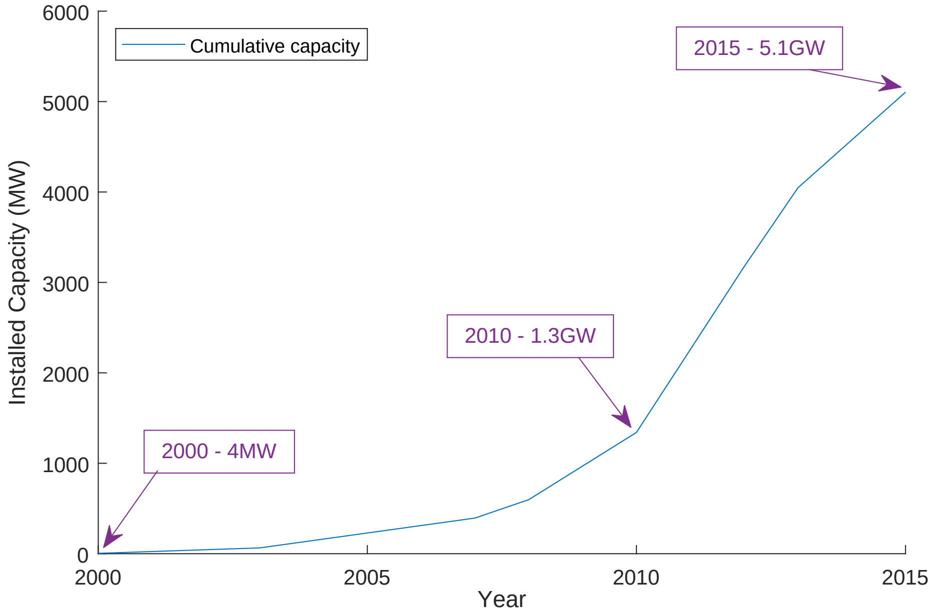

Figure 2.4: Offshore wind capacity in the UK — 2000 to 2015 (Adapted from BVG Associates (2021d))

By the end of 2015, 46% of the total operational capacity of offshore wind across Europe was located within the UK, representing the largest share of any country. This installed base consisted of 27 grid-connected wind farms, with a total generating capacity of 5,061MW (EWEA 2016). The rapid rise in UK installed capacity up to 2015 is shown in Figure 2.4, and illustrates the acceleration in developments through the 2010s to reach over 5GW in deployment (BVG Associates 2021d). The next highest contributors were Germany (3,295MW) and Denmark (1,271MW), with 18 and 13 installed farms respectively. For the following years, the UK also had the highest number of projects at the consenting stage, with a 55% share of the total EU consented capacity. Since the dawn of the century, and the first demonstration offshore wind farm at Blyth, the UK experienced a strong growth in the offshore wind industry driven by world-leading climate change policy and support mechanisms put in place at a governmental level.

2.2 The Paris Agreement

In December 2015 at the 21st Conference of the Parties (COP21) in Paris, the Paris Agreement (henceforth the "Agreement") was adopted by 196 parties to the United Nations Framework Convention on Climate Change (UNFCCC). The Agreement is a legally binding international treaty aimed at tackling the threat of climate change, within the over-arching societal need for sustainable development. The headline target of the Paris Agreement was set regarding global temperature rise and commits to (United Nations 2015, Article 2.1(a)):

> "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change"

There is also recognition that different parties to the Agreement would have different capabilities and national circumstances, which would thus translate into varying responsibilities towards the goals of the Agreement. The finer details, background and ramifications of the 27-page 'Adoption of the Paris Agreement' (United Nations 2015) could be a full report in itself, but the main point with which people are most likely familiar is the statement on global warming. These headline warming figures were used by governments around the world to make further, more ambitious commitments to reducing greenhouse gas emissions.

Another key aspect was the condition that adopting Parties should aim for global emissions of GHG to peak as soon as possible after the adoption and ratification of the Paris Agreement, and to accelerate reductions thereafter. Again, it was recognised that certain Parties may take longer to reach their peak emissions given, for instance, their varying energy resources and level of economic development, but the aim nonetheless was to achieve (United Nations 2015, Article 4.1):

> "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"

Parties to the Agreement committed to producing 'nationally determined contributions' (NDC) detailing what they intend to achieve through successive time periods, with the first to be submitted in 2020. They were then bound by the Agreement to pursue domestic mitigation measures to ensure the objectives within the NDC are met.

No one Party alone can stop climate change. A global, legally binding, agreement such as this is critical in ensuring a co-ordinated effort to mitigate both the level of GHG emissions and the effects from global warming. As stated by the European Commission in their 'Road from Paris' communication, the Agreement represented the first step in the fight against climate change "moving from action by a few to action by all" (European Commission 2016, p3).

2.3 2016 – 2020: A Post-Paris Agreement World

After signing the Paris Agreement in April 2016, both the UK and the wider EU region were bound by law to meet the targets of the Agreement and mitigate the effects of climate change. Both regions already had ambitious GHG emission goals for 2030 and beyond prior to COP21, as discussed in Section 2.1, but the urgency and accountability of reaching these targets was intensified. There was also recognition that beyond mitigating the effects of climate change, and avoiding the catastrophic consequences should GHG emissions and global temperature rise be allowed to continue unchecked, there was the potential for economic benefits to be delivered by transitioning the energy sector and the wider economy to more sustainable practices.

At the European level, it was recognised in 2018 that while the existing targets for 2030 went beyond those within the Paris Agreement for the same year, with no further legislation in place only a 60% emissions reduction would be realised by 2050 — falling short of the ambitions of the Energy Roadmap 2050 and not contributing sufficiently to the temperature reduction required under the Agreement (European Commission 2011b; European Commission 2018). Within the UK, the CCC advised in 2016 that the focus should remain on the existing carbon budgets and delivering policies which would enable these to be met, rather than instituting further stretch goals on GHG emissions at that point in time (CCC 2016). However, there was similar recognition here as at an EU level that the existing pledges were insufficient to contribute fully to the 2°C warming goal, and fell far short for delivering the ambitious 1.5°C scenario.

2.3.1 The Energy Trilemma

The energy objectives of the UK Government, set by the Department of Energy & Climate Change (DECC) until 2016 when it was merged with some of the responsibilities of Department for Business, Innovation & Skills (BIS) to create the new Department for Business, Energy & Industrial Strategy (BEIS), have often been termed the 'Energy Trilemma' (National Audit Office 2016). There are three main, inter-related concerns surrounding the energy transition — namely decarbonisation, energy security, and energy affordability — with the term trilemma reflecting how these objectives are often conflicting, and the challenge in ensuring that policies to target one area do not adversely impact upon the other considerations. The policies and legislation discussed in the previous sections to target GHG emissions were the key starting point for the decarbonisation objective for the newly created BEIS, though at both an EU and UK level policy also targeted the other two points of the trilemma.

Energy security and resilience is concerned with ensuring an uninterrupted energy supply, often termed 'keeping the lights on'. One of the key aspects of this in the UK is the capacity market, introduced with the EMR programme, where generators are paid a steady income for being available to provide capacity whenever the grid requires it (DECC 2013a; National Audit Office 2016). However, one criticism of the capacity market is that it can appear to incentivise carbon-intensive technologies as fossil fuel generators have been successful in the market, which is in direct opposition to the decarbonisation aspect of the trilemma (National Grid 2017).

In 2015 the EU set out their *Energy Union* strategy, with a view to delivering "secure, sustainable, competitive and affordable energy" for all Member States (European Commission 2015, p2). The Energy Union envisioned states collaborating to ensure security of energy supply and reducing reliance on imports from outwith the EU, which at the time stood at 53% of the energy use of the bloc. However, one barrier to the ambitions of the Energy Union is that individual Member States have vastly varying stances on energy supply security and the renewable energy transition required to fight climate change. As outlined by Mata Pérez et al. (2019), there is a threat that the divergent priorities and differing renewable energy capabilities could lead to essentially 'two Europes'. On the one hand, they detail the mostly Western European Member States who are motivated by climate ambitions and maximising the socio-economic benefits of the renewable energy transition. On the other, the paper considers the countries (mostly located in Eastern Europe) with a high dependence on energy imports and a large workforce in the fossil fuel industry, who would face a high monetary and societal cost to transition to renewable energy. The challenge here for the EU is to reconcile these differences in ambition and priority, and ensure there does not become an East-West separation in economic benefit, GHG emissions levels and security of energy supply against external fluctuations.

With regards to energy affordability, it is recognised that transitioning the energy system away from established, fossil fuel technologies to cleaner energy sources will incur substantial costs and that passing these onto consumers should be minimised. One of the main factors of importance in the UK is targeting fuel poverty, which is broadly defined as when a household cannot afford to adequately heat their home (National Audit Office 2016). In 2018 (the latest year, at time of writing, where figures were available for all four nations) 15% of English households were defined as being in fuel poverty, while the figures for Scotland, Wales and Northern Ireland were 25%, 12% and 18% respectively (BEIS 2021a). It should be noted that each devolved nation had varying criteria for when a household was classed as being in fuel poverty, and as such these figures cannot be combined to produce one percentage for the whole of the UK. However, it is clear from the statistics that across the whole UK a significant proportion of households struggled with energy costs. Much research has been focused on the issue of fuel poverty (e.g. Primc et al. (2021)), and it remains a key area for policy intervention both within the UK and the EU.

A further consideration for policymakers relates to how the general public impart importance to energy affordability compared with the other aspects of the trilemma. One study from Demski et al. (2017) used survey results from a representative British sample to judge the public perception of energy affordability and its apparent importance as compared with other energy related issues. They found that across various questions, affordability was prioritised the highest among other energy policy issues. For example, 24% thought that affordable energy prices was the salient issue, versus 17% who chose 'prevent[ing] climate change'. In ranking the importance of governmental priorities, 40% assigned the highest importance to 'keeping energy bills affordable', while 32% selected energy security, and only 27% believed that tackling climate change ought to be the top priority for policymakers. These results are perhaps surprising given the climate emergency and the importance placed on reducing GHG emissions by the UK government, especially following the ratification of the Paris Agreement. However, one consideration of the results presented in Demski et al. is that this study utilised data from a survey carried out in 2012. It would perhaps not be naive to believe that the perceived importance of climate change mitigation in particular may have increased in the years following the survey, as new information and a growing public awareness of the climate emergency developed.

To target the issues of the trilemma, the UK Government Clean Growth Strategy was published in 2017 with the twin goals of reducing greenhouse gas emissions and growing national income (BEIS 2017b). It was estimated that between 2015 and 2030 the UK low carbon economy could grow by 11% per year — 4 times larger than the estimate for the economy as a whole — with a wide estimate for a contribution of between £60bn and £170bn in goods and services by 2030. Recognition remained within the Clean Growth Strategy that achieving the levels of GHG emissions set out in the carbon budgets would be challenging. Though there had been early success in decarbonising sectors such as power, intense focus would be required to make similar progress in other areas such as heating, which at the time accounted for 32% of emissions in the UK. The strategy was particularly focused on ensuring that any actions taken to tackle climate change must not negatively impact the economy, and neither consumers nor businesses should experience high energy costs due to the energy transition. To that end, the key objectives of the strategy and the subsequent government approach to reducing GHG emissions were outlined as follows (BEIS 2017b, p10):

1. To meet our domestic commitments at the lowest possible net cost to UK taxpayers, consumers and businesses
2. To maximise the social and economic benefits for the UK from this transition

A number of proposals were laid out within the strategy to achieve these objectives, targeting areas such as household energy efficiency and low carbon transport, with a ban on sales of new conventional fossil fuel burning cars by 2040 proposed. Additionally, £2.5bn in funding was ring-fenced for investment in low carbon innovation up to the year 2021, 25% of which was to be targeted at the power sector.

Although the Clean Growth Strategy proposed many ambitious policies targeting the transition to a low carbon economy — and framed this for one of the first times as a positive change which could provide economic benefits to the UK — the government was yet to put many of the policies in place to deliver on the targets. The CCC assessed the proposals of the Clean Growth Strategy and found that even assuming the policies outlined were all delivered in full, the fourth and fifth carbon budgets (covering years 2023 – 2027 and 2028 – 2032 respectively) would still not be met (CCC 2018). To this end, they advised that the government must act quickly to confirm and legislate for all of the proposals in the strategy, whilst also developing further plans to tackle the shortfall to the carbon budgets.

In the same year as the Clean Growth Strategy was published, the Scottish Government also released the Scottish Energy Strategy, outlining their vision for energy in Scotland by 2050 (Scottish Government 2017). One of the headline targets from the strategy was the aim for 50% of Scotland's heat, transport and electricity consumption to be supplied from renewable energy sources by 2030. Contrasting this with the EU[4] target from 2014 of a 27% renewable energy share across the region by 2030, as shown in Figure 2.5, the Scottish target shows the belief that the government had in their ability to expand the sector, and reflects the potential of the strong renewable energy resource within the country (European Commission 2014). Scotland already had an existing target of generating 100% of the electricity demand from renewable sources by 2020 — so this 50% target for the whole energy system a decade later is representative of the challenge of decarbonising heating and transportation. The scale of the challenge was especially conspicuous given that heating accounted for 51% of energy use in Scotland as of 2015, with 79% of households heated primarily by natural gas (Scottish Government 2017). In 2015 only 17.8% of final energy consumption was met by renewable sources, so a fundamental shift in policy and public engagement would be required to meet the 2030 target. The strategy also focused on ensuring that the energy transition would bring economic benefits to the nation, and assist in tackling inequalities such as fuel poverty.

Around this time, there began discussions that we may in fact begin to be able to move beyond the trilemma. For instance, a varied energy mix utilising different resources may alleviate fears around 'keeping the lights on' as there should be multiple options for our energy supply (Chisholm 2018). Additionally, throughout the 2010s costs for renewable energy dropped significantly, bringing them into line with conventional fossil fuel generation for the first time (IRENA 2021). For instance, over the decade 2010 – 2020, the global average costs of solar photovoltaic fell by 85% and those for offshore wind dropped 48%. In many regions, this means that it will now be cheaper

[4]EU comparison used as equivalent UK figure for the same year was not available.

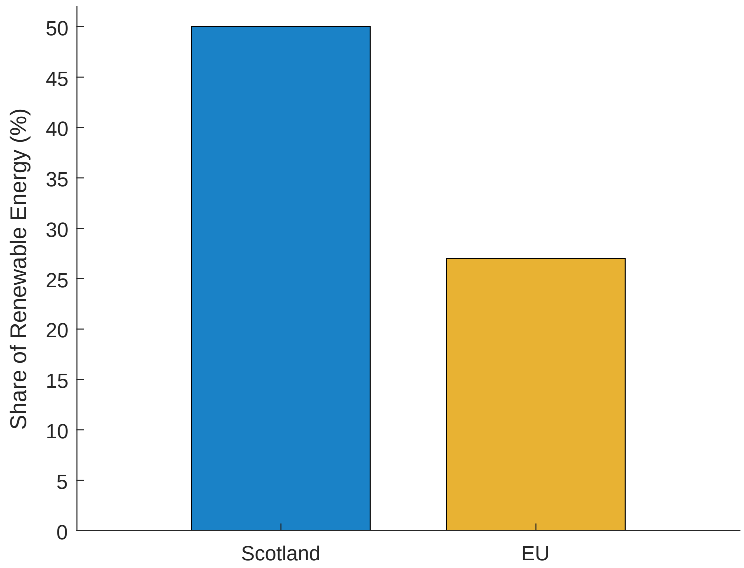

Figure 2.5: Targeted share of renewable energy in total consumption by 2030 (Source: Scottish Government (2017) and European Commission (2014))

to install new renewable energy capacity within an electricity system than it would to build a new fossil fuel plant (IRENA 2021). Considering solely within the UK, a 2020 estimate for costs of new electricity generation by 2025 gave large-scale solar photovoltaic plus both on- and offshore wind lower levelised costs of energy (LCOE) than gas generation (BEIS 2020c). This recognised decrease in global costs of renewable energy and estimate for the future within the UK combine to indicate that the decarbonisation and affordability points of the trilemma may no longer be in opposition.

2.3.2 Net Zero

In 2018, the Intergovernmental Panel on Climate Change (IPCC) delivered its Special Report on the impacts of global warming of 1.5°C above pre-industrial levels, as requested by the UNFCCC at COP21 (IPCC 2018). The aim of the report was to reconcile and assess global research on the effects of 1.5°C global warming, and also make a comparison of the potential impacts as compared with 2°C of warming. The report estimated that human activities had contributed approximately 0.8 – 1.2°C of warming by 2017, and 1.5°C would be reached between 2030 and 2052 if there were no change to the warming rate. They proposed that reaching 'net zero' CO_2 emissions would halt further warming, and the temperature would then only be determined by the cumulative emissions until the point net zero was reached. The term net zero is defined in the report as "anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals" (IPCC 2018, p24), which is in line with the statement on balancing emissions within the Paris Agreement as discussed in Section 2.2.

At 1.5°C of warming, there are predicted to be less severe impacts versus 2°C, though significant changes to the environment would still be seen compared with what we currently experience, with land areas seeing higher temperature increases than the global mean. For example, mid-latitudes are predicted with high confidence to be subjected to a 3°C increase in hottest temperatures at 1.5°C of global warming, and a 4°C increase for a respective 2°C global change (IPCC 2018). Meanwhile, high-latitudes will experience increases to their extreme cold nights of between 4.5°C and 6°C, corresponding to global temperature increase of 1.5°C and 2°C respectively. It is not only in terms of absolute temperature where climate impacts would be seen, risks from both drought and heavy precipitation events are increased at 2°C versus 1.5°C, and global mean sea level rise is projected with medium confidence to be 0.1m lower at a 1.5°C level of warming, though will still pose a serious risk to low-lying coastal areas.

Reaching even the more challenging aim of limiting warming to 1.5°C will still see significant impacts to both animal and human lives. However, compared with a 2°C temperature increase, extinction of species is predicted to be much lower at 1.5°C as loss of habitat due to climactic changes or catastrophic events such as forest fires will be reduced (IPCC 2018). Though significant risks to humans remain if global warming increases to 1.5°C, these are lower than if the temperature is allowed to increase to 2°C. For instance, achieving the lower temperature target could "reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050" (IPCC 2018, p9).

Clearly, it is imperative that governments around the world pay attention to these predictions, taking the necessary actions to pursue 1.5°C and avoid the more severe climate-related risks projected at 2°C of warming. The report recognised that to limit warming to 1.5°C there would have to be "far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems" at an unprecedented scale (IPCC 2018, p15). Of course, changes to all of these sectors were also necessitated under a 2°C scenario, but the depth and speed of the transitions need to be stronger if 1.5°C is to be achieved.

Following the report, in 2019 the Committee on Climate Change advised the UK government to amend the existing target of an 80% reduction in GHG emissions from 1990 levels to reaching net zero by 2050 (CCC 2019). They advised that clear policies to facilitate the decrease in GHG emissions should be instigated urgently, especially considering that existing policy was already insufficient to meet even the original target. Though many sectors had already seen progress or had policies directed at their decarbonisation, it was recognised that delivering upon these had to go faster and further than previously envisioned in order to reach net zero. For example, it was recommended that the phase-out of new petrol and diesel cars should be brought forward from the 2040 target set out in the Clean Growth Strategy, and plans on how to effectively deliver on this target had to be produced swiftly (CCC 2019; BEIS 2017b). Additionally, decarbonising heating and the roll-out of large-scale carbon capture, utilisation and storage (CCUS) were advised to progress with increased urgency. In their assessment, the CCC estimated that meeting the net zero target would cost 1 – 2% of GDP by 2050, the same as the expected (and accepted) cost when the 80% target was set. This preservation of costs reflected the reduction in the price of low-carbon energy since the Climate Change Act was ratified, and as such it was expected that the tightening of the target to net zero should not be un-palatable to the government in economic terms (Climate Change Act 2008; CCC 2019).

On this advice, the UK government amended the Climate Change Act in June 2019 to alter the 2050 target to achieving net zero, becoming the first major world economy to enact such a law (Climate Change Act 2008 (2050 Target Amendment) Order 2019). For Scotland, the CCC advice was to reach net zero by 2045, reflecting the capacity that Scotland has to remove more carbon emissions than the UK as a whole — this was legislated in 2019 by the Scottish Parliament as an amendment to the Climate Change (Scotland) Act 2009 (CCC 2019; Scottish Parliament 2019a). Within the amendment to the UK Climate Change Act, there was no explicit legislation that international aviation and shipping (IAS) emissions would be included within the target or that purchasing international offsets would be excluded — in direct opposition to the CCC advice (Carbon Brief 2019). The government did however suggest that they intended UK shares of IAS to be included in the future.

Shortly after the IPCC Special Report, the EU proposed a net zero target for 2050 in their *Clean Planet for All* long-term strategy (European Commission 2018). Similar to the UK, this did not propose any new policies for achieving the vision. Instead, the intention was to lay out the potential benefits and challenges for the EU in the pursuit of net zero and frame how the bloc would deliver this within the framework of its Paris Agreement and UN Sustainable Development Goal commitments. Both the European Council and the European Parliament endorsed the net zero objective in 2019 (European Commission 2021). However, it was not until 2021 that the target of climate-neutrality was enshrined into EU law. The *European Climate Law* set not only the net zero for 2050 target, but also an intermediate target for 2030 of a 55% reduction in GHG emissions from 1990 levels (European Parliament and Council of the European Union 2021).

2.3.3 Offshore Wind Progress

Post-Paris Agreement, the progress of the offshore wind industry within the UK continued at pace. From the 5GW installed capacity in 2015, the extent of the technology increased in the following years as further projects from the early rounds of seabed leasing were fully installed and came online. The second CfD auction was carried out in

2017 where three offshore wind farms, with a combined capacity of 3.2GW, won funding at strike prices of £57.50 to £74.75/MWh for delivery by 2023 (BEIS 2017a). This was significantly lower than the previously achieved strike price for the first round of auctions in 2014 of £114/MWh, and the lesser of the two strike prices brought offshore wind prices lower than gas generation for the first time (Carbon Brief 2017).

In 2019, the UK Government published the Offshore Wind Sector Deal as part of their Industrial Strategy, placing offshore wind as a key energy generating asset for the future (BEIS 2019c). With the Sector Deal, the government aimed to maximise the economic benefits for UK industry whilst transitioning to a cleaner energy system which can meet the net zero target by 2050. Committing to investment in future CfD auctions and in building a UK supply chain, the Sector Deal set an ambitious target of 60% UK content in offshore wind projects by 2030 — an increase on the 32% estimated in 2017 and approximately 50% for 2019 intimated within the Deal (Noonan and Smart 2017; BEIS 2019c). Crucially, the report also set out a target of 30GW installed capacity by 2030. At the time of the Deal in 2019, there was approximately 10GW of operating capacity in UK waters, so this represented a targeted threefold increase in capacity in only ten years — an ambitious undertaking which demonstrated the confidence the government had in offshore wind as a crucial technology for the race to net zero (BVG Associates 2021d; BEIS 2019c).

Linking back to the EMR Delivery plan discussed in Section 2.1.1, the 10GW installed capacity in 2019 was in line with the prediction for 2020 (DECC 2013a). The Sector Deal estimated that with 30GW of deployment, 27,000 jobs could be supported within the sector by 2030, an increase from approximately 7,200 in 2019 (BEIS 2019c). Contrasting again with earlier estimates, 7,200 jobs is drastically less than the 30,000 FTE jobs by 2020 predicted by the 2013 Offshore Wind Industrial Strategy, though as covered in Section 2.1.1 this strategy utilised a 16GW capacity prediction (DECC & BIS 2013). This discrepancy could be down to a number of factors, namely the Sector Deal figure details only direct employment within the sector, while it is unclear from the 2013 figure if direct, indirect or induced jobs are included in the estimate.

Later in 2019, the third round of CfD auctions in the UK were carried out, with the results announced in September of that year. Offshore wind was the most successful technology in the auction, with six projects and a capacity of 5.5GW granted funding (BEIS 2019b). The strike prices of the successful applicants were at a record low, ranging from £39.65 – £41.61/MWh for delivery in 2023/24 and 2024/25 respectively. Of the six wind farms, two were in Scottish waters (Forthwind and Seagreen Phase 1 with 12MW and 454MW capacity respectively), while three of the four in the English region were phases A, B and C of the Dogger Bank project with 1.2GW of capacity each. Once completed, the Dogger Bank project will collectively be the largest operational offshore wind farm in the world. Some research has suggested that the form of the CfD auctions in the UK encourages 'speculative bidding', as there is no penalty for non-delivery (Welisch and Poudineh 2020). It remains to be seen if this is the case for most of the low-strike price round 2 and 3 wind farms — more data should soon be available as these progress through construction and begin operating, when it should become clear if the successful bid prices were indeed feasible in reality[5].

In 2020, the Scottish Government outlined their Sectoral Marine Plan for Offshore Wind Energy, which represented a strategic process for facilitating future offshore wind developments within Scottish waters (Scottish Government 2020c). At that time, there were six operational offshore wind farms in Scotland, with a capacity of approximately 900MW, and a further eight in the pipeline for a total of 5GW (Scottish Government 2020b; Scottish Government 2020c). In response to technological advancements and policy commitments at the UK level outlined in the Sector Deal, a framework for the first offshore wind leasing round solely administered in Scotland was detailed within the Plan. Facilitated by Crown Estate Scotland[6], *ScotWind* leasing was launched in 2020 with opportunities for new projects in deep water made available to developers — a key step in developing offshore wind technology beyond the shallow, near-water locations that are ubiquitous in most existing sites.

[5]See Chapter 5 for detail on the progress of the offshore wind sector in the years to 2024.

[6]In 2017, management of Crown Estate property in Scotland was devolved to a new body, Crown Estate Scotland. The Crown Estate retained management rights for assets in England, Wales and Northern Ireland (Scottish Parliament 2019b).

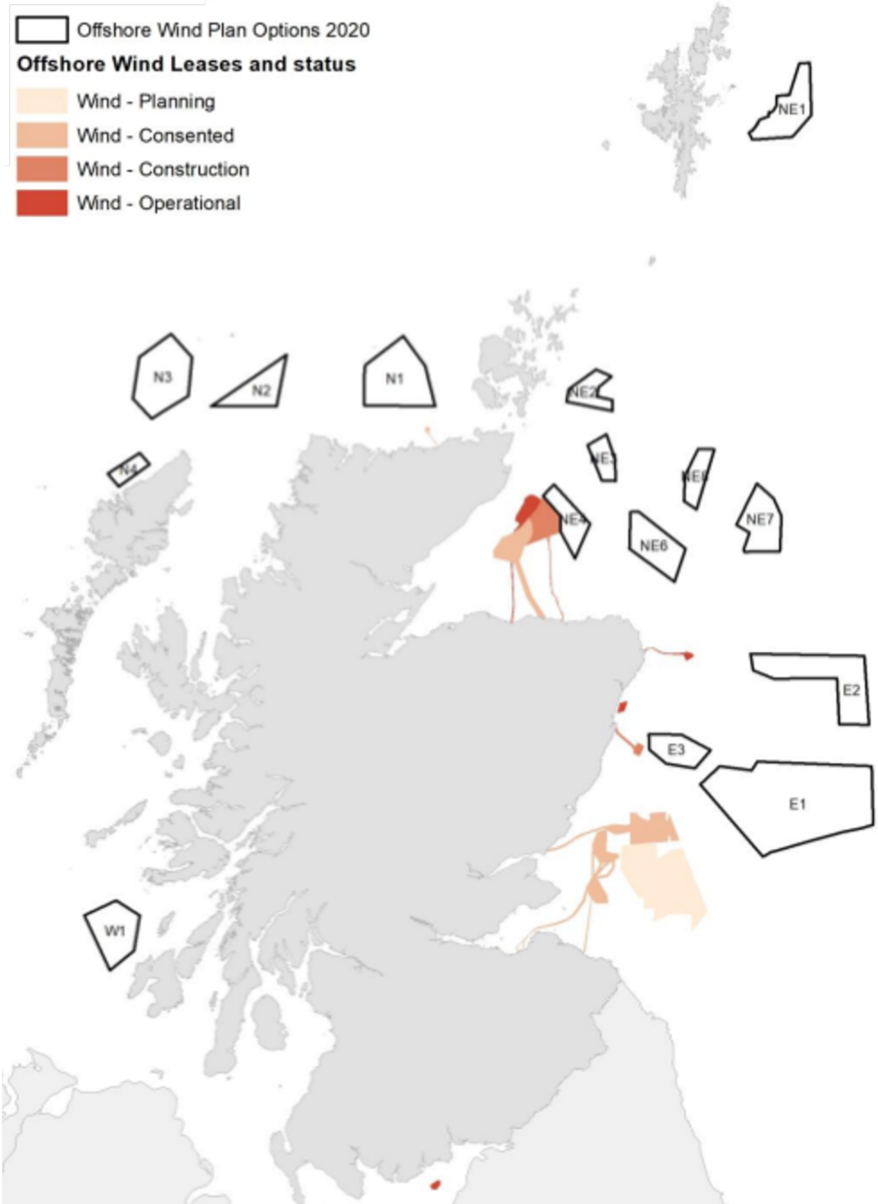

Figure 2.6: ScotWind Leasing Plan Options and locations of existing offshore wind developments (Source: Scottish Government 2020c)

For leasing under ScotWind, 15 'Plan Options' across four regions were outlined, with these zones shown in Figure 2.6 alongside the location of existing offshore wind developments in Scottish waters. These four regions, around the East (E), North East (NE), North (N) and West (W) of Scotland were determined after multiple consultations and assessments, with a view to minimising environmental impacts and any cumulative effects of projects sited close to one another (Scottish Government 2020c). The majority of the offshore wind farms constructed or planned in Scotland to date have been situated to the East, around the Firth of Forth, or the North East, around the Moray Firth. These areas have relatively lower water depths than areas further from shore, suitable for fixed-bottom offshore wind turbines and with comparative ease of access for construction and maintenance, resulting in their selection for the earliest generation of projects (Scottish Government 2019). However, with technological improvements, such as the potential for deeper waters to be accessed via floating wind technology, areas with strong wind resource around the North and West of Scotland are now more feasible for development, and thus were proposed as Plan Option areas within the Sectoral Marine Plan.

As part of ScotWind Leasing, developers had to propose a project entirely located within one of the Plan Option areas, with a minimum capacity of 100MW and not exceeding a footprint of 860km^2 (Crown Estate Scotland 2020b). An application did not need to cover the entire Plan Option area, though the chosen layout had to represent a spatial density of at least 1MW/km^2 to ensure efficient use of the seabed. There was also no stipulation within the rules of the leasing round on the type of technology that a project must use (i.e. fixed-bottom or floating wind). When granted an Option Agreement through ScotWind, developers have a maximum of 10 years to carry out investigations of the site and perform development activities before applying for consent and ultimately the seabed lease (Crown Estate Scotland 2020b). When a developer enters into an Option Agreement with Crown Estate Scotland, they will pay an option fee based on the area of seabed they are proposing for the project. In addition, once a project is operational developers pay a quarterly rent to Crown Estate Scotland for the use of the seabed, which is payable at £1.07/MWh of output of the wind farm[7].

A key part of the ScotWind leasing process was with regards to developing the Scottish supply chain for offshore wind. A successful supply chain requires investment

[7]Indexed to the Consumer Price Index.

in both people and infrastructure, and the best way to attract this investment is with a "clearly visible future market for supply chain capability and growth" (Crown Estate Scotland 2020b, p4). In Chapter 5 of this thesis, the supply chain requirements of ScotWind are analysed in detail, including a comprehensive review of the data surrounding the successful projects in Section 5.3. Chapter 6 extends from this, and presents a case study of the potential economic impacts for the UK that may arise from the ScotWind developments.

Looking forward, the Scottish Government Offshore Wind Policy Statement, published in 2020, set a target of 8 – 11GW of installed capacity by 2030 (Scottish Government 2020b). This could be viewed as a reasonable aim given the 5GW of existing and consented developments at the time, a pipeline of projects that could be hoped for following ScotWind, and the 30GW target for the UK by the same year set in the Offshore Wind Sector Deal (BEIS 2019c). This interim target for 2030 would contribute greatly towards the 75% GHG emissions reduction and 50% renewable energy supply in final energy consumption required by the Scottish Energy Strategy, and represent a strong step towards net zero (Scottish Government 2017).

2.4 Into the 2020s

In December 2020, the UK Government published a new, major policy paper for the energy system. The Energy White Paper set out the plans the government had for the net zero transition to 2050, via a strategy for the energy system that: transforms energy; supports a green recovery from the Covid-19 pandemic; and creates a fair deal for consumers (BEIS 2020e). Within the White Paper, one of the headlines was an increase in the targeted level of offshore wind by 2030 from 30GW to 40GW. The scale of this challenge is illustrated in Figure 2.7, demonstrating the transition required within the sector to reach 40GW capacity from the 10GW base installed in 2020. Within this 40GW, a 1GW goal for floating wind developments was also targeted, a significant undertaking given the installed capacity for all of Europe was 62MW (0.062GW) at the

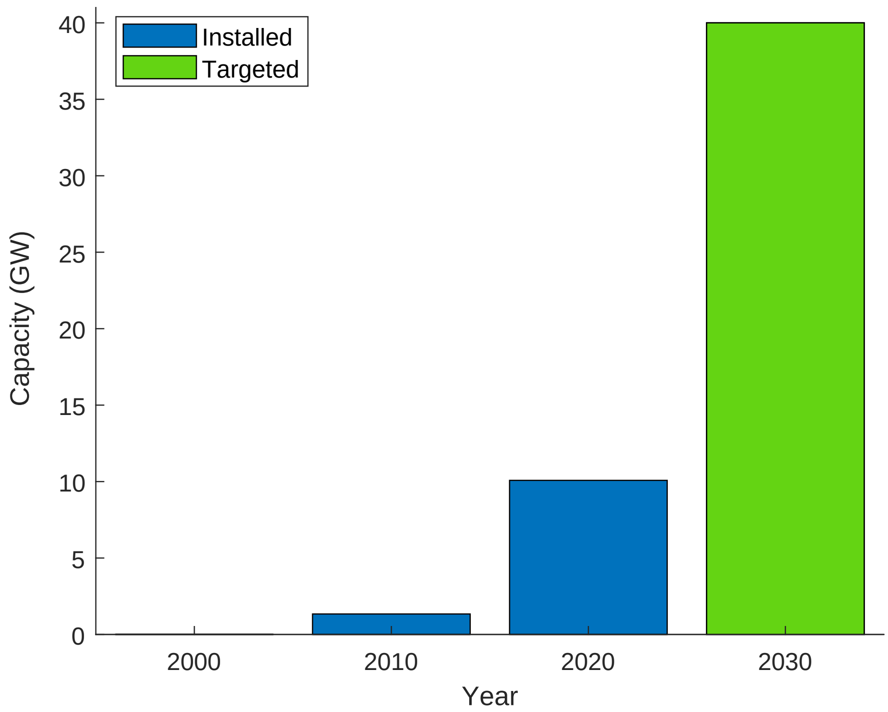

Figure 2.7: Offshore wind capacity in the UK: growth to 2030 (Adapted from BVG Associates (2021d) and BEIS (2020e))

end of 2020 (WindEurope 2021b). However, growth within the UK is underway with the 50MW Kincardine floating wind farm off Aberdeen, the largest installed anywhere in the world at time of commissioning, beginning operation in 2021.

In terms of transitioning the energy system towards a net zero future, the electricity sector was identified as having a pivotal role, not only for power supply but also in decarbonising heating and transportation. It was predicted within the White Paper that electricity demand could double by 2050, but no specific generation mix was targeted to fulfil this rise in demand. Instead, the government policy was that the electricity market should "determine the best solutions for very low emissions and reliable supply, at a low cost to consumers", rather than for the government to take a role in dictating the market structure (BEIS 2020e, p42). However, a strict policy framework would still require to be put in place by the government to facilitate this, and ensure that green technologies are those which see success in a competition-driven market — not more

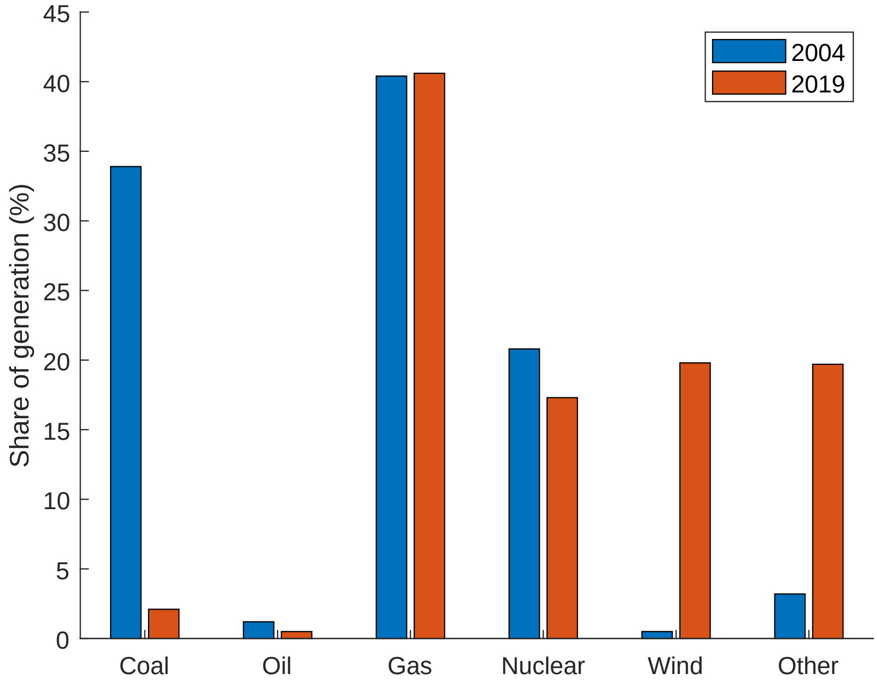

Figure 2.8: Share of UK electricity generation by source — 2004 to 2019 (Adapted from BEIS (2020b))

polluting technologies that can remain low-cost if, for example, carbon penalties are not sufficient. Even without a specific energy mix targeted, most modelling scenarios run by BEIS showed renewables as the main generation source in 2050, followed by nuclear power and gas with CCUS. However, it is not clear how the expansion of nuclear is expected to account for such levels of generation in a market-driven electricity sector, given the high costs of construction for the technology. Additionally, at present there are no large-scale CCUS projects in the UK, so development will require to progress at pace if it is to contribute towards the net zero goal. There is currently no clear policy mechanism in place to support this, though the White Paper states an intention to deploy at least one plant by 2030.

By the end of the 2010s, the progress in the first two decades of the century in decarbonising the power sector was clear, with coal having been almost completely phased out of UK electricity generation. A comparison of the generation mix in 2004

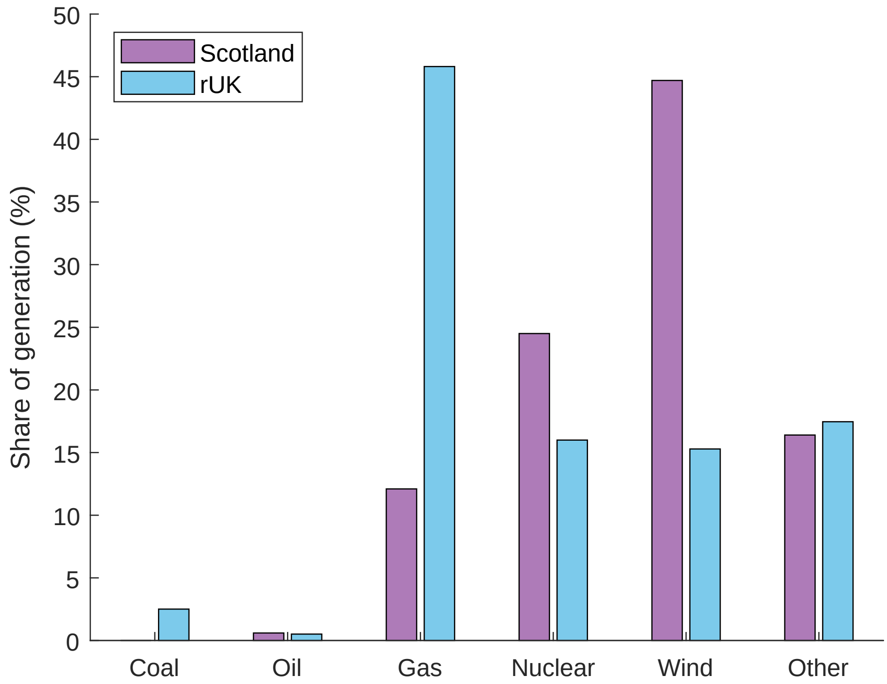

Figure 2.9: Share of Scottish and rest of UK (rUK) electricity generation by source — 2019 (Adapted from BEIS (2020b))

(when the first commercial offshore wind farm was commissioned) and 2019[8] is demonstrated by Figure 2.8. Much change is evident from the graph, though generation by gas remained prevalent in the electricity mix and even slightly increased its percentage share compared with the early 2000s. This is in contrast with the shares in 2015, shown in Figure 2.2 back in Section 2.1, where gas power generation had decreased from turn of the century levels. In the years between 2015 and 2019, coal power generation plummeted — particularly in Scotland where the last coal-fired power plant closed in 2016. Considering the data for the two years, it is clear that a combination of gas and wind power has been used to plug this gap in electricity production.

Considering this, it is interesting to review the differences in the electricity mix between the constituent countries of the UK, and how this may contribute towards meeting the net zero target. In particular, a comparison between shares in Scotland

[8]Data from 2019 has been used to illustrate the landscape at the turn of the decade, as 2020 was a non-typical year due to the Covid-19 pandemic.

and the rest of the UK (rUK) is shown in Figure 2.9. The salient points from this data are the differences in gas and wind generation between Scotland and the other nations. In 2019, Scotland generated 12% of its electricity from gas, while it constituted 63% of Welsh supply and around 44% in both England and Northern Ireland — combining to 41% for the UK as a whole (BEIS 2020b). Wind power generated a higher proportion of Scottish electricity than in the rest of the UK, 45% versus 15%. The rUK constituent nations varied widely in their share of wind energy, with 14%, 18% and 33% for England, Wales and Northern Ireland respectively. Though it should be noted that whilst England utilised the lowest share of wind power, in absolute terms it generated the most. Looking to the future, the share of wind power generation is likely to increase for England when the next phase of large offshore wind farms currently in construction come online. For instance, the combined Dogger Bank project alone is predicted to be able to supply 5% of the UK's electricity once operational (Equinor 2021). As of 2019, wind power supplied 19.8% of the total energy generated in the combined UK. For the first time, offshore wind provided an almost equal share as onshore wind, with both approximated at supplying 9.9% of the total energy generated in the UK that year (BEIS 2020d).

Within Scotland, 2020 was a record year for renewable energy production, with the equivalent of 97.4% of Scottish electricity consumption provided by renewable sources — falling just short of the 100% target (Scottish Government 2021a). For total energy consumption, 24% was delivered by renewable energy — around half of the 50% goal for 2030 mandated in the Scottish Energy Strategy (Scottish Government 2017). This illustrates the progress still required to decarbonise sectors other than electricity production, with heating still primarily provided by gas and transportation remaining dominated by fossil fuels. Considering offshore wind energy specifically, in 2020 there was 894MW of operational capacity and the technology provided over 10% of the gross electricity consumption for the year (Scottish Government 2020b; Scottish Government 2021a).

Contrasting this 894MW installed capacity with the target of 10.6GW set out in the

2010 *Offshore Wind Route Map* for Scotland, as shown in Figure 2.10, it is clear that there is a discrepancy between the aspirations of the time and the development of the sector in reality[9] (OWIG 2010). In terms of the socio-economic benefits estimated at the time, the deployment of the full 10GW capacity was predicted to bring 28,000 FTE jobs and a cumulative GVA of £7.1bn to Scotland by 2020. Of course the much smaller capacity achieved would also be expected to deliver less in the way of benefits. This is apparent in the estimate of 3,100 direct FTE jobs supported by the Scottish offshore wind industry in 2021 and a direct GVA of £1.2bn for the same year — drastically lower than the impact predicted for 2020 (Fraser of Allander Institute 2023). For the UK as a whole, the installed capacity in 2021 was 10.4GW (compared with a predicted 16GW) and the estimated employment supported by the offshore wind sector was 19,600 direct FTE jobs (compared with a predicted 30,0000 direct FTE jobs) (DECC & BIS 2013; OWIC 2022; DESNZ 2024c).

The reasons for failure to maximise the potential of the sector are manifold and have been the subject of research within the industry. The Scottish Offshore Wind Energy Council (SOWEC) commissioned a report on the opportunities within the sector, which set out recommendations for how to develop the industry to its fullest potential and maximise the benefits for Scotland (SOWEC 2021). The report outlined some of the reasons for the lack of progress, and detailed how the reality of development delivered slightly less in the way of benefits than the most negative case, Scenario D, proposed in the 2010 OWIG report (OWIG 2010). Broadly speaking, the Scottish pipeline of projects from 2010 suffered from a number of delays and cancellations that ultimately led to a much lower than predicted deployment. Some of this was caused by the differing financial situation in Scotland, where higher electricity transmission costs led to concerns for developers and difficulty in securing funding via the CfD scheme (SOWEC 2021). The delay in deploying the full potential of offshore wind in Scottish waters has unsurprisingly meant that the Scottish supply chain did not developed as predicted, with a corresponding lack of new jobs created to support the sector.

[9]Note: The data displayed in Figure 2.10 uses 2021 as the latter year, due to availability of employment figures for Scotland.

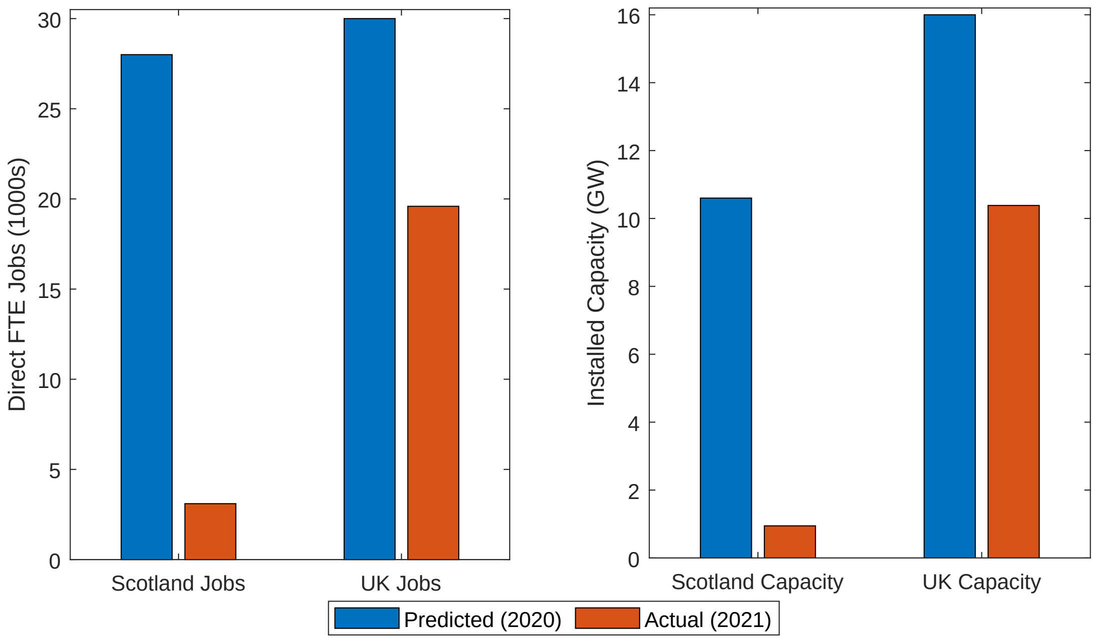

Figure 2.10: Predictions for job numbers and capacity of offshore wind in 2020 compared with observed data for 2021 (Source: Adapted from OWIG (2010), DECC & BIS (2013), OWIC (2022), Fraser of Allander Institute (2023) and DESNZ (2024c))

As of the start of 2021, 2.3GW of offshore wind was either operational or under construction in Scotland, with an additional 2.9GW consented[10]. To facilitate the maximum economic benefit of these projects will require the development of the Scottish supply chain — specifically in areas such as turbine manufacture, which for a 1GW wind farm could account for approximately the same FTE years as the O&M over the lifetime of the project — highlighting the importance of developing the supply chain to deliver the greatest amount of jobs within Scotland (SOWEC 2021; BVG Associates 2021b). With the aim of ensuring that the full capacity of offshore wind is deployed, and to maximise the economic benefits for Scotland, the SOWEC report outlined a number of recommendations to the offshore wind industry (SOWEC 2021):

1. Strategic collaboration to create a Scottish Floating Offshore Wind Cluster

[10] The results of the ScotWind leasing round, announced in January 2022, saw a further 27.6GW of projects granted Option Agreements to develop the seabed.

2. Support for Scottish suppliers to get them ready to bid for and win work
3. Celebrate and sell Scottish success
4. Plan for future growth and the next generation of innovations
5. Plan for energy transition and a future of far-from-shore, mixed-use energy projects

The key takeaway from this report was that there is a great opportunity for Scotland to capitalise on the growing floating wind sector. By getting in on the ground floor a flourishing supply chain is possible, bringing with it some of the economic benefit that has not yet been realised from the 2010 ambition.

2.4.1 Offshore Wind Leasing

In February 2021 the Crown Estate held Round 4 of offshore wind leasing for England and Wales. Only 8GW of capacity across four potential seabed areas was made available for applicants in the first leasing round for a decade. This represented a significant drop on the 32GW of capacity that was secured in Round 3 back in 2010. There was criticism within the offshore wind sector on the number of sites made available for leasing given the targeted 40GW of capacity by 2030 and the position of offshore wind as a key asset in the transition to net zero (RenewableUK 2021).

To set option fees for Round 4, an auction was utilised for the first time in Europe, where in the past fixed annual fees had been set by the Crown Estate. This was despite warnings from some in the offshore wind industry that the high demand due to the length of time since new seabed leases were allocated, coupled with the limited acreage made available for capacity, could lead to an auction with very high bids and a knock-on increase in costs (WindEurope 2021a). Ultimately, developers bid the expected large fees in order to secure the right to build new capacity in the UK, with no announcements at the time of Round 4 on when any further auctions may take place[11]. Six projects from four bidders were successful in being granted a lease through Round 4, with consortia featuring oil & gas majors Total and BP among the winning bids. The option fees of the successful projects ranged from £76,000 – £154,000/MW/year, an unprecedented amount that totals £879m per year to be paid until the sites begin construction (WindEurope 2021a; Noonan 2021). It remains too soon to tell whether these high option fees will translate into higher strike prices at subsequent CfD auctions, or if they may be passed on in energy bills to consumers.

Soon after the results of Round 4 were released, Crown Estate Scotland announced a delay to the deadline for ScotWind Leasing applications in order to carry out a review of the option structure. ScotWind had been operating under a fixed cost structure rather than carrying out an open auction for leases as seen for England and Wales. The unprecedented bids in Round 4 prompted a reconsideration, to ensure that Scottish leases were not being undervalued (Crown Estate Scotland 2021a). The updated option structure was released in March 2021, with the maximum fee that could be paid by an applicant increased from £10,000/km^2 to £100,000/km^2. The closing date for applications to ScotWind Leasing was set for 16$^{\text{th}}$ July 2021, with 27.6GW capacity ultimately successful in being granted Option Agreements through the leasing round (Crown Estate Scotland 2023e).

Offshore wind is set to play a huge part in the decarbonisation of the UK, with the planned 40GW by 2030[12] able to power every home in the country. With the electrification of transport and heating, renewable energy will have to provide a larger share of final energy consumption towards 2050, which could require as much as a four-fold increase in low-carbon electricity generation (BEIS 2020e). Additionally, the technology could also play a role in decarbonising transport if there is an expansion of hydrogen fuel usage alongside electric vehicles, with the most progressive case in the National Grid 2020 *Future Energy Scenarios* outlining a potential 24GW of offshore

[11] For details on Leasing Round 5, expected in 2025, see Chapter 5: Section 5.2.4.4

[12] In April 2022, the government released their British Energy Security Strategy, which increased this target to 50GW by 2030, with 5GW floating wind (BEIS 2022a).

wind solely for clean hydrogen production (National Grid ESO 2020). The 'Leading the Way' scenario envisions this non-networked offshore wind will utilise floating wind platforms far offshore for the greatest wind resource, coupled with in-situ electrolysis and desalination facilities to create green hydrogen which will be piped back to shore.

2.4.2 Decarbonisation Progress

In December 2020, the UK submitted its first NDC with regards to its commitments under the Paris Agreement. Within this, the UK set a target of reducing GHG emissions by at least 68% below 1990 levels by 2030 (BEIS 2020f). For comparison, the EU target is for a 55% reduction by the same year, which is illustrative of the ambition of the UK target (European Parliament and Council of the European Union 2021). This commitment was informed by guidance from the CCC in their report on the Sixth Carbon Budget for the UK, which advised the 68% level as a step on the way to the reduction proposed for the period 2033 – 2037 of the carbon budget (CCC 2020c). The mandated levels for the first six carbon budgets are given in Table 2.1, with the Sixth Carbon Budget setting a legally binding target of reducing GHG emissions by 78% by 2035 (BEIS 2021d). The sixth budget was the first to be set after the net zero target was instituted, and thus reflects a higher level of ambition than some of the preceding budgets. At the time, this was recognised as the most ambitious climate change target in the world, taking the UK more than three-quarters of the way to net zero. Additionally, the Sixth Carbon Budget incorporated the UK share of international aviation and shipping for the first time — something which had long been advised by the CCC but never previously adopted (CCC 2020c).

Though this latest carbon budget target is laudable, there is concern that current policies are not sufficient to reach this or net zero. Indeed, the CCC have previously advised that though on track to beat the third carbon budget[13], the UK does not have the policies or infrastructure in place to meet the fourth or fifth budgets, before

[13] The final statement for the third carbon budget reported GHG emissions in 2022 as 50% lower than the base year (DESNZ 2024b).

Table 2.1: UK carbon budgets (Source: Priestly (2019) and CCC (2020c))

Budget	Period	Reduction below 1990 levels
1st	2008 – 2012	25%
2nd	2013 – 2017	31%
3rd	2018 – 2022	37% by 2020
4th	2023 – 2027	51%
5th	2028 – 2032	57%
6th	2033 – 2037	78% by 2035

even considering the more ambitious target for 2035. Additionally, the fourth and fifth budgets were set when the 2050 target was for an 80% reduction, so to achieve net zero would require us to outperform these two mandates for a more realistic stepping stone to the middle of the century — meaning even more progress would be required (CCC 2020a). Clearly targeted policy and legislation is required urgently to help the UK meet its carbon budgets and Paris Agreement commitments. To that end, the CCC have outlined a number of recommendations to the government, as discussed in Section 2.3.2, and subsequently in their yearly progress reports to Parliament (CCC 2020a; CCC 2021). One critical point is that consumer behaviour will be key looking towards to net zero. To date, UK policy has focused mainly on areas such as the power sector, and good progress has been made here as previously mentioned. However, sectors which are less technologically focused have so far made little progress, and consumer choices will be crucial in decarbonising, for example, agriculture and aviation by making changes to diet and reducing demand for flights (CCC 2021).

When the UK left the EU in January 2020, as a result of the Brexit vote, the nation was no longer bound by much of the legislation at a European level that was discussed earlier in this chapter. While the UK had domestic legislation and policy on energy and climate change — such as the Climate Change Act, carbon budgets, and commitments under the Paris Agreement — one area which required new powers to be set into law was on the subject of carbon trading. To replace the EU ETS, the UK established its own emissions trading system in 2021 (Froggatt and Kuzemko 2021). Though not coupled to the EU system, the possibility of doing so in the future was left open — with the precedent for international linkage set by an agreement between Switzerland and the EU.

In November 2021, the UK hosted the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow. This was a crucial opportunity for the UK to demonstrate climate leadership and collaborate with other nations to commit to strengthening their climate targets in a concerted effort to achieve the 1.5°C goal of the Paris Agreement. As an outcome from COP26, nations adopted the Glasgow Climate Pact and, among other items, agreed to make collective efforts to amend their existing emissions reduction plans to what is required to limit the global average rise in temperature to 1.5°C. For the first time, nations also agreed to phase-out unabated coal power generation (United Nations 2021). Despite these advances it is clear that a number of imperatives remain for the UK if reaching net zero is to become a reality. Most critically, by addressing the policy gap to ensure that the levels of GHG emissions legislated in future carbon budgets and in the NDC are achieved.

2.5 Conclusion

Throughout this chapter, a chronological review of changes in the UK energy system, and the policies that govern it, has been presented. The progress through the first two decades of the 21st century is clear, with renewable energy technologies accounting for a growing share of electricity generation and the cost of developing projects decreasing. Considering the UK, in 2021 40% of electricity generation was from renewable energy sources, while the proportion was even higher in Scotland (DESNZ 2024c). This marks a stark increase from the turn of the century when fossil fuels dominated electricity supply. Offshore wind generation has seen a particularly sharp growth from its first commercial installation in the UK in 2004, with the technology now positioned as key for transitioning the UK energy sector away from fossil fuels.

Clearly, there is still a long way to go if the UK and the wider, global community are to meet net zero by 2050. However, looking at offshore wind in particular, there is huge potential in the pipeline as we progress towards 2030. Considering the latest Crown Estate leasing round and ScotWind, if the full capacity of both these auctions gain consent and progress through to project completion then 36GW of new capacity will come online. Combined with existing capacity and that in development, this would exceed the target for 2030, and presents opportunities for the development of the UK supply chain to facilitate these projects and maximise the economic benefit that can be achieved.

The latter point is clear from the narrative through the preceding sections, with a stark shift in attention within policy in recent years from offshore wind being deployed solely as a tool for decarbonisation towards a desire to capitalise on the potential economic benefits from the growth of the sector. The primary pathway to achieve this is via the supply chain, with increased levels of local content in new projects manifested through increased purchasing in the UK economy and the development of new businesses and projects opening the possibility of job creation. However, in order for these benefits to be sustainable and business to be retained long-term, the supply chain companies must be able to compete fully within the market both at home and further afield.

Chapter 3

Review of Existing Literature

The energy sector is one of the most crucial in any economy, with its output feeding in to all other industries as well as our day-to-day lives. In recent years, much focus globally has been placed onto the energy transition — with efforts invested into the growth of renewable energy sources and away from fossil fuels[1]. Within the existing body of academic literature, there are a breadth of studies which have sought to contribute to the sphere of knowledge around the economic impact of energy related matters, and increasingly on the benefits (or otherwise) of renewable energy technologies. When scaling up the offshore wind sector in the UK to meet governmental targets, it will be critical to ensure that models for the economic impact of the sector are fit for purpose and appropriately measure the impacts of the industry, in order to fully maximise the potential benefits of its growth. Additionally, understanding the link between the economic impacts of offshore wind and decisions taken by developers in the supply chain could help policymakers to shape policies and support for the industry in the most effective way.

Research into the offshore wind sector has been varied, but the focus within this chapter will be on how economic modelling could be, and has been, applied to further

[1]Chapter 2 provides a detailed discussion on climate policies and the development of renewable energy.

the understanding of the industry, and what considerations have been investigated that relate to engineering decision making. The UK has been a market leader in terms of installed capacity of offshore wind, and the technology has been positioned as key for the future power sector, so it is interesting to understand how that has translated into a focus of study. To aid in the assessment, a broader view of economic analysis of the renewable energy sector will first be carried out — to better understand the modelling techniques employed and illustrate how offshore wind research fits in the context of the wider body of literature.

An area of crucial importance both in economics and in engineering decision making for offshore wind is the matter of costs, with financing and minimising the investment required to build new projects critical from a business standpoint. Some of the key factors in the costs of offshore wind, and how these have developed since the nascent days of the industry, will also be discussed through this chapter. Related to costs is the consideration of the supply chain, with increasing focus being placed in the UK on raising the level of local content in new offshore wind developments. Research on local content requirements has featured in the academic literature surrounding the energy sector for many years, and this chapter is finalised by a review of these studies to understand how their findings could be used to provide insight into the possibilities for developing offshore wind in the UK.

Each of these aspects can be found within this chapter as follows: Section 3.1 presents a review of the salient academic literature covering economic modelling, from the wider field of study relating to renewable energy to a narrower scope focused on the offshore wind industry; this leads into an assessment of literature on the costs of offshore wind development in Section 3.2; before a view on supply chain and local content considerations is presented in Section 3.3. Section 3.4 summarises the chapter.

3.1 Economic Modelling

In recent years there has been much research carried out on the economics of offshore wind as the sector has expanded and become of greater importance in the context of government policies, with the technology being targeted as critical in the race to decarbonise the energy sector. As this emphasis has grown, there has been increased importance placed on understanding the economic impacts of the wider renewable energy transition, as well as on the contributions of individual technologies such as offshore wind. The contemporary literature on the subject is broad, but a number of studies fall into some general categories based on the analysis method they use — for instance: Input-Output (IO) models (e.g. Connolly 2020; L. Liu et al. 2020), Computable General Equilibrium (CGE) modelling (e.g. Lecca et al. 2017; Graziano et al. 2017), value-chain analysis (e.g. Kandrot et al. 2020; Schallenberg-Rodriguez and Inchausti-Sintes 2021) or survey methods (e.g. Fragkos and Paroussos 2018). Additionally, both *ex-ante* and *ex-post* measures have been considered — where ex-ante describes looking to the future and utilising existing data to make predictions, while ex-post is a direct assessment of historical data to assess the impact of an intervention. Generally speaking there are some key metrics that appear in most of the literature as outputs of these models, allowing for comparisons to be made between studies and as guides for policy makers. These may include employment levels (for example, full-time equivalent (FTE) jobs), gross value added (GVA), or GHG emissions. Costs of renewable energy developments are also frequently researched, with levelised cost of energy (LCOE) a common measure.

One final key point to understand the general impacts discussed in the literature is the difference between the types of impacts discussed, namely: direct, indirect, and induced effects. For a given sector, say electricity generation, direct effects are those which can be attributed to the activities carried out within the sector. Indirect effects are those which are stimulated by the activities of the electricity sector, typically further down the supply chain. For example, a company which supplies parts to an offshore wind farm has to itself purchase parts from other businesses. These secondary businesses do not directly serve the electricity generation sector so are termed indirect effects (Jenniches 2018). Induced effects capture further impacts beyond those caused directly by the activities of the sector. For instance, by increasing employment through a new development, the wages of the new employees are then spent throughout the wider economy in sectors such as hospitality, which would not be directly attributed to the original electricity sector but have been *induced* through its activities (Schallenberg-Rodriguez and Inchausti-Sintes 2021).

The remainder of Section 3.1 covers discussions on two of the prevalent modelling types and their application in renewable energy research, with a review of IO analysis in Section 3.1.1, and CGE modelling in Section 3.1.2. The section is concluded by a more general review of the extant literature surrounding offshore wind in Section 3.1.3.

3.1.1 Input-Output Analysis

Input-Output (IO) is an economic analysis method developed by Wassily Leontief in the 1930s and is widely used across a variety of sectors such as academia, government and industry (Miller and Blair 2009b). IO accounts are used to display the interdependency of a range of economic sectors across a region (or number of regions), detailing how the outputs of one sector are utilised as an input to others. The rows of an IO table represent sales both between industries and to aspects of final demand — users like households, government, or exports — with total sales across all end use summing to a value for gross output. The columns meanwhile represent purchases made by a sector from all other industries and value added inputs in the form of, for example, taxation and labour. The summation of all elements in a column produces the gross input to a given sector, which will equal the gross output for that sector calculated by the summation of its row (Erickson and Kane 2017). A detailed appraisal of the IO modelling framework, outlining how it is of particular use for analysing the interconnectedness of the economy, and the assumptions inherent in the model can be found in Appendix A, while the the equations that govern its application are presented in Chapter 4.

One critical area that has been identified within the study of renewable energy is the lack of disaggregation of the sectors within the economic tables. For example, the Scottish IO tables utilise the Standard Industrial Classification 2007 (SIC2007) sectoral breakdown, but for the power sector only include section D, sector 35.1 (D35.1) which covers electricity generation, transmission, distribution and trade (Scottish Government 2020a). In the full SIC breakdown each of these four aspects of electricity supply are allocated their own sectoral code (D35.11 – D35.14) (ONS 2010). This level of aggregation in input-output tables clearly raises difficulties when attempting to analyse the impacts of changes within the electricity generation sector only, or the impacts of different generating technologies such as offshore wind. Additionally, there may be economic impacts caused by offshore wind developments that are not captured by the electricity production sector, such as the manufacture of turbine parts being attributed to a non-electricity related sector, so purchases and sales with regards to capital formation activities within electricity generation may be lost.

The awareness that the existing sectoral breakdowns of IO tables are not suitable for fully understanding the impacts of specific technologies is not new, and there is a significant body of research using disaggregation to analyse at a more detailed level. For instance, disaggregation has been performed on IO tables for the purposes of structural analysis of a nation's electricity industry, providing a picture of how individual generating activities influence other industries within the country and how the electricity sector as a whole is embedded throughout the economy (Duarte et al. 2017). This is important because a clearer understanding of the nature of the sector and any inter-country links can be used to guide future best-practice and ensure that the economy is arranged in the best way to target the issues of the energy trilemma[2]. To this end, disaggregated IO accounts have also been used to investigate carbon emissions and how they can be attributed to different sectors of the power industry, or relative carbon intensities between different generating technologies (e.g. L. Liu et al. 2020; Su et al. 2017; F. Luo et al. 2020).

[2]The three main challenges for energy policy: affordability, sustainability, and security. The trilemma is discussed in more detail in Chapter 2, Section 2.3.1.

Disaggregation has also been used to facilitate investigations into groups of technologies that cannot be fully understood at the wider breakdown of the IO tables. For example, Stebbings et al. (2020) utilised IO tables from the Office for National Statistics to analyse the marine economy within the UK. Here, they disaggregated the sectors within the IO tables to extract the data related to marine activities such as offshore wind, coastal tourism, and fishing. Through this research they determined that marine activities contribute more to the UK economy than previously thought, demonstrating again the importance of detailed levels of disaggregation in order to correctly attribute the economic impacts of a sector — something which has clear ramifications for policy development and ensuring optimum benefits are delivered in the future. At a more specific level than the marine economy, this process has also been employed to consider the economic impacts of the growth of the offshore wind energy sector. Considering one example, Connolly (2020) used both IO and CGE modelling to perform an ex-ante analysis of the regional economic impacts that could be expected within Scotland under the planned increase in offshore wind capacity to 2025. This particular study demonstrated the differences in outputs that can be garnered whether utilising IO or CGE modelling, and produced a possible range of GVA and employment that could be seen in Scotland in the future.

The disaggregated IO models discussed above have been developed across a variety of world regions, namely: China (F. Luo et al. 2020); Spain (Duarte et al. 2017); Canada (L. Liu et al. 2020); USA (Faturay et al. 2020); Singapore (Su et al. 2017); UK (Stebbings et al. 2020); and Scotland (Connolly 2020). Thus it is clear that input-output modelling is a common and widespread economic analysis tool. However, there are disadvantages to using this type of modelling that are well-known, other than the issue of the level of aggregation which has already been discussed. In particular they relate to some key assumptions required for IO models: firstly, it is assumed that any increased demand by a given sector can be readily fulfilled by the sectors which supply it; and secondly the ratio of a sector's inputs to outputs are assumed to be fixed (Allan et al. 2014b). These assumptions may not always be the case as, for example, increased demand may mean a change in the cost of labour or materials — this cannot be captured in an IO model (Connolly 2020). These restrictions can be relaxed in a CGE model, but this comes with an increase in data requirements and model complexity (Allan et al. 2014b).

Finally, the use of IO modelling requires the existence of a suitable set of IO accounts. Many national statistics agencies produce these, for instance the UK (ONS 2022d) and Scottish Governments (Scottish Government 2021b). Additionally, there are multiple attempts to produce multi-region IO tables which contain information across many countries around the world, to facilitate analyses of inter-region trade as well as that within an individual nation. For example, the World Input-Output Database (WIOD) provides IO tables covering 43 countries and an aggregated 'rest of the world' region, each with data for 56 industrial sectors (Timmer et al. 2016). One further example is the Eora Global Supply Chain Database, which has collated time-series data for 190 countries at a detailed 15,909 sector level (Eora 2021).

3.1.2 Computable General Equilibrium Models

Computable General Equilibrium (CGE) modelling is a multi-sectoral economic analysis method which, similarly to IO, allows for interdependencies between sectors to be assessed. CGE is not constrained by the same demand-driven assumptions as IO and is considered more flexible than the latter method. For instance, a CGE model could set limits on the amount of labour available such that increased demand couldn't be automatically filled, or allow for changes in input prices that would mean a change in input ratios would be better for a purchaser (Gilmartin and Allan 2014). A more detailed explanation of the CGE modelling framework, and a comparison with the IO method, can be found in Appendix A.

As with IO modelling, CGE has been implemented for a variety of studies on the energy sector across a comparably wide global range. For instance, CGE analysis has been utilised for assessments of the economic impact of the energy transition and the expansion of renewable energy. Examples cover studies on the economic effects of: improvements to energy efficiency in Canada, found to increase GDP by 2% and employment by 2.5% between 2002 and 2012 (Bataille and Melton 2017); the increased share of renewable energy that could be expected in Malaysia following the introduction of a Feed-in-Tariff (Chatri et al. 2018); and the potential employment impacts in Chile through the transformation of the energy sector, which found that renewable technologies could provide up to 5.3 times more jobs per GWh than coal and up to 7.7 times more than natural gas (Nasirov et al. 2021).

One particular area of study has been research into the economic impacts of emissions trading schemes in, for example, Australia (Meng et al. 2018) and Turkey (Kat et al. 2018); and similarly on the effects of introducing carbon taxes (e.g. Allan et al. 2014a and Guo et al. 2014, in Scotland and China respectively). Common throughout these studies is the finding that an emissions trading scheme or carbon tax would be effective in reducing emissions, with a generally small economic cost. Indeed, it was found that the application of a carbon tax could stimulate the economy for the Scottish study, if the revenue from the tax was funnelled into reducing income tax within Scotland (Allan et al. 2014a). For the Chinese study, it was found that a moderate level of carbon tax would slightly reduce economic growth within the country but be effective at reducing emissions (Guo et al. 2014). However, the recommendation from this research was that alongside implementing a modest carbon tax, the Chinese government should pursue the expansion of 'clean coal technology', though it is not clear what this refers to or the impact that not abating coal would actually have on emissions. Beyond these examples it is obvious that CGE studies into the socio-economic impacts of the energy transition are widespread, and indeed a literature review of climate mitigation studies utilising the method identified 154 articles on the subject (Babatunde et al. 2017).

In a similar manner to that described in Section 3.1.1 for Input-Output analysis, CGE has also been used to analyse at a more disaggregated sectoral level. For instance, the ex-ante regional economic impacts of marine developments in Scotland have been considered, which found that short-term impacts tend to be overstated by IO models compared to CGE, while longer term effects are understated by the former (Gilmartin and Allan 2014; Allan et al. 2014b). This illustrates how crucial it is to choose the most suitable model for the purposes of any given study, particularly if the results are to be used to guide decisions on policy or advise upon predicted impacts that may have wider ramifications. Fragkos and Paroussos (2018) utilised a combination of employment factors from surveys and CGE analysis to investigate the employment impact of renewable energy expansion across the EU. In this study the authors found that there is a net positive effect on FTE jobs in 2050, with most direct roles created in construction of solar photovoltaic, supply of biofuels, or manufacturing and installation of wind turbines. Though no mention is made of the split in employment between onshore and offshore wind, this research indicates that the overall wind industry will be second only to solar PV across Europe in terms of energy sector job levels by 2050.

With relation to the offshore wind sector in particular, CGE has been utilised by a number of studies in recent years. In 2017, Lecca et al. carried out a study into the circumstances under which the (then) UK offshore wind targets for 2030 could be met through a reduction in levelised costs, when stimulated only by an improvement in learning rates (Lecca et al. 2017). In the same year, a second study modelled the economic impact of a growing UK offshore wind sector with increased levels of domestic content, and additionally considered the case where investors are more cautious and expect government subsidies to end in the future (Graziano et al. 2017). This study illustrated the importance of a transparent and sustained policy support structure for offshore wind, to ensure that positive economic impacts are delivered in the UK with a growth in capacity. The magnitude of said impacts could also be expected to increase if the levels of local content in UK offshore wind farms is improved — a crucial factor when considering the since increased local content target of the Offshore Wind Sector Deal (BEIS 2019c). An additional study, by Connolly (2020) and previously discussed in the context of IO in Section 3.1.1, also performed CGE modelling for the regional case of Scotland and found that planned future wind developments are expected to deliver significant economic benefits — namely a potential £3.88bn GVA impact and

83,000 person years of employment.

3.1.3 Economic Impact of Offshore Wind

As previously discussed, research into the economic impact of offshore wind developments has been carried out using a variety of measures across various global economies. Considering the literature from recent years, where the policy landscape could be considered to be similar to the present, a range of studies have been presented on a spectrum of economic impacts relating to offshore wind. This then represents the contemporary state of offshore wind economic research, and demonstrates the themes which are often repeated across different studies or where, indeed, there are gaps in the literature.

One body of recent studies on renewable energy has touched on offshore wind within the wider electricity sector. As discussed in Section 3.1.1, economic accounts are typically not aggregated at a level where even the wider renewable sector is separated from other types of electricity, so not all studies break down to the level of individual technologies. Herbes et al. (2020) consider the European markets of the UK, Germany, France and Italy and assesses the likelihood of voluntary consumer demand replacing government led subsidy schemes for renewable energy. They found that none of the regions under consideration are as yet in a position for consumer led markets to effectively support renewable electricity generation. Though not explicitly mentioned, offshore wind is one technology that, in the UK at least, is still benefiting from government subsidies in the form of Contracts for Difference (CfD). As such, this study is instructive despite the sector not being specifically addressed. Looking to the future when upwards of 40GW of offshore wind is expected to be online, it cannot be assumed that state support will continue at current levels — especially as the UK previously outlined a plan for a market-driven energy mix, in the 2020 Energy White Paper — so it is important to understand whether the market will continue to drive offshore wind expansion under these circumstances (BEIS 2020e).

Bogdanov et al. (2021) present an energy scenario where the system in 2050 is

100% renewable energy driven, proposing a potential route to the requirements for limiting global warming to 1.5°C. This study models an interesting pathway to global decarbonisation, where high-electrification is expected to account for the majority of the shift from fossil fuels, and accounts for an 89% share of total primary energy demand by 2050 under their scenario. Aggregating to 145 global sub-regions, the authors propose that major reductions in the costs of renewable electricity, solar PV in particular, are the main drivers behind decarbonisation. To this end, they expect that solar PV will be the dominant electricity generator by 2050, supplying 76% of global demand. Though the full details behind this finding are not provided, it is perhaps unlikely that globally solar PV will reach these levels. Equatorial regions with good solar conditions could be expected to contribute to this percentage a great deal but for the UK, as an example, they predict the energy system to be solar PV based with an approximately 50% generation share. This is at odds with the current UK expectations for the energy mix by 2050, where offshore wind is expected to dominate, and potentially unlikely due to prevailing weather conditions in the country. However, the UK Energy White Paper does plan for a market-driven energy sector so if costs of solar PV reduce to the levels proposed by Bogdanov et al., the energy mix estimated in the study could become reality.

Employment in renewable energy is a popular area of research. One recent study attempted to model the long-term employment impact of a range of energy technologies to assess the net job creation from the energy transition in the UK (Arvanitopoulos and Agnolucci 2020). They proposed that previous studies did not fully consider fossil fuel or nuclear power generation when assessing renewable energy jobs, so net employment estimates were not produced. The authors suggested that though more jobs were created in the short-term for new renewable energy projects, only three out of four of these were sustained longer term. In absolute terms, they also found that for each new GWh of electricity, renewable energy supported more jobs than the equivalent amount of nuclear or gas — though it was noted that each new renewable plant typically produced lower levels of electricity than either nuclear or gas, which could account for the difference. However, it is still notable that renewable energy developments are found to have a sustainable impact on employment. The study also looked to the future, considering possible energy system scenarios to 2030, and found that net positive employment was created under all considered routes. The results of this research are evidence that the transition to cleaner energy can result in positive employment impacts, and the authors proposed that policymakers ought to support the continued development of renewables as a facilitator of new jobs. Additionally, a 2021 report by the Fraser of Allander Institute at the University of Strathclyde was commissioned by Scottish Renewables to investigate the economic impact of the renewable energy sector in Scotland (Fraser of Allander Institute 2021). This assessment found that in 2019 the renewables sector provided £2,250m in GVA and 22,660 FTE jobs to the Scottish economy. Within this, offshore wind supported 4,700 FTE jobs, 1,400 of which were direct employment, and £447m GVA.

Various model types have been utilised to investigate the economic impacts of offshore wind, estimating future or existing GVA and employment supported by the sector. From Norway, Rocha Aponte et al. (2021) utilised an IO model to analyse the potential value creation and employment supported by the Norwegian engineering, procurement, construction and installation (EPCI) sector servicing non-domestic offshore wind developments. One study from Ireland looked at the possible future impacts of offshore wind on the Irish economy using a value chain analysis (Kandrot et al. 2020). Meanwhile, a hypothetical extraction of the offshore wind sector in Scotland was performed to analyse the employment supported by the sector and its contribution to GDP (Allan et al. 2021). This study performed three hypothetical extractions: one from an IO table with an aggregated 'electricity' sector; a second from a table which had the electricity sector disaggregated into individual generating technologies and non-generation activities; and finally, an expansion on the second case where spending related to new capacity installations was separated from that of existing operations. This method allowed the authors to compare the differing results and demonstrate the importance of a disaggregated IO table for understanding the energy system. The data for this study was from 2010, the latest year where UK IO tables were available at the time, and it was found that for the third case 10,243 FTE jobs were supported by the offshore wind sector (direct, indirect and induced employment). This was appreciably higher than the 1,546 FTE jobs calculated for the second case, and 1,173 for the 'aggregated' case, indicating that a significant amount of employment is generated during the investment phase where capacity is being built. Thus the study concludes that not only is it imperative that disaggregated data used, but that it is critical to understand the economic impacts from different stages in a project lifecycle to make effective policy decisions.

The state of the art in offshore wind technology could be considered to be the development of floating wind. Looking to the future, the deployment of floating wind platforms could open up new deep water locations for offshore wind farms, unlocking the technology for regions across the world not endowed with the shallow, near shore locations that are ubiquitous in the UK. For water depths of more than 60m, applicable for almost 60% of US offshore wind resource and 70% of that in Scottish waters, traditional fixed bottom wind turbine foundations are unsuitable and so floating structures would be required in order to capture energy (Hannon et al. 2019). As of 2020, 62MW of floating offshore wind had been installed globally, including the world's largest floating farm at Hywind Scotland which accounted for 30MW of that capacity[3] (Hannon et al. 2019; WindEurope 2021b). Within the UK, the Energy White Paper set out plans for 1GW floating wind by 2030, a significant growth on the 32MW over the two operational farms in 2020, while there was a global pipeline of 5.9GW of floating wind (BEIS 2020e; Hannon et al. 2019).

Floating wind is still a nascent technology compared to the fixed-bottom foundations which have been used for decades. As such, the economic literature surrounding floating developments is more limited than for their fixed counterparts. In 2018 ORE Catapult produced a report for Crown Estate Scotland on the macroeconomic benefits of floating wind in the UK, projecting that the sector could support 17,000 FTE jobs

[3] The Hywind Tampen project, operational from August 2023, is now the largest floating wind farm with a capacity of 88MW. The global installed capacity as of July 2024 was estimated at over 270MW, with a global pipeline of around 240GW (IRENA 2024a).

and £33.6bn GVA by 2050 (ORE Catapult 2018). Castro-Santos et al. (2020) carried out a case study on the economic feasibility of floating wind in Portugal, calculating potential LCOE, internal rate of return, and net present value for a range of platform types and geographical locations around the Portuguese coast. A further study considered the socio-economic impact of developing a 200MW floating wind farm in Gran Canaria (Schallenberg-Rodriguez and Inchausti-Sintes 2021). Here, the authors used IO modelling to evaluate the employment and GVA impact of the new project, considering scenarios with varying levels of investment in the Canary Islands, Mainland Spain or the rest of Europe.

The economy of the Canary Islands is driven by tourism, with different industrial and manufacturing capabilities as compared with Mainland Spain. As such, varying impacts on the economic metrics were found depending on where within the Islands or mainland the labour and parts were sourced (high local content vs. low local content scenarios). After performing a value-chain analysis to understand the relevant capabilities to meet the demands of the new floating array by Canarian or Mainland Spanish companies, it was found through IO analysis that the indirect effects of the development were higher in Spain than the Canary Islands as the sectors of the economy have higher linkages. Additionally, the authors concluded that due to the tourism-led nature of the Canary Island economy, more employment would be generated locally than for the same level of investment on the mainland. This was due to lower 'industrialisation' of the Canarian economy, meaning that more employees would be needed to carry out the same level of work — especially during the capital expenditure (CAPEX) phase of the development (Schallenberg-Rodriguez and Inchausti-Sintes 2021). This research was interesting as it represents one of the only attempts found to characterise the impacts of individual floating wind developments, and demonstrates through the use of well-established economic techniques the potential benefits that could be brought to a developing renewable energy economy by investing in new technology.

3.2 Cost of offshore wind

Over the past decades as the installed capacity of offshore wind has increased, costs have generally come down. This is most easily evident in the UK in recent years when considering the subsidy prices awarded at CfD auctions, with a decrease in the strike prices[4] of winning projects since the first round. In the early years of the 21st century, offshore wind cost significantly more than wind developments onshore, which in turn were more expensive than electricity generated from fossil fuels (Junginger et al. 2004). As capacity grew in the years into the 2010s, counterintuitively the average installed costs for new offshore wind developments actually increased — mainly due to projects increasing in size and moving to locations further from shore (IRENA 2019). Other drivers of the cost increase were improvements in the technology as it diverged away from simply situating existing onshore technology in the sea, and there may have been impacts due to changes in the price of raw material such as steel influencing the cost of parts such as turbines or foundations (IRENA 2019; Greenacre et al. 2010). Costs for offshore wind installations in the UK peaked early in the 2010s and the trend has been generally decreasing since.

Within an offshore wind project, the main cost is attributed to CAPEX, with one estimate putting the initial investment in a new development at around three-quarters of the total lifetime costs of a project (Diaz and Guedes Soares 2020). Studies in various world regions conclude differing but largely congruent estimates, such as a 67% share of total costs for CAPEX in Malaysia (Alsubal et al. 2021). A large component of this CAPEX investment is on the turbines themselves, with a global estimate from IRENA putting their share as high as 45%, and a 2017 NREL report for the US market estimating them to account for 34% of total CAPEX (IRENA 2019; Stehly et al. 2018). Considering the UK, it has been estimated that a single 10MW offshore wind turbine, including the tower, costs approximately £10 million (BVG Associates 2019). Based

[4]The strike price is the price per unit of electricity generated, in £/MWh, that a project will receive through CfD.

on a representative 1GW array with one hundred 10MW turbines, in 30m water depth and 60km from shore, 30% of the total lifecycle cost for the farm may be spent on initial turbine CAPEX (BVG Associates 2021c). For the same example wind farm: 70% of the overall cost is attributed to the development, procurement and installation of the array; while 28% of the spend is on operations and maintenance expenditure (OPEX) during the lifetime of the project; and remaining spend is attributed to decommissioning of the farm. Again, these overall shares are largely in-line with those found in the previously mentioned studies.

One way in which offshore wind costs are measured in the literature is through levelised cost of energy (LCOE), which indicates the minimum price per unit of electricity where a return on capital investment can be obtained (Bosch et al. 2019). LCOE is a relatively simple metric and is used across different generating technologies to facilitate comparisons between them and to compare costs between developments. LCOE is typically expressed in £/kWh or £/MWh (or relevant currency), and is defined as (Johnston et al. 2020):

$$\mathrm{LCOE} = \frac{\text{total lifetime costs}}{\text{total energy produced}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{3.1}$$

Where I_t is the investment expenditure in year t, M_t is the operations and maintenance (O&M) expenditure in year t, F_t is any fuel expenditure for the same year, E_t is the energy generated in year t, and r is the discount rate. By including the discount rate, this ensures that LCOE accounts for the change in value of investments over time. The life of an offshore wind asset could be longer than 25 years, and as such the importance of any spend in CAPEX or OPEX is dependent on the year of investment, with money spent in the future having less of an impact than the same amount spent now. Inputs to LCOE may vary between countries and as such care must be taken when making any comparisons between regions. One example given by Johnston et al. (2020) is the cost of

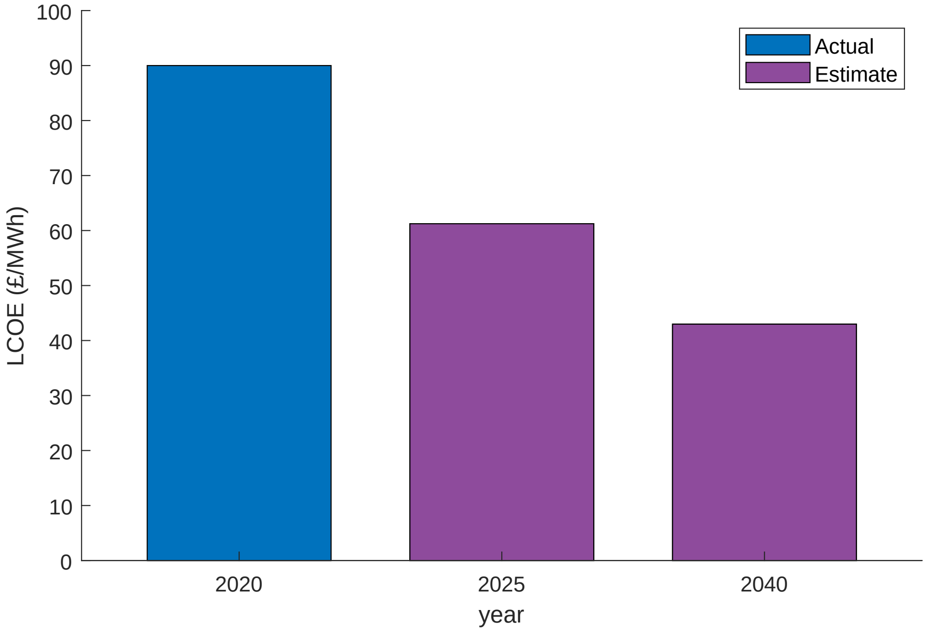

Figure 3.1: LCOE of UK offshore wind projects – actual and estimated (all in 2020 prices) (Source: IRENA (2021), BEIS (2020c) and HM Treasury (2025))

connecting a new development to the grid, which is the responsibility of the wind farm developer in the UK so would be included in the investment when calculating LCOE — however grid connection costs are the purview of transmission system operators in some other countries so their investment costs would differ.

The LCOE of offshore wind projects commissioning in the UK in the year 2020 was estimated at around £90/MWh[5] [6], while BEIS forecast this would drop to £61/MWh by 2025 and £43/MWh by 2040 (converting 2018 prices to 2020 prices) (IRENA 2021; BEIS 2020c; HM Treasury 2025). As demonstrated by Figure 3.1, this would be a substantial drop off in price over the short time between 2020 and 2025, with a further deep reduction expected in the following years. This would leave offshore wind with the second lowest LCOE of the technologies assessed in the BEIS report, with only large-scale solar PV projects cheaper in 2040. This represents a significant decrease in the anticipated costs of offshore wind from the previous BEIS report in 2016. At that

[5] Converting 115 USD/MWh to GBP at 2020 exchange rates (ONS 2025).

[6] The latest available data, for projects commissioning in 2023, estimates the LCOE of offshore wind in the UK at £47/MWh (converting USD to GBP at 2023 exchange rates) (IRENA 2024b; ONS 2025).

point, the prediction was that offshore wind LCOE would be £106/MWh by 2025. The estimates for all of the assessed renewable technologies decreased between 2016 and 2020, but that of offshore wind was the steepest, demonstrating the improvements made across the sector in the intervening years.

This drop in costs was also evident in the strike prices of the first three CfD Allocation Rounds (AR) run in 2015, 2017 and 2019[7]. It should be noted here that strike prices are not the same as LCOE, and differences in the two will be seen. For one, LCOE does not take into account revenues and so is not influenced by any subsidies which a particular development may be receiving. Additionally, strike prices are set with supplementary inputs that are not part of the LCOE model such as transmission losses or allocation of risk (BEIS 2020c). It is also crucial to note when considering CfD that contracts are always calculated in 2012 prices. Nonetheless, it has been observed that the two metrics are broadly compatible with one another as LCOE may be one input into a developer choosing their bid price, or in the setting of the administrative strike price for the CfD auction by BEIS (BVG Associates 2021c; BEIS 2020c). To this end, the strike prices in the third CfD auction round included those for projects to be commissioned in 2024/25 at a cost of around £40/MWh. This is lower than the £57/MWh LCOE estimated for 2025 by BEIS, but when inflation is considered this would bring the two measures into alignment. Furthermore, any offset may be exacerbated by the Dogger Bank A, B and C projects being awarded capacity in AR3 and skewing the results. Collectively, these three arrays will make the largest offshore wind farm in the world once operational, so they are not representative of the reference farm used to make the LCOE assessment in the BEIS report. Additionally, the development can benefit from economies of scale and the projects are situated with an advantageous wind resource at their location far from shore.

As a whole, new renewable energy developments are now cheaper than new fossil fuel power generation across most of the world, and for large-scale solar PV and on-

[7]The reduction in strike prices continued into AR4 in 2022, with strike prices of £33/MWh achieved. The CfD scheme is discussed in detail in Chapter 5.

shore wind the prices are often cheaper than even existing fossil fuel technology (IRENA 2019). With this being said, offshore wind is still generally more expensive than its onshore counterpart — however, its installation costs and LCOE have reduced as the sector has scaled. Though new developments in deeper water and with floating technology are likely to see price increases from those currently installed, it is anticipated that these will see cost reductions at a faster rate than occurred for fixed-bottom arrays as much experience has now been gained and there is increased policy support for new developments in the UK (ORE Catapult 2021).

3.3 Supply Chain & Local Content

One key area of emphasis for the UK offshore wind sector going forwards is the development of the local, domestic supply chain, with the Offshore Wind Sector Deal setting a target of 60% local content in new offshore wind farms by 2030 (BEIS 2019c). The implementation of local content requirements has been found in the literature to be one of the main ways that governments have sought to develop their domestic industry for renewable energy technologies in recent years, with competitive tender auctions growing in prevalence globally and local content increasingly a stipulation in the auction rules (Hansen et al. 2020). Methods to develop a local supply chain in the wind energy industry have been considered for many years, with research even in the early years of the 20$^{\text{th}}$ century attempting to identify methods for its growth. One study, from Lewis and Wiser (2007), highlighted the importance of a strong home market for wind energy developments if local manufacturing were to succeed — demonstrating how a pipeline of projects is necessary if local content is to occur. In their study, the authors proposed multiple avenues for 'localisation', or the development of domestic manufacturing, and the importance of governments being clear as to which model they aimed for. The proposed options were, simply: local industry could develop to manufacture whole systems; certain components only; or to serve as an assembly base for imported components. Additionally, new business could be targeted with a view towards innovation, or foreign manufacturers could be pursued to establish a local presence. The latter point was demonstrated as a result of local content requirements set in multiple countries in a study by Hansen et al. (2020), who found that much of the local content developed in Brazil following the implementation of renewable energy policy came from subsidiaries of foreign suppliers.

The first stage in growing local content levels is the establishment of a strong domestic supply chain. However, there are a number of barriers to overcome in an industry such as offshore wind if the UK is to increase its supply capabilities, and while local content requirements have been postulated as a way to overcome them there are conflicting views as to the efficacy of this type of policy action. Generally speaking, when requirements have been set at a government level, local content has been found to increase more in sectors such as product development or in the manufacture of lower complexity components — as opposed to seeing the establishment of producers of high-value wind turbine parts like blades or nacelles (Hansen et al. 2020; Bazilian et al. 2020). Existing capability in manufacturing sectors with similar complexity to the wind components was outlined as an advantage (Scheifele et al. 2022). Countries with a large domestic market for wind energy were also found to have better results, which should theoretically play in the UK's favour regarding an offshore wind supply chain with strong wind resource found all around the British coast. Perhaps the largest barrier to developing local content in the UK is the prevalence of large, well-established companies in the global supply chain, and the availability of (comparatively) cheap imports from markets such as China. Early adopters in the onshore wind industry, in countries such as Spain, benefitted from a focus on local content before the year 2000 and gained many years of experience while the sector grew at scale (Scheifele et al. 2022). However, other early adopters, such as Denmark, did not employ local content requirements and also saw their manufacturers become highly embedded in the global supply chain — demonstrating that early mover advantage could be more important than the imposition of local content requirements.

One of the hallmarks of a strong domestic supply chain, and a crucial stage if it is to be sustainable long-term, is developing to the extent that businesses can export and successfully compete on the global market. This was the focus of a study by Scheifele et al. (2022), where the possible link between local content requirements and ultimate export competitiveness of the supply chain was investigated. The authors determined that — having considered 17 countries who implemented local content requirements in the wind and/or solar PV industries out of a wider dataset of 124 countries — in the majority of cases there was no clear improvement in export capability due to the local content policy, even when domestic production may be incentivised. Some key findings of the study were that long learning processes and the complexity of wind component technology are crucial barriers to supply chain development and ultimate export capability, with existing capability in related manufacturing fields an advantage.

Considering the UK, the latter point could be particularly prescient in the case of floating wind. As discussed in Section 3.1.3, the UK has the largest floating wind installed capacity in the world — albeit part of a low global total. It has also been highlighted as an area where local content could be gained (SOWEC 2021), with a 1GW installed target for 2030 from the Offshore Wind Sector Deal and multiple gigawatts of capacity predicted from the ScotWind leasing round[8]. There is clearly an opportunity for the UK to gain the advantage as an early adopter in floating wind technology, particularly by drawing on learned experience from the well-established oil and gas sector domestically, and ultimately export this knowledge to other markets. If some form of policy relating to local content could be targeted specifically at the floating wind sector, the UK could benefit in a similar way as seen in Spain and China when local content requirements were established for their respective wind industries in the late 1990s (Scheifele et al. 2022). Ultimately, though the literature demonstrates conflicting views on the true extent of the benefits of local content requirements, the findings generally exhibited some level of effectiveness (Hansen et al. 2020). The UK has not, to date, mandated specific levels of local content in offshore wind, choosing to focus on the organic development of the supply chain through policy and relying on the industry

[8]The more recent INTOG and Celtic Sea leasing rounds are expected to bring further floating wind capacity across the UK.

to collectively purchase more domestic content[9].

3.4 Summary

Throughout this chapter, the relevant literature surrounding the development of the offshore wind industry in the UK has been reviewed. From an economic modelling standpoint, studies utilising IO and CGE methods were found to be prevalent within research from around the world and have been used to investigate impacts from employment to GVA. One critical aspect garnered from these studies was the importance of disaggregation of the electricity sector in data tables to properly understand the economic impacts from individual technologies such as offshore wind. The extant literature has been in general agreement that the energy transition will deliver positive economic benefits in terms of increased employment and additional GVA. It was also demonstrated that different modelling and analysis techniques may produce different results from the same basic data. This illustrates the dangers of comparing metrics from different studies without a full understanding of the methods undertaken to produce the results. There is uncertainty inherent in any model; assumptions mean that they are never going to be able to fully represent the complexity of a real-world system. However, this does not mean that the results are not useful. The studies considered in Section 3.1 illustrated how a sustained policy structure could impact upon the levels of economic benefits delivered, and the results from either ex-post or ex-ante studies can be used by policymakers as a benchmark of the current landscape to measure against future progress, or to guide decision making for the future.

One area of study which straddles both economic and engineering decision making is the cost associated with offshore wind. It is understood that developers will wish to minimise their costs from a business standpoint, thus investing less in the UK economy if cheaper inputs can be sourced elsewhere. However, on the contrary, reduced spend on imports could result in higher UK spend and greater levels of local content. Generally

[9]Chapter 5 of this thesis presents a detailed overview of UK supply chain policy and local content.

speaking, lower costs to build a new project will result in lower costs of energy; which should ultimately be beneficial to consumers if the savings are passed on in the form of reduced energy bills. LCOE is one crucial way in which the economics of a development are assessed. This has fallen drastically in recent years, as developers find they can build offshore wind farms for cheaper than previously predicted. The reduction in cost has many factors, including but not limited to: efficiency improvements from learning-by-doing, cheaper parts, and economies of scale. One additional aspect may be the reduced cost of financing new wind farm developments, due to the reduction in risk from the sustained subsidy scheme of the CfD. This, in turn, could ultimately be said to have led to reductions in the achieved strike prices in successive CfD rounds.

Related to the costs of offshore wind are considerations on supply chain and local content. With the 60% target for local content in developments by 2030 as set out in the Offshore Wind Sector Deal, there exists a huge opportunity going forwards to deliver more in the way of economic benefits to the UK by increasing the use of the domestic supply chains. Literature on the efficacy of local content requirements has reached conflicting conclusions, with content levels generally found to increase overall, but often concentrated in the project development sector or the manufacture of lower value components. Greater benefit has typically been demonstrated by early adopters of a technology, who can capitalise by gaining experience in a nascent industry before it develops at scale. The floating wind industry could offer this opportunity in the UK, if existing experience in offshore wind and the oil and gas sector can be exploited to develop a local supply chain for floating technology. It remains to be seen how the next generation of projects from ScotWind or that may win subsidies through upcoming CfD auctions will approach the issue of supply chain procurement and local content, with the UK supply chain as yet not able to fully compete for contracts with cheaper options from abroad.

Evident from the existing literature is the difficulty there is in reconciling all of the many, varied aspects of research surrounding offshore wind in terms of: economic modelling of GVA and employment impacts; local content levels; supply chain development;

developer decision making; and how policy actions affect all of these both individually and collectively. Though no study could ever hope to be exhaustive, clearly there are advantages to be gained if the whole-system understanding can be improved. Currently, there are conflicting agendas within the sector between the desire to maximise socioeconomic benefits like employment, output and emissions reductions; and market-driven considerations from developers requiring the lowest cost options. The scale of the challenge facing us is clear. Not only are we in the midst of a global climate crisis, there is policy commitment to maximising the benefits of the energy transition for offshore wind, and the net zero targets beyond. To maximise the socioeconomic benefits to the nation that could be delivered with the successful implementation of this plan, it is therefore crucial to fully understand how the system works and different aspects interact with each other, with the aim of all aspects being reconcilable with each other and all sides of the industry developing a better awareness of how their own area of interest relates with others. This outcome could then be used to guide future decisions to address any remaining policy gaps for meeting GHG emissions targets, ensuring the best possible chance for limiting global warming.

Chapter 4

Electricity's Role in Decarbonisation: Structural Decomposition Analysis

4.1 Introduction

In the years following the Kyoto Protocol in 1997, growing awareness and emphasis on the dangers of climate change rose globally, with nations around the world introducing legislation to limit their greenhouse gas (GHG) emissions. As detailed in Chapter 2, the UK Climate Change Act (2008) was the first framework in the world to set a legally-binding target for the reduction of GHG emissions (Lockwood 2013). At the time, this mandated an 80% reduction in GHG levels by 2050 from the 1990 baseline (Climate Change Act 2008). This has since been updated, reflecting the developing climate change landscape and prevailing scientific evidence, to a target of 'net zero' by 2050 (Climate Change Act 2008 (2050 Target Amendment) Order 2019). Between the years 2010 and 2018, following the introduction of the Climate Change Act (2008), the UK succeeded in reducing its annual GHG emissions from around 600MtCO_2e[1] to just less than 450MtCO_2e, a reduction of 25% (BEIS 2019a). The largest contributor to this change was the energy supply sector, which provided a 99MtCO_2e drop. This reduction can be tracked to the changing electricity supply mix in the UK as fossil fuels, in particular coal, have been phased out in favour of increasing the share of renewable energy sources such as wind power.

The aim of this chapter is to investigate the main driving factors behind the reductions observed in UK GHG emissions to date, and quantify the specific contribution of the electricity sector. Particular attention will be paid to how changes manifest at a sectoral level, demonstrating the impact of the supply chain. Using multisectoral environmentally extended Input-Output (IO) tables for the UK from 2010 and 2018[2], a Structural Decomposition Analysis (SDA) was performed. This allowed for an ex-post assessment of how changes in each of final demand, emissions intensity, and production technology in both the electricity sector and the wider economy contributed to the overall change in emissions seen over this period. The significant change in electricity supply over the timeframe of interest could be expected to have caused a drop in outright emissions from generation, though beyond this a transition in the pattern of economic inputs to the electricity sector will also have occurred. To account for these changes, the SDA methodology was extended to allow for the separation of the electricity supply chain from the rest of the economy. An additional novelty in the presented method is the extension to analyse the impact due to the change in specific fuel types, with the resultant drop in emissions due to changes in both coal and natural gas usage assessed in isolation.

The remainder of this chapter is presented as follows: firstly, this introductory section is completed by a review of the salient literature on decomposition analysis techniques in Section 4.1.1, before an outline of the novelty of the work detailed within this chapter is presented in Section 4.1.2. Following this, Section 4.2 then provides

[1] megatonnes of CO_2 equivalent (MtCO_2e).

[2] The latest year of IO tables available for the UK at the time of this work.

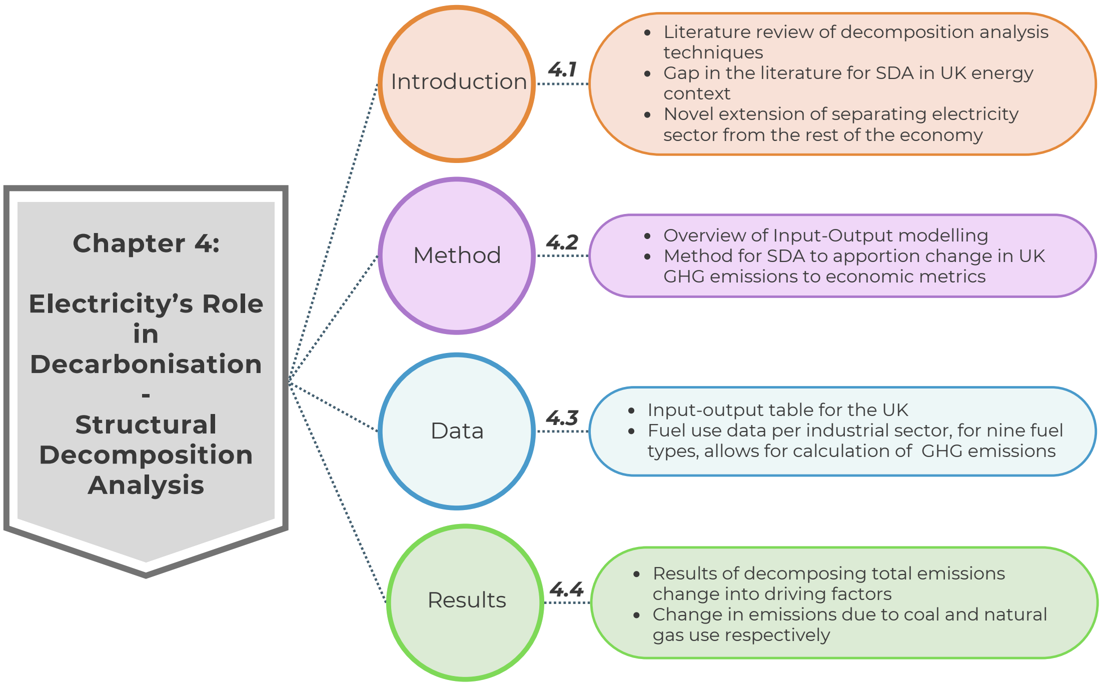

Figure 4.1: Chapter 4 structure and highlights

first an overview of the fundamentals of input-output modelling, and subsequently outlines the SDA methodology followed for this analysis. The datasets utilised for the study, namely input-output tables for the UK and fuel usage per industrial sector, are detailed in Section 4.3. The results of the SDA are then presented throughout Section 4.4, where the change in emissions due to total fuel usage, and due to coal and natural gas specifically, are detailed in turn. The chapter is completed by a discussion on how the physical changes within the UK energy sector relate to the results demonstrated by the SDA, in Section 4.5, while Section 4.6 concludes. A summary of the key elements of this chapter structure is visualised in Figure 4.1.

4.1.1 Literature Review

This section presents a review of the relevant literature surrounding economic activity within the field of energy and electricity generation, with a particular focus on methods investigating how changes in the energy landscape have impacted economic structure. As demonstrated throughout Chapter 2, the electricity sector in the UK has changed significantly throughout the past two decades — transitioning from a system dominated by fossil fuel generation to one increasingly comprised of renewable sources like wind power. It is clear that the transition of the electricity sector will have brought about significant changes to the structure of the economy, both in terms of the energy now being used throughout industry but also in the pattern of purchases between sectors as a result of new technologies.

One method of economic analysis which enables investigation of these patterns is Input-Output (IO) analysis, a well-established technique which has been widely applied across the energy field, as demonstrated by Chapter 3 of this thesis. In IO analysis[3], an input-output table shows purchases and sales between all sectors of the economy, which allows for analysis of the inter-dependencies between sectors and how one is used as an input to another (Miller and Blair 2022b). Value added inputs like labour, and final demand from non-industrial actors such as government, households, and export are also accounted for in the table. The data describing the interconnectivity of the economy can then be further extended with metrics such as employment or emissions per sector. For instance, Markandya et al. (2016) combined multi-regional IO tables with employment by sector across the EU to assess the impact of the low-carbon energy transition; while L. Liu et al. (2020) utilised an environmentally extended IO model to investigate the environmental impact of different industries in Canada.

In many cases, however, it may be of interest to look at the changes in a given metric over a period of time. Furthermore, there may also be a desire to investigate the driving forces behind these changes. There are two key tools which are used for this purpose, namely Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA). Both of these techniques have been widely applied in the study of energy and emissions[4]. Whilst both methods present a way to analyse the driving factors behind a

[3]An overview of the IO framework can be found in Appendix A.

[4]See Su and Ang (2012) and H. Wang et al. (2017) for detailed literature reviews of both methods.

change in indicator, they incorporate different data and modelling techniques[5]. The key difference is that IDA does not utilise IO data, considering solely the output per sector ($\mathbf{x}$) and the metric of interest; while SDA makes use of IO methodology and incorporates final demand ($\mathbf{f}$) and technical coefficients ($\mathbf{A}$) (Hoekstra and van den Bergh 2003). As such, one advantage of IDA is in its simplicity and lower data requirement. IDA has been applied extensively in the UK energy context, with Hammond and Norman (2012) identifying ten works in addition to the analysis of carbon emissions that they present.

However, for this study, SDA has been chosen as the preferred methodology. The application of SDA allows for a more detailed decomposition than IDA, whilst also capturing indirect effects (Hoekstra and van den Bergh 2003). The SDA process models the whole economy, with changes in supply and demand as well as changes in production technology captured through the IO framework. With this work the focus is on the contribution of the electricity sector to change in emissions. Understanding that the electricity generation mix has changed over the time period of interest, differences in production technology within the IO data are obviously crucial, and thus inform the decision to utilise SDA. In using this method, the driving forces behind the overall change in GHG emissions can be investigated more closely. This analysis is also more informative to policymakers, who are likely to be interested in how changes at an economic level to aspects such as production technology are impacting emissions (H. Wang et al. 2017).

SDA has been applied widely across the field of energy and emissions related research. Early studies included Wier (1998), who looked at the change in emissions of three different greenhouse gases in Denmark between 1966 and 1988 due to factors such as energy intensity, final demand changes, and household energy consumption. Su and Ang (2012) presented an assessment on the prevailing methods of SDA in energy research, reviewing studies which had been performed in the field across sixteen dif-

[5]For more detail on the application of IDA, and differences from SDA, Hoekstra and van den Bergh (2003) provide a comprehensive comparison of the two techniques.

ferent nations and regions for indicators from energy multipliers to emissions. Later, H. Wang et al. (2017) assessed the results of 67 studies from 2010 to 2015, showing that the application of SDA in this field was growing. Examples across the literature show that the SDA method has been utilised for studies of many regions and considering a range of factors. For instance, Brizga et al. (2014) concentrated their research in the Baltic states, investigating the impact of drivers such as population change on CO_2e emissions. For China, L.-J. Liu and Liang (2017) assessed changes in different pollutants, while F. Luo et al. (2020) employed a disaggregation of the Chinese power sector to analyse carbon emissions. Cansino et al. (2016) considered the impact of drivers such as the carbonisation factor and consumption patterns on CO_2 emissions in Spain; whilst Llop (2017) performed a regional study for Catalonia that assessed changes in energy output due to technological and structural changes. Analysing the carbon emissions of Singapore, Su et al. (2017) assessed the impact of four different categories of final demand.

Further, some studies have employed multi-regional IO (MRIO) analysis with SDA to look at changes in environmental factors on a global level or due to international trade. Examples include Dietzenbacher et al. (2020), who incorporated energy transition as a driving factor in global energy use; and Jiang et al. (2021) where the change in global carbon emissions was decomposed into drivers such as domestic and international input structure, and carbon intensity. Additionally, SDA on MRIO data was employed by Q. Wang and Yang (2020) to consider imports and exports on the oil intensity of Germany.

Across all of these studies, the application of SDA for energy or emissions research within the UK has been lacking. Su and Ang (2012) performed a comprehensive literature review of the field, and from 43 studies they found only one dedicated to UK emissions over the publication period of 1999 – 2010. In this study, Baiocchi and Minx (2010) used global, environmentally-extended, MRIO tables to assess the CO_2 emissions caused by UK consumption. Notably, this research assessed the impact of UK activity on global emissions, incorporating imports, rather than looking solely at emissions produced within the UK. A later review by H. Wang et al. (2017) again identified only this study. Beyond this, only one other journal paper explicitly looking at the UK has been found during this review. Kulionis and R. Wood (2020) utilised MRIO tables covering the period 1970 to 2009 to perform an SDA on the energy footprint of each of Denmark, the UK, France, and the USA. Through this study, they showed the decoupling of energy footprint and economic growth for each country, considering driving factors including energy efficiency, population and, production technology. Other studies using the alternative IDA method have been identified for the UK (e.g. Hammond and Norman (2012) and Norman (2017)), but no further studies utilising SDA for an assessment of the UK energy sector have been found during this review.

This demonstrates that there is much scope for the application of the widely established SDA method within the field of energy and emissions research in a UK context, given the significant changes in the energy mix which have occurred with the transition from fossil fuels. This is particularly the case through utilisation of UK specific IO tables and emissions data, with the two studies previously identified both making use of MRIO tables (Baiocchi and Minx 2010; Kulionis and R. Wood 2020).

4.1.2 Novelty

As demonstrated through the review in Section 4.1.1, there is a gap in the literature for the application of SDA to a UK energy context. In this chapter, a structural decomposition analysis is performed to investigate the main driving factors behind GHG emissions reductions in the UK between 2010 and 2018, which targets this gap and contributes to the understanding of decarbonisation progress in the UK.

Whilst it has been shown that SDA has been widely applied in energy and emissions research, this has not translated to many papers analysing the UK. As previously mentioned, those two which have been identified both utilised MRIO data as opposed to UK specific tables. This may be indicative of restrictions in data availability, with only the latest year of UK industry-by-industry input-output analytical tables readily available online (ONS 2022d). As SDA requires at least two years worth of data, this is clearly a limiting factor in the type of analysis that can be performed. For the work in this thesis, an IO table for the UK from 2010 has been sourced which, when combined with the latest published by the UK government for 2018, has allowed for an SDA covering a reasonable timeframe to be performed (Fraser of Allander Institute 2022).

Additionally, two novel extensions to the standard SDA method are presented. Firstly the impact of technology change from one particular sector is separated from the impact of production technology in the remaining sectors combined. Specifically, the impact of change in production technology of the electricity sector is considered as its own driver. Whilst change due to production technology is a widely analysed driver (e.g. F. Luo et al. (2020), Kulionis and R. Wood (2020), Cansino et al. (2016), Brizga et al. (2014), Baiocchi and Minx (2010)), none of these make a distinction on the contribution of a given sector.

Secondly, the results of performing an SDA on the impact of two different fuel types are presented, along with the main results of production emissions from total fuel use. This contributes an additional relevance in showing the impact on UK emissions of changing levels of coal and natural gas use, as the most polluting and highest percentage of electricity generation respectively. By separating these from the total fuel use, the results can be more closely analysed to emphasise the role that decarbonisation can play in reducing GHG emissions. This is of relevance to policy makers to reassert the importance of the transition to renewable energy sources.

4.2 Method

Within this section the method followed for the structural decomposition analysis performed within this work is described. This involved the use of environmentally extended input-output tables for two years, to assess how changes in different facets of the economy impacted GHG emissions in the UK. It is recognised from headline emissions data that the GHG emissions of the UK dropped between the years 2010 and 2018 (BEIS 2019a). The purpose of performing an SDA is to separate how changes within the economy contributed to this overall decrease (Miller and Blair 2022a). Before the calculations describing the SDA are outlined, an overview of the basics of IO analysis is presented first in Section 4.2.1, to aid the reader in their understanding of the SDA method which follows in Section 4.2.2.

4.2.1 Input-Output Model

In order to analyse IO accounts, it is instructive to start by considering the data from the table in mathematical terms. As explained by Miller and Blair, the IO system "consists of a set of n linear equations with n unknowns; therefore, matrix representations can readily be used" (Miller and Blair 2022b, p10). Thus, to start developing the analysis, the data in the IO table can first be expressed in linear algebra before extending to matrix form. Beginning with the intermediate demand section of the table, this encapsulates the sales from sector i to sector j, which are denoted z_{ij}. Taking a simple, two sector scenario, the total output, x, from each of sectors 1 and 2 can then be given by:

$$\begin{aligned} x_1 &= z_{1,1} + z_{1,2} + f_1 \\ x_2 &= z_{2,1} + z_{2,2} + f_2 \end{aligned} \tag{4.1}$$

Where x_1 and x_2 are the gross outputs of sector 1 and sector 2 respectively, z_{ij} are the elements of intermediate demand, and f_1 and f_2 are the aggregated final demand of sectors 1 and 2 (i.e. households, government and exports combined to one value). In more general terms, the above equations can be written as:

$$x_i = z_{i,1} + z_{i,2} + ... + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{4.2}$$

Where there exist equations for x_1, x_2 and so on, all the way to x_n for an economy with n sectors. As part of IO modelling, one aspect of interest is often the impact that a change within one particular sector will have on the wider economy. To assess this, 'technical coefficients', a_{ij}, are defined which denote the ratio of inputs required by sector j to produce one unit of its output (Miller and Blair 2022b):

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{4.3}$$

Where, for example, the technical coefficient $a_{1,2}$ represents how much sector 2 would need to purchase from sector 1, in order to produce one unit of output. In IO analysis, technical coefficients between two sectors are assumed to be fixed. This means that relationships between sectors cannot change — if sector 2 needs to double its output, the purchases it makes from sector 1 also need to double (Erickson and Kane 2017). Using the definition of the technical coefficients, a_{ij}, the equations for gross output x_i can be re-written to remove the intermediate sales z_{ij}. Again considering the two sector case, Equations 4.1 then become:

$$\begin{aligned} x_1 &= a_{1,1}x_1 + a_{1,2}x_2 + f_1 \\ x_2 &= a_{2,1}x_1 + a_{2,2}x_2 + f_2 \end{aligned} \tag{4.4}$$

Rearranging Equations 4.4 to group together the x_i terms:

$$\begin{aligned} (1 - a_{1,1})x_1 - a_{1,2}x_2 &= f_1 \\ -a_{2,1}x_1 + (1 - a_{2,2})x_2 &= f_2 \end{aligned} \tag{4.5}$$

At this point, it then becomes instructive to start considering the system of linear equations in matrix form, to account for an economy with n sectors rather than the simple, two sector case. Using matrix algebra, Equations 4.5 can be rewritten as:

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{f} \tag{4.6}$$

Where $\mathbf{I}$ is an $n \times n$ identity matrix, $\mathbf{x}$ is an $n \times 1$ column matrix of the gross output values x_i, $\mathbf{f}$ is an $n \times 1$ column matrix of the values for final demand f_i, and $\mathbf{A}$ is a matrix of technical coefficients, a_{ij}, given by:

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{\mathbf{-1}} \tag{4.7}$$

Where $\mathbf{Z}$ is a matrix of intermediate inputs z_{ij}, and $\hat{\mathbf{x}}^{\mathbf{-1}}$ is the inverse of a diagonal matrix of gross output x_i, extending from the algebraic form of Equation 4.3. So long as $(\mathbf{I} - \mathbf{A})$ is singular, using basic matrix algebra the system of n linear equations represented by Equation 4.6 can be solved for $\mathbf{x}$:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f} \tag{4.8}$$

Where $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is known as the 'Leontief inverse matrix', with elements l_{ij} (Miller and Blair 2022b). Each element, l_{ij}, captures the output needed from sector i to produce one unit of final demand for sector j — with the Leontief inverse accounting for both the direct and indirect input requirements to allow for a change in the level of final demand (Erickson and Kane 2017). Reading down column j in $\mathbf{L}$ will hence show the direct and indirect input requirements on all sectors i to generate one additional unit of output in sector j.

These steps form the basis of input-output accounting and modelling. Through the application of shocks to the model of the economy described by the IO table, Equation 4.8 and the Leontief inverse matrix can be used to analyse the overall impact as it ripples through the economy.

4.2.2 SDA Methodology

The application of an SDA allows for the change in a given metric, for instance, GHG emissions levels, to be split into the impact caused by the change in a number of chosen variables (Dietzenbacher et al. 2020). The change in each driving factor gives how much the GHG emissions would have changed had all other variables remained constant.

Considering first the simple case of a change in output between two years, an additive SDA can be performed to decompose this overall change into the contribution of different factors (Miller and Blair 2022a). Taking the formula detailing gross output from Equation 4.8, it then follows that the change in gross output between two years (year 0 and year 1) can be expressed as:

$$\Delta \mathbf{x} = \mathbf{x}^1 - \mathbf{x}^0 = \mathbf{L}^1\mathbf{f}^1 - \mathbf{L}^0\mathbf{f}^0 \tag{4.9}$$

Given this change in gross output, it is reasonable to suggest that this has been driven through changes in the technical coefficients from the IO table (presented through changes to the Leontief inverse matrix, $\Delta\mathbf{L} = \mathbf{L^1} - \mathbf{L^0}$) and changes to final demand ($\Delta\mathbf{f} = \mathbf{f^1} - \mathbf{f^0}$). In order to decompose these changes, Miller and Blair (2022a) propose firstly considering only data from year 1 for $\mathbf{L}$ and year 0 for $\mathbf{f}$:

$$\Delta \mathbf{x} = \mathbf{L}^1\left(\mathbf{f}^0 + \Delta\mathbf{f}\right) - \left(\mathbf{L}^1 - \Delta\mathbf{L}\right)\mathbf{f}^0 = \Delta\mathbf{L}\mathbf{f}^0 + \mathbf{L}^1\Delta\mathbf{f} \tag{4.10}$$

Instead, different weightings of year 0 for $\mathbf{L}$ and year 1 for $\mathbf{f}$ could be assessed:

$$\Delta \mathbf{x} = \left(\Delta\mathbf{L} + \mathbf{L}^0\right)\mathbf{f}^1 - \mathbf{L}^0\left(\mathbf{f}^1 - \Delta\mathbf{f}\right) = \Delta\mathbf{L}\mathbf{f}^1 + \mathbf{L}^0\Delta\mathbf{f} \tag{4.11}$$

Both Equations 4.10 and 4.11 follow from simple algebra of the initial expression for $\Delta\mathbf{x}$. Alternative combinations of year 0 and year 1 data are of course possible, as Miller and Blair (2022a) discuss. However they posit that, in general terms, it is reasonable to take an average of the above equations as a way to decompose $\mathbf{\Delta x}$ into the contributions of technology change and final demand change:

$$\begin{aligned} \Delta\mathbf{x} &= \left(1/2\right)\left[\Delta\mathbf{L}\mathbf{f}^0 + \mathbf{L}^1\Delta\mathbf{f} + \Delta\mathbf{L}\mathbf{f}^1 + \mathbf{L}^0\Delta\mathbf{f}\right] \\ &= \left(1/2\right)\Delta\mathbf{L}\left(\mathbf{f}^0 + \mathbf{f}^1\right) + \left(1/2\right)\left(\mathbf{L}^0 + \mathbf{L}^1\right)\Delta\mathbf{f} \end{aligned} \tag{4.12}$$

Where the first term encapsulates the impact on the overall change in output due to technology change, and the second the impact due to changes in final demand. This method of averaging the possible decompositions has been utilised throughout the published literature on SDA (e.g.: Dietzenbacher and Los (1998), Brizga et al. (2014), Llop (2017)).

For the work in this chapter, the aim was to decompose the change in GHG emissions between two years. In IO analysis, a physical quantity can be calculated by the use of output coefficients. For this environmentally extended case, emissions-output coefficients were used when attempting to quantify the change in emissions between the two years of interest. From IO analysis, the vector of GHG emissions per sector can be explained by (Miller and Blair 2022a):

$$\boldsymbol{\epsilon} = \hat{\mathbf{e}}\mathbf{x} = \hat{\mathbf{e}}\left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{f} = \hat{\mathbf{e}}\mathbf{L}\mathbf{f} \tag{4.13}$$

Where $\boldsymbol{\epsilon}$ denotes GHG emissions and $\hat{\mathbf{e}}$ is the diagonal matrix of emissions intensity (or emissions per unit output). Therefore, when considering the change in emissions ($\Delta\boldsymbol{\epsilon}$) between year 0 and year 1, this is given by:

$$\Delta\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^1 - \boldsymbol{\epsilon}^0 = \hat{\mathbf{e}}^1\mathbf{L}^1\mathbf{f}^1 - \hat{\mathbf{e}}^0\mathbf{L}^0\mathbf{f}^0 \tag{4.14}$$

Similarly to that shown in Equations 4.9 to 4.12, the SDA process then allows for this change in emissions to be decomposed into the change attributable to any number of different aspects of the economy.

The analysis utilised here followed an additive approach with a similar methodology to that described by Brizga et al. (2014) in their analysis of the drivers of GHG emissions in the Baltic States and Llop (2017) when assessing energy output in Catalonia. Specifically, the chosen method was based on that outlined by Miller and Blair (2022a) which assessed three main factors: change in emissions intensity, change in final demand, and change in production technology[6]. Using these variables as the contributors to change in CO_2e emissions, and following the same method as for Equation 4.12, the calculation from Equation 4.14 instead becomes (Miller and Blair 2022a):

$$\begin{aligned}\Delta\boldsymbol{\epsilon} = &\left(1/2\right) \underbrace{\left(\Delta\hat{\mathbf{e}}\right)\left(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1\right)}_{\text{Emissions coeff. change}} \\ &+ \left(1/2\right) \underbrace{\left[\hat{\mathbf{e}}^0\left(\Delta\mathbf{L}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1\left(\Delta\mathbf{L}\right)\mathbf{f}^0\right]}_{\text{Technology change}} \\ &+ \left(1/2\right) \underbrace{\left(\hat{\mathbf{e}}^0\mathbf{L}^0 + \hat{\mathbf{e}}^1\mathbf{L}^1\right)\left(\Delta\mathbf{f}\right)}_{\text{Final demand change}}\end{aligned} \tag{4.15}$$

Where $\Delta\boldsymbol{\epsilon}$ is the change in emissions between year 0 and year 1, $\hat{\mathbf{e}}$ is the emissions-output coefficient, $\mathbf{L}$ is the Leontief inverse matrix, and $\mathbf{f}$ is a vector of final demand. The superscripts *0* and *1* refer to years 2010 and 2018 respectively, while Δ indicates the change in a given variable between year 0 and year 1. Each line in Equation 4.15

[6] Technology change encompasses "any factor that causes a change in a technical [...] coefficient" (Rose and Casler 1996, p42), resulting in changes to the Leontief inverse, **L** (Miller and Blair 2022a).

calculates the change due to one specific aspect of the economy. In each case, it is the impact had one contributing factor changed while the others remained constant (Brizga et al. 2014).

To further analyse the change in production technology, the second part of Equation 4.15 was separated into 3 calculations — change within the electricity sector (self-purchases and production inputs to sector) and the change in the rest of the economy. This was due to the fact that, in the case of emissions, the electricity sector (sector D35.1)[7] was expected to be a large contributor. By separating into components of technology change this would illustrate the relative contributions of the supply chain for the electricity sector and the production inputs to the rest of the economy. Self-purchases of sector D35.1 from itself, which likely reflect change in level of trading activity rather than change in input structure, were also separated to remove any chance of this skewing the data. Thus the technology change from line two of Equation 4.15 was split into these three aspects as shown below:

$$\begin{aligned} \text{Technology change} = & \left(1/2\right) \left[\hat{\mathbf{e}}^0 \left(\Delta\mathbf{L}_{D35.1}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1 \left(\Delta\mathbf{L}_{D35.1}\right)\mathbf{f}^0\right] \\ & + \left(1/2\right) \left[\hat{\mathbf{e}}^0 \left(\Delta\mathbf{L}_{D35.1-self}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1 \left(\Delta\mathbf{L}_{D35.1-self}\right)\mathbf{f}^0\right] \\ & + \left(1/2\right) \left[\hat{\mathbf{e}}^0 \left(\Delta\mathbf{L}_{else}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1 \left(\Delta\mathbf{L}_{else}\right)\mathbf{f}^0\right] \end{aligned} \tag{4.16}$$

Additionally, to distinguish the impact of decarbonising the electricity sector, the change due to the emissions intensity of sector D35.1 was separated from the change attributable to all remaining sectors as follows:

$$\begin{aligned} \text{Emissions coeff. change} = & \left(1/2\right) \left(\Delta\hat{\mathbf{e}}_{D35.1}\right) \left(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1\right) \\ & + \left(1/2\right) \left(\Delta\hat{\mathbf{e}}_{else}\right) \left(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1\right) \end{aligned} \tag{4.17}$$

[7] The sectors of the IO table are provided in Table B.1.

With $\Delta\hat{\mathbf{e}}_{\mathrm{D35.1}}$ representing a diagonal matrix of the change in emissions coefficient for the electricity sector, while $\Delta\hat{\mathbf{e}}_{\mathrm{else}}$ is a diagonal matrix of the change in emissions coefficient for all sectors excluding D35.1. Combining Equation 4.17 with the split for technology change in Equation 4.16, the final equation, expanded from Equation 4.15 is as follows:

$$\begin{aligned}
\Delta\boldsymbol{\epsilon} = &\left(1/2\right)\left(\Delta\hat{\mathbf{e}}_{D35.1}\right)\left(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1\right) \\
&+ \left(1/2\right)\left(\Delta\hat{\mathbf{e}}_{else}\right)\left(\mathbf{L}^0\mathbf{f}^0 + \mathbf{L}^1\mathbf{f}^1\right) \\
&+ \left(1/2\right)\left[\hat{\mathbf{e}}^0\left(\Delta\mathbf{L}_{D35.1}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1\left(\Delta\mathbf{L}_{D35.1}\right)\mathbf{f}^0\right] \\
&+ \left(1/2\right)\left[\hat{\mathbf{e}}^0\left(\Delta\mathbf{L}_{D35.1-self}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1\left(\Delta\mathbf{L}_{D35.1-self}\right)\mathbf{f}^0\right] \\
&+ \left(1/2\right)\left[\hat{\mathbf{e}}^0\left(\Delta\mathbf{L}_{else}\right)\mathbf{f}^1 + \hat{\mathbf{e}}^1\left(\Delta\mathbf{L}_{else}\right)\mathbf{f}^0\right] \\
&+ \left(1/2\right)\left(\hat{\mathbf{e}}^0\mathbf{L}^0 + \hat{\mathbf{e}}^1\mathbf{L}^1\right)\left(\Delta\mathbf{f}\right)
\end{aligned} \tag{4.18}$$

Where each line details the change in UK GHG emissions ($\Delta\boldsymbol{\epsilon}$) due to the change in a given variable, namely: emissions intensity of the electricity sector; emissions intensity of all other sectors combined; technology change of sector D35.1 (excluding self-purchases); technology change of D35.1 only; technology change for the rest of the economy; and final demand.

4.3 Data

Within this section, the data employed for the SDA is outlined and a summary of the pre-processing performed on the environmentally extended input-output tables is provided. Firstly, the economic data within the IO tables is discussed in Section 4.3.1. Section 4.3.2 then outlines the fuel usage data that was used to calculate production emissions from each sector for both 2010 and 2018.

4.3.1 Input-Output Tables

For the purposes of this analysis, IO tables for the UK in the years 2010 and 2018 were utilised. Due to limitations in the availability of data, 2010 was the earliest dataset which could be located (Fraser of Allander Institute 2022). Additionally, data covering 2018 was the most recent to have been published at a UK level at time of writing (ONS 2022d). Both IO tables used SIC 2007 classification for their industry sector breakdown, but each employed a different level of aggregation of sectors which had to be made compatible (ONS 2010). Originally, the 2010 dataset covered 103 sectors while there were 105 sectors for 2018. The two datasets were compared, and sectors were aggregated to ensure that both tables contained the same sectoral breakdown. The resultant tables represented 100 sectors each, which are shown in Appendix B in Table B.1.

Each of the IO tables were in current prices for their respective years. In order to make the data within the two tables compatible for the SDA calculations, the 2010 values were inflated into 2018 prices. The UK Government GDP deflator series was utilised, with the GDP deflator for 2010 and 2018 allowing for inflation between the two years to be accounted for (HM Treasury 2025).

4.3.2 Fuel Use Emissions

For the SDA, the UK IO tables from 2010 and 2018 were environmentally extended with data on fuel use across all industrial sectors, to investigate how changes in the structure of the economy influenced greenhouse gas emissions. Only production emissions by industry were considered, with household emissions excluded from this study. The fuel use data, published by the ONS (2022b), detailed the usage of eight types of fossil fuels (plus an aggregate 'other' fuel category[8]) across 131 industrial sectors over a 31

[8]'Other' fuels are listed as: anthracite, blast furnace gas, burning oil, coke, coke oven gas, colliery methane, LPG, lubricants, naptha, OPG, orimulsion, peat, petroleum coke, refinery misc., sour gas, SSF, waste oils, and waste solvent (ONS 2022b).

year period from 1990 to 2020. This data outlined the usage of each fuel type in megatonnes of oil equivalent (Mtoe), and employed the same SIC 2007 classification of industrial sectors as that used in the IO tables. To make the sectors used for this analysis consistent with that of the IO data, the 131 rows of the fuel use tables were aggregated to cover the same 100 sectors as described in Table B.1.

For confidentiality reasons, some rows within each of the fuel use tables were suppressed and only the total for the industrial section was provided. For these cases, the total for the section and the values which were available for non-confidential sectors within that section were used to calculate the value attributable to those missing sectors. This amount was then split evenly amongst the confidential sectors as an estimate. For the purposes of this analysis, the fuel use and resultant GHG emissions inferred by these estimates were assumed to be small when compared to the use across the economy, such that a rough estimation on the confidential sectors was appropriate.

In order to calculate the GHG emissions caused by fuel use across the economy, the values were first converted from Mtoe into kWh using a standard toe-kWh conversion (BEIS 2022b). From this, a fuel-specific conversion factor was then used to transform the gross calorific value of each fuel in kWh into the CO_2 equivalent emissions in $kgCO_2e$. The conversion factors used for each fuel are included in Table 4.1. For the case of the eighteen fuel types combined into the 'Other' fuels category, conversion factors were not available for all. Here, an average conversion factor was calculated using those which were provided, weighted by the fuel types which contributed the highest amount of fuel use. The total $kgCO_2e$ emissions from the nine fuel categories included in Table 4.1 were summed across the 100 sectors of the economy to provide an estimate of the total production emissions due to fuel use from each industrial sector in both 2010 and 2018.

Table 4.1: Conversions from kWh to kgCO_2e. Taken from (BEIS 2022b).

Fuel	Conversion
Coal (industrial)	0.324
Natural gas	0.183
Petrol (av. biofuel blend)	0.230
Diesel (av. biofuel blend)	0.237
Fuel oil	0.268
Gas oil	0.257
Aviation spirit	0.244
Aviation turbine fuel	0.248
Other fuels	0.266

4.4 Results

Within this section, the results of the structural decomposition analysis are presented. Firstly, Section 4.4.1 provides an overview of the total change in emissions between 2010 and 2018, showing the industrial sections which contributed the most. This is followed by the results of the SDA itself in Section 4.4.2, where the driving factors of the overall change are analysed, with the novel contribution of fuel-specific SDA for coal and natural gas presented in Section 4.4.3. Finally, Section 4.4.4 looks more closely at emissions intensity as a contributor to reduction in GHG emissions.

4.4.1 Total Emissions

Considering first the overall change in emissions, from the fuel use data described in Section 4.3 a total reduction in production emissions in the UK of 127MtCO_2e between 2010 and 2018 is calculated. The graph in Figure 4.2 shows the total change in GHG emissions split into the contribution of each industrial section (A – T [9]). Section D (electricity, gas, steam and air conditioning supply) saw the largest change, with a reduction of 97MtCO_2e over the period of interest. Within this, 96MtCO_2e was due to

[9] See Table B.1 for sections and sectors.

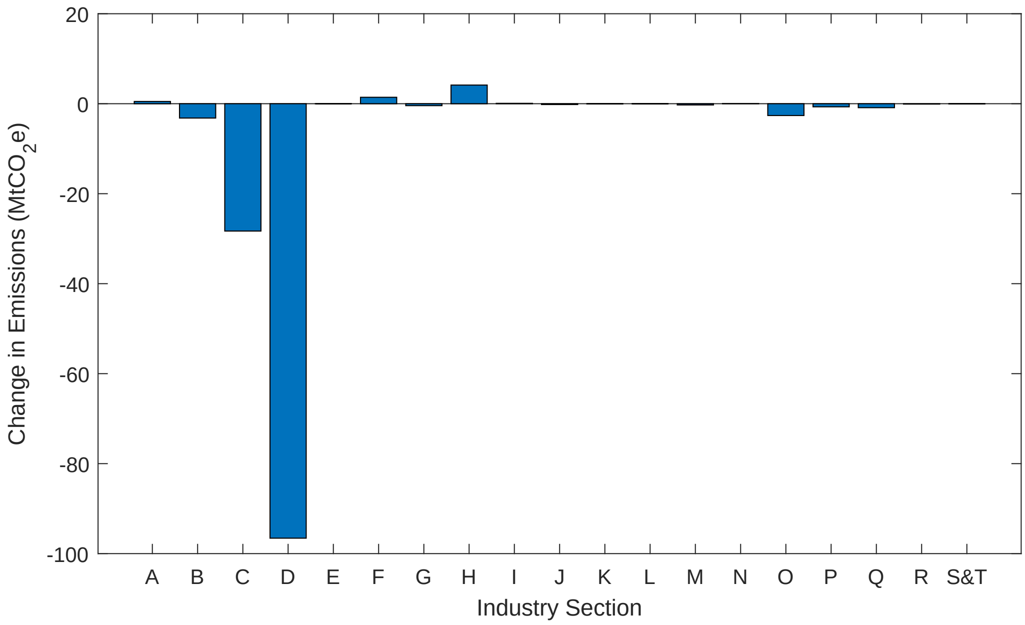

Figure 4.2: Change in GHG emissions per industrial section 2010 – 2018 (Adapted from data by ONS (2022b))

the electricity sector (D35.1: electric power generation, transmission and distribution) with the remainder from sectors D35.2 and D35.3. As such, sector D35.1 contributed over 75% of the total change in emissions across the economy between the two years.

The second largest contributor was Manufacturing (Section C), which saw an overall reduction in production emissions of 28MtCO_2e due to changes in fuel use. Of this section total, an 11MtCO_2e reduction came from sector C19 (manufacture of coke and refined petroleum products). There are 43 sectors aggregated within the Manufacturing section and, of these, 36 experienced a reduction in GHG emissions, with the 7 which saw an increase collectively totalling 0.8MtCO_2e. As such, it is clear that beyond sector C19 there was a widespread reduction in emissions across the manufacturing section.

The industrial section which showed the third largest change in emissions due to fuel use was Section H (Transportation and Storage). Of the three largest contributing sections, Section H was the only one to show an increase in production emissions, experiencing a rise of 4MtCO_2e. Whilst there was a large jump in absolute terms from the 97MtCO_2e and 28MtCO_2e changes seen from sections D and C respectively, it is still of interest that the third largest contributor to overall change in emissions was an increase. At a sectoral level, the increase in emissions shown by Section H was driven by an increase in emissions from the air transport sector (H51).

The remaining sixteen industrial sections had a combined reduction in emissions due to fuel use of 6MtCO_2e, with eleven individual sections experiencing a decrease. This data combines to show that the reduction in GHG emissions in the UK between 2010 and 2018 was concentrated in only a small section of the economy, with the electricity sector the overwhelming main contributor.

4.4.2 SDA Results

It was established in Section 4.4.1 that fuel use production emissions in the UK saw a 127MtCO_2e reduction between the years 2010 and 2018. Whilst this analysis showed that the decrease was concentrated within the electricity sector, it is useful to understand what has changed within the economy to drive this headline figure. This section presents the results of the SDA to disaggregate the overall drop in emissions into the contribution of changes in the economy discussed in Section 4.2.

Following the calculation described by Equation 4.18, the results of the SDA showing the contribution due to emissions intensity reductions, production technology changes, and change in final demand are shown in Figure 4.3. The largest contributor to emissions reduction in the UK between 2010 and 2018 was found to be a change in the emissions intensity of the economy which, had everything else remained as 2010, caused a drop in emissions of 166MtCO_2e. Within this, 114MtCO_2e was due to the change in the emissions per unit output of the electricity sector, while the remaining 52MtCO_2e accounted for all other sectors of the economy. The reduction of this block was concentrated in two sectors, C19 (manufacture of coke and petroleum products) and H51 (air transport), which together contributed 43% of the 52MtCO_2e of changes due to emis-

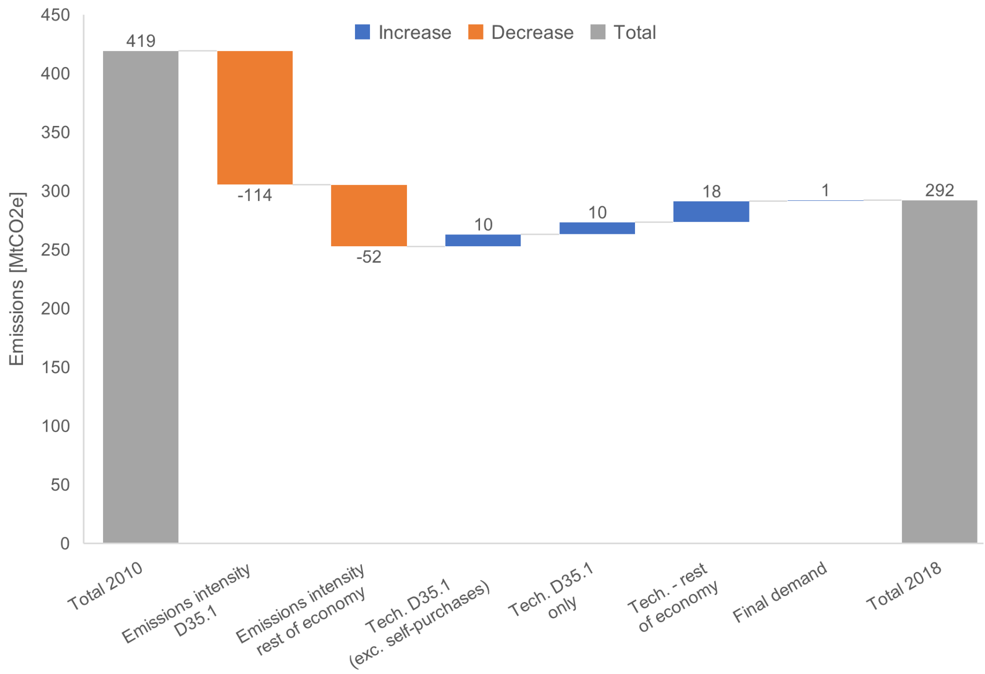

Figure 4.3: Waterfall diagram showing contribution to emissions change in the UK between 2010 and 2018

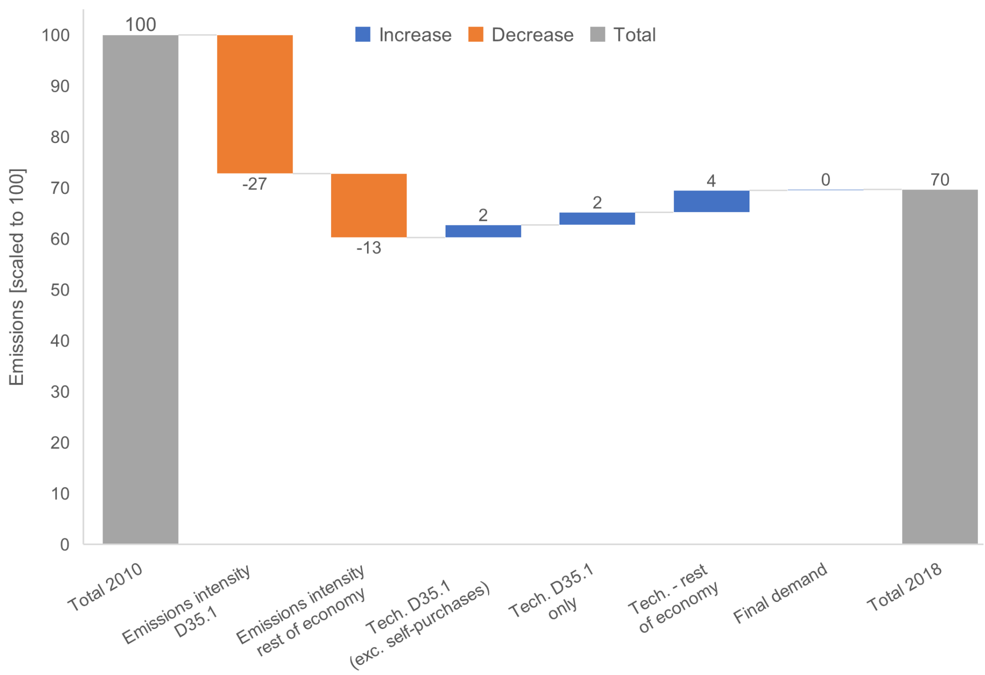

Figure 4.4: Waterfall diagram showing percentage contribution to emissions change in the UK between 2010 and 2018

sions intensity of the rest of the economy with around 11MtCO_2e each. The remaining 57% was contributed by the other 97 sectors combined, with all exhibiting a change of less than 3MtCO_2e. The variation in emissions intensity across the economy is further assessed in Section 4.4.4.

In terms of the contribution of other changes in the economy, had emissions intensity and production inputs remained constant then there would have been a small expected increase in emissions from the UK of 1MtCO_2e due to an increase in the level of final demand. Alternatively, the changes in only production technology, with all other variables fixed as the 2010 case, would have led to a more substantial increase in emissions. Isolating the interconnections of sector D35.1 with the rest of the economy indicates an increase of 20MtCO_2e, while the remaining sectors would have contributed 18MtCO_2e. However, of the 20MtCO_2e estimated for the electricity sector roughly half is due to purchases the sector made from itself, which indicates an upturn in trade rather than reflecting technology change over the period of interest. The remaining 10MtCO_2e then is that which can be attributed to changes within the production inputs to sector D35.1.

Figure 4.4 shows the data from the waterfall diagram in Figure 4.3 scaled to 100, allowing the results to be read in percentage form. This more clearly shows there was an overall 30% reduction in production emissions due to fuel use between the two years of interest. However, considering a scenario where no decarbonisation took place in the UK, changes to production technology and final demand would have caused an increase in UK GHG emissions of 8%. If changes in emissions intensity from sectors other than sector D35.1 are included, there would have been an overall decrease in GHG emissions, but only of 5%. This shows that whilst economy-wide energy intensity improvements have played a significant role in reducing emissions, between 2010 and 2018 changes to the energy intensity of the electricity sector have been the most consequential.

4.4.3 Fuel-Specific SDA

This section presents the results of performing the SDA process outlined in Section 4.2 on the usage of specific fuel types. Whilst the results in Section 4.4.2 disaggregate the changes due to the usage of all nine[10] fuel categories combined, the results shown here considered only the usage of coal and natural gas respectively. Coal is discussed first, in Section 4.4.3.1, and natural gas is considered in Section 4.4.3.2.

4.4.3.1 Emissions due to Coal Usage

Considering the coal use first, Figure 4.5 shows the change in coal-related emissions. Starting from a level of 121MtCO_2e in 2010, there was a 92MtCO_2e reduction in emissions from coal use to 2018, when 29MtCO_2e was observed. From emissions intensity changes in sector D35.1, there was a drop of 87MtCO_2e, whilst the remaining sectors saw a 14MtCO_2e drop.

As with the case for all fuels combined, emissions from coal use would have seen an increase due to changes in production technology between 2010 and 2018. Changes due to the electricity sector were again the main contributors, with a rise of 11MtCO_2e attributable to sector D35.1. However, unlike for the case with all fuels, technology change from the rest of the economy and due to variation in final demand would both have contributed a small decrease — each in the region of around 1MtCO_2e.

The most notable difference between the results for coal and those presented in the previous section is the ratio between the reduction due to emissions intensity changes of sector D35.1 and emissions intensity of the other sectors. While for all fuels D35.1 still contributed the most, the scale of the bars in Figure 4.5 is more striking. This shows that the electricity sector saw a much larger reduction in emissions intensity due to changes in coal use than the rest of the economy combined.

[10]See Table 4.1 for list of fuels.

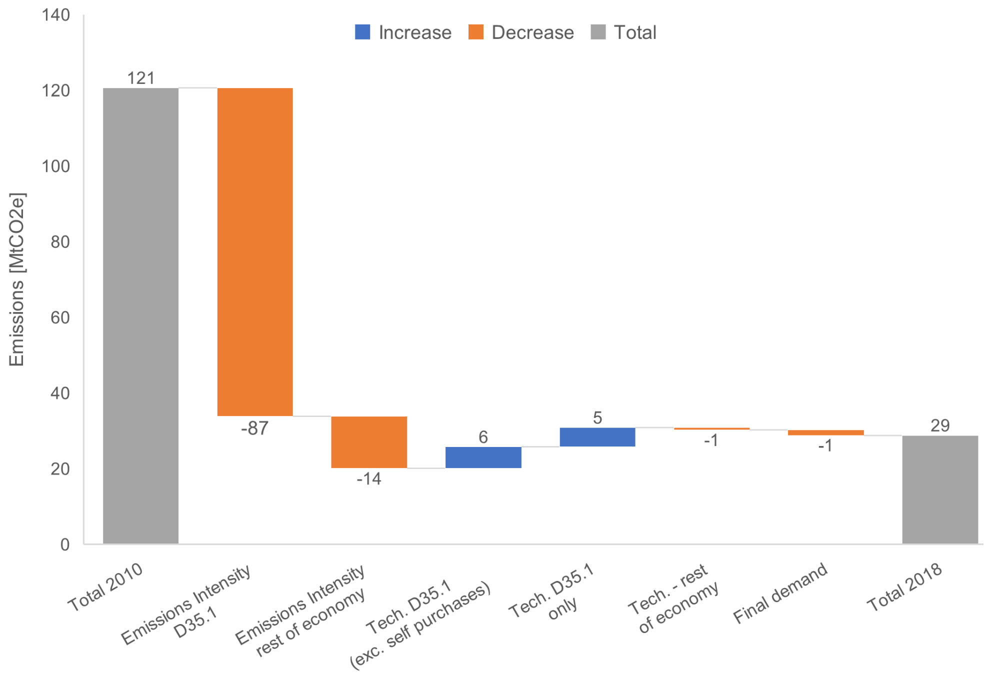

Figure 4.5: Waterfall diagram showing emissions change in the UK due to coal use between 2010 and 2018

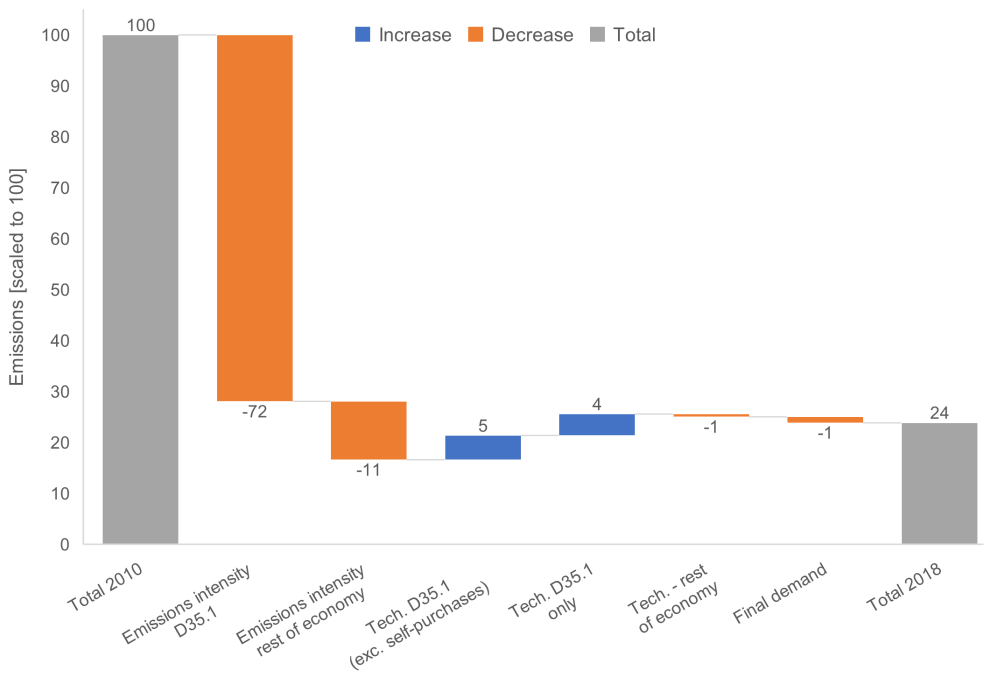

Figure 4.6: Waterfall diagram showing percentage change in emissions in the UK due to coal use between 2010 and 2018

In percentage terms, shown in Figure 4.6, had only emissions intensity of the electricity sector changed, there would have been a 72% reduction in GHG emissions from coal. On the contrary, had the emissions intensity of D35.1 remained the same, while the other driving factors were allowed to change, there would have been only a 4% decrease in GHG emissions — though driven mostly by improvements in emissions intensity from the rest of the economy. As it were, combining all aspects of the SDA together shows that there was a 76% reduction in emissions due to coal use between 2010 and 2018. This analysis demonstrates the role that reducing coal use in electricity generation has played in decarbonisation.

4.4.3.2 Emissions due to Natural Gas Usage

The largest percentage of UK electricity generation in both 2010 and 2018 was from natural gas use, with over 40% generated from this fuel (BEIS 2023). As such, the SDA process was applied again for natural gas use across the economy[11], with the resulting waterfall diagram showing the relevant contributions provided in Figure 4.7.

A much smaller overall reduction in emissions was observed due to changes in natural gas usage than for the case of all fuel use or for coal, with a 24MtCO_2e drop between 2010 and 2018. However, as with the previous cases, a change in the emissions intensity of the electricity sector was the main contributor, with a fall of 27MtCO_2e observed had other variables been held constant.

The percentage change in each facet of the economy due to natural gas usage is shown in Figure 4.8. Comparing this with the percentage changes due to coal use from Figure 4.6, the main difference is clearly that emissions intensity of the electricity sector from coal dropped significantly, while there was a much smaller drop for natural gas. Another key result from the natural gas graphs is that the SDA shows a 21% drop in emissions of the electricity sector due to this fuel, while natural gas usage for electricity

[11]While the impetus for assessing natural gas usage was its importance in electricity generation, the assessment here also includes its use in all other sectors for purposes beyond gas-powered generation. For instance, as a feedstock for ammonia production (BEIS 2020a).

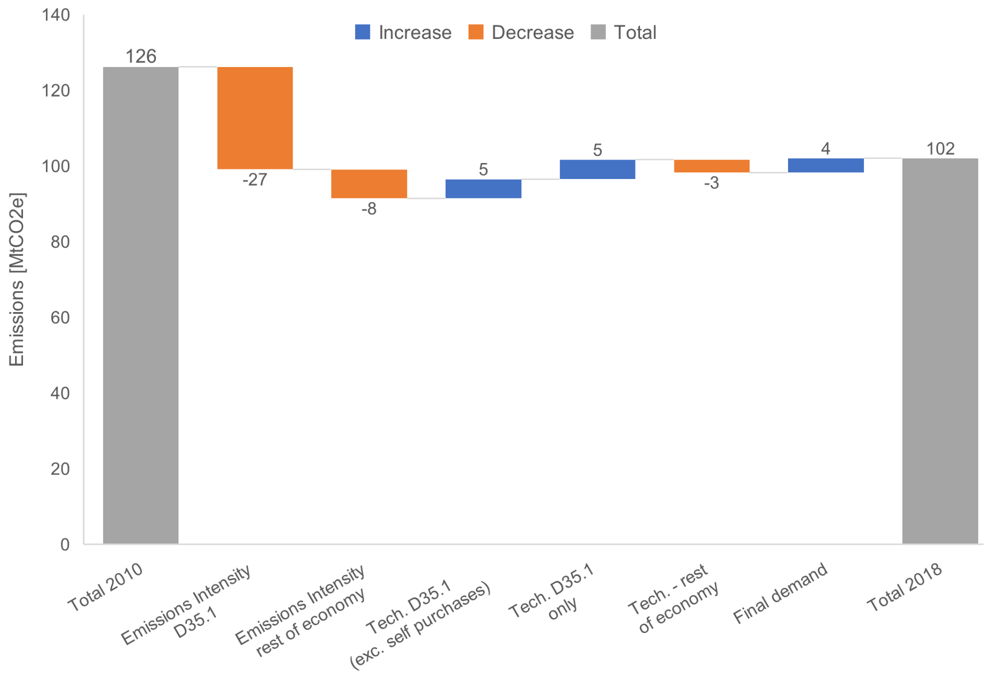

Figure 4.7: Waterfall diagram showing emissions change in the UK due to natural gas use between 2010 and 2018

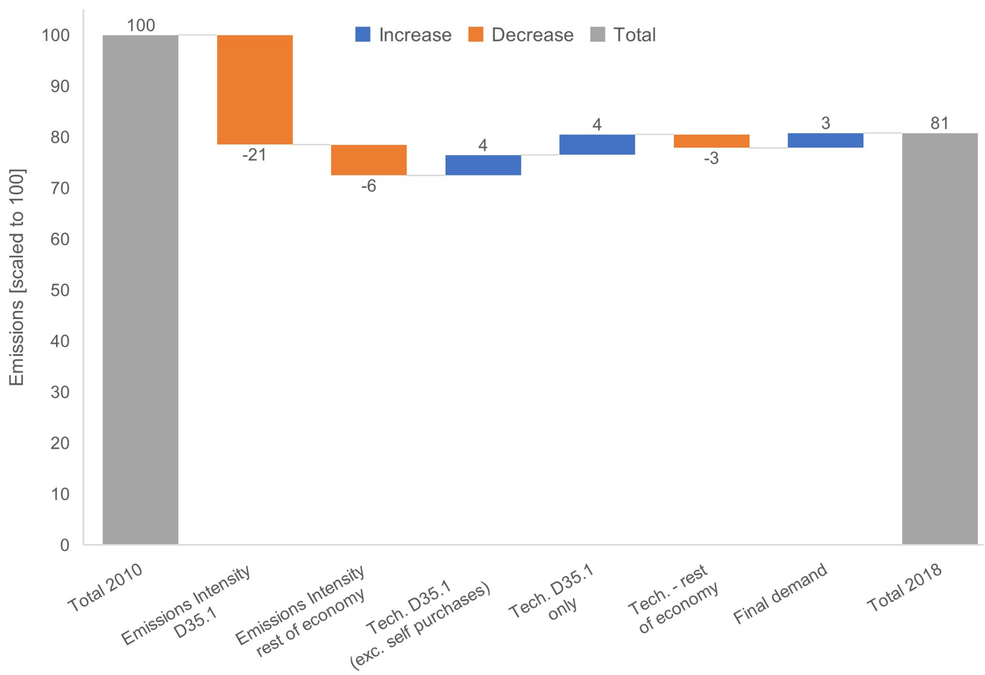

Figure 4.8: Waterfall diagram showing percentage change in emissions in the UK due to natural gas use between 2010 and 2018

only reduced by about 5% between 2010 and 2019. This indicates that there are other aspects contributing to decarbonisation than just outright levels of fuel use. In both years under investigation, emissions from natural gas use were in fact higher than that from coal, demonstrating that while reductions have been observed there is still scope for further cuts if natural gas usage can be limited.

4.4.4 Emissions Intensity

From the results shown in Figures 4.3 to 4.8, it is clear that changes in emissions intensity were the main drivers of overall UK emissions change between 2010 and 2018. In this section, changes in the calculated emissions intensity across all industries are presented, to further assess its contribution.

The emissions intensity (emissions per unit output) of the sixteen industrial sections, as calculated for both 2010 and 2018, is provided in Table 4.2. The data within the table shows that all bar one of the sections of the economy saw a decrease in emissions intensity between 2010 and 2018. Within this, Section D showed the largest drop of 66%. This aligns with the results presented in Section 4.4.2, specifically Figure 4.3 which demonstrated how a change in emissions intensity of the electricity sector (D35.1) was the biggest contributor to the reduction in GHG emissions. The only section to show an increase in emissions intensity was Section B, representing the sectors associated with mining and quarrying. While the outright emissions due to fuel use for this section decreased between 2010 and 2018, the gross output of the section also reduced — leading to an increase in the measure of emissions per unit output.

Though the remaining industrial sections all showed a reduction in emissions intensity, to varying extents, not all sections saw a corresponding reduction in outright emissions — as discussed in Section 4.4.1. This indicates that while it has been shown to be a large contributor, emissions intensity was not the only factor in play. This supports the application of the SDA to demonstrate how other aspects of the economy, such as final demand, were driving emissions changes.

Table 4.2: Emissions intensity of each industrial section in the years 2010 and 2018

SIC Section	**Emissions Intensity 2010 (tCO_2e per £m output)**	**Emissions Intensity 2018 (tCO_2e per £m output)**	**Change [%]**
A	205	191	-6%
B	318	329	+3%
C	210	138	-35%
D	**1571**	**534**	**-66%**
E	60	49	-18%
F	49	39	-21%
G	37	32	-13%
H	518	478	-8%
I	37	32	-15%
J	5	3	-38%
K	0.8	0.5	-31%
L	4	3	-30%
M	10	6	-40%
N	22	16	-28%
O	37	21	-42%
P	24	16	-35%
Q	29	24	-16%
R	21	14	-30%
S & T	22	18	-22%

4.5 Discussion

Overall, it is clear that the efforts to transition the electricity sector to cleaner energy sources have been the main contributors to the reduction seen in UK GHG emissions between 2010 and 2018. Had the emissions intensity of the sector not fallen significantly, then changes in production technology across the economy and an increase in final demand would have led to more GHG emissions than seen in 2010. In particular, the transition away from coal as an electricity generation source has provided the largest cut in emissions, while the level of natural gas use still prevalent in the energy mix shows that there is significant scope for improvement on the 2018 numbers.

Linking back to the discussion of renewable energy development and climate change considerations in Chapter 2 earlier in the thesis, the timeframe covered by the SDA represents a period where there was much occurring across the policy landscape to encourage the decarbonisation of the energy sector. Prior interventions, such as the Renewables Obligation (RO) scheme in place since 2002, would be expected to have increased the share of renewables leading up to 2010, but also impact the transition in the 2010–2018 period under analysis (DECC 2013a). However, it was following the Climate Change Act (2008), where legally binding GHG emissions targets were set for the UK, that there was a greater incentive for the transition away from fossil fuels and the growth of renewable energy sources. This is illustrated by Figure 4.9, which shows the percentage of each generation type in the electricity mix for 2010 and 2018. The data shows that coal use dropped from almost 30% of the electricity mix in 2010 to around 5% in 2018. The majority of this drop was replaced with wind generation. While this accounted for only 2.7% of the sector in 2010, it had increased to 17.1% by 2018 — with about half attributable to onshore and offshore wind respectively. From the graph, 'Other' sources include solar PV, hydro, and bioenergy generation, with the majority of the 19% in 2018 produced by bioenergy.

Recalling the results of the SDA presented in Section 4.4.2, with no other economic changes there would have been a 27% drop in UK GHG emissions due to reductions in the emissions intensity of the electricity sector from 2010 to 2018 (see Figure 4.4). This follows from the changes in the electricity mix, as the percentage of highly polluting coal dropped and renewable sources increased. However, one limitation of this study is that the electricity sector is not disaggregated into different generation types and only intuitive observations can be ascribed from knowing the electricity mix in both years. As such, the exact impact of (for instance) the increasing share of wind energy and

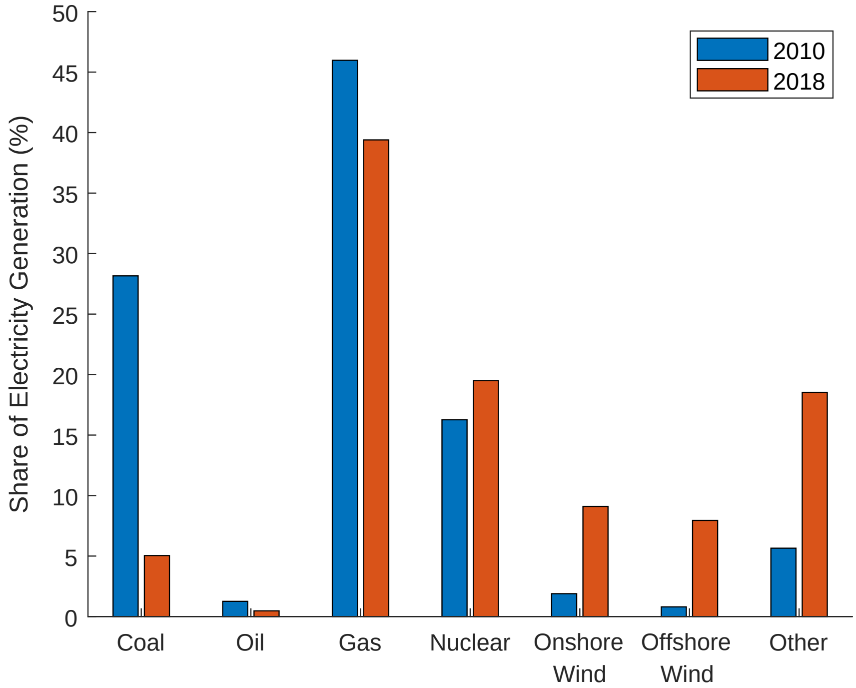

Figure 4.9: Electricity generation in the UK by source 2010 – 2018 (Adapted from BEIS (2023))

how this has instigated changes in production technology across industries cannot be determined at present.

However, the changes demonstrated in Figure 4.9 are still instructive. The fossil fuel share of electricity generation dropped from 75% to 45% between 2010 and 2018 — a fall of 30% (BEIS 2023). From the SDA results of all fuel types in Section 4.4.2, there was a 27% reduction in GHG emissions that would have occurred from changes in emissions intensity of the electricity sector. Even without attributing this change to specific energy types, it is still reasonable to trace it to the reduction in fossil fuels and increase in wind energy and other renewables.

As such, the results of the SDA presented here have shown that the transition from fossil fuel to renewable electricity sources in the UK drove a reduction in GHG emissions between 2010 and 2018. This is informative for policy makers by showing that decarbonisation has been the primary factor in emissions reduction, whilst drivers such as production technology and final demand may otherwise have caused an increase in emissions. Specifically, had the emissions intensity of the electricity sector not been reduced, UK GHG emissions would have only decreased by 5% over the period of interest. Excluding emissions intensity reductions across the rest of the economic sectors, GHG emissions would have increased by 8%. The fuel-specific SDA has also demonstrated that while substantial emissions reductions have been seen from the fall in coal usage, there has been limited progress when considering natural gas use across all industries, with much scope for improvement remaining here.

Combining these observations, this emphasises that whilst there is still scope to further decarbonise the electricity sector, focus should not be lost on other sectors of the economy and on reductions through drivers other than emissions intensity. The Climate Change Committee (CCC) has highlighted priorities beyond industrial production emissions, such as increased heat pump usage by households and a rise in the share of electric vehicles for transportation, but argue that there are insufficient plans in place to decarbonise industry (CCC 2024). If future policy hopes to achieve further deep reductions in production emissions on the journey to net zero in the UK, the SDA results within this chapter demonstrate where emphasis ought to be placed.

4.6 Conclusion

Throughout this chapter, the results of a structural decomposition analysis considering the driving forces behind changes in UK greenhouse gas emissions have been presented. For the period of 2010 to 2018, national IO tables were environmentally extended with fuel use data to analyse the resultant production emissions of the UK. A novel decomposition of production technology by sector was introduced, to further analyse the specific role that the electricity sector has played in reducing emissions. A further novel extension was the application of the SDA method to breakdown the contribution of individual fuels, namely coal and natural gas.

The results showed that the most significant driving factor of the change in GHG emissions was changes to the emissions intensity of the electricity sector — contributing a 114MtCO_2e reduction with other factors held constant. This translated to a 27% reduction on 2010 emissions levels. However, had emissions intensity, including that of other sectors, remained as in 2010 (the case of no decarbonisation efforts), the UK would have seen an 8% increase in GHG levels due to changes in production technology and final demand. The fuel-specific SDA results showed that production emissions due to coal use dropped significantly over the period, reducing by 76%; natural gas emissions did also experience a reduction, but still remained at 81% of their 2010 level.

The UK has a commitment to reach net zero emissions by 2050. In 2020, the total GHG emissions were approximately 405MtCO_2e[12], with energy supply the second largest contributor after transport (BEIS 2022c). This demonstrates that there is still both a need and much scope to reduce emissions further within the UK. The analysis performed here helps to illustrate the driving forces behind the overall changes that we have seen thus far, which can help to inform policy makers on where the focus needs to be placed for the future.

[12]This value includes emissions from sources such as residential and agriculture, which were excluded from the analysis of production emissions in this chapter.

Chapter 5

Offshore Wind Supply Chain Policies and Local Content

5.1 Introduction

The offshore wind industry in the UK has developed significantly since the first installation in the year 2000[1]. Now, the UK has the second largest installed capacity of offshore wind in the world — second only to China — with 14GW operational in 2024 (GWEC 2023). However, despite the success in deployment, around half of the content in domestic offshore wind farms is sourced from markets abroad. Though the reasons for this are manifold, increasing the UK content in the offshore wind supply chain is a key priority looking forwards, with the 2019 Offshore Wind Sector Deal setting a target of 60% UK content in new offshore wind farms by 2030 (BEIS 2019c).

The supply chain landscape for the offshore wind industry has changed in recent years, with increasing costs and delivery bottlenecks contributing to delays and cancellations across the industry worldwide (GWEC 2023). This has led to an intensifying

[1]The evolution of the offshore wind sector in the UK between 2000–2021 is discussed within the history of renewable energy policy presented in Chapter 2.

of focus on the supply chain, with the view that a strong supply chain can support the continuing growth of offshore wind, contributing to the achievement of deployment targets and climate change goals. With this in mind, supply chain planning will be ever more crucial if the UK is to continue to develop its offshore wind capacity. Given the national target for 60% UK content in offshore wind by 2030, from the approximately 50% today, the question arises as to what policy actions may be required to stimulate the local supply chain to meet this goal. In order to understand the potential answers to this query, it is important to first understand where we are now with regards to supply chain planning, and how this has evolved across the development of the offshore wind industry to date. For instance, has changing focus over the years influenced a rise in local content, which in 2013 was estimated at roughly 30% (DECC & BIS 2013), and what role can policy play in stimulating future increases?

Through consideration of policy actions, the aim of this chapter is to improve the understanding of how supply chain planning for offshore wind has been encapsulated within UK legislation to date, and demonstrate what may need to be put in place to improve levels of local content and facilitate future growth within the sector. The key mechanisms for developing the supply chain within the UK will be identified, with the second part of the chapter dedicated to reviewing the Supply Chain Development Statements (SCDS) which are produced as an output of one of these key mechanisms — as part of the ScotWind offshore wind leasing round. The installed capacity of projects proposed through ScotWind would see the UK meet its installation targets if they all progress as planned, so the supply chain plans produced by participants provide a strong representation of industry views on the current capability of the UK supply chain. By demonstrating how progress has been made to date, and assessing the present status of the sector, recommendations will be proposed for where future policy action ought to be placed in order to meet governmental goals for local content levels and the supply chain.

The remainder of this chapter is split into two main sections and a discussion, with the structure shown in Figure 5.1. Section 5.2 presents a review of the development of

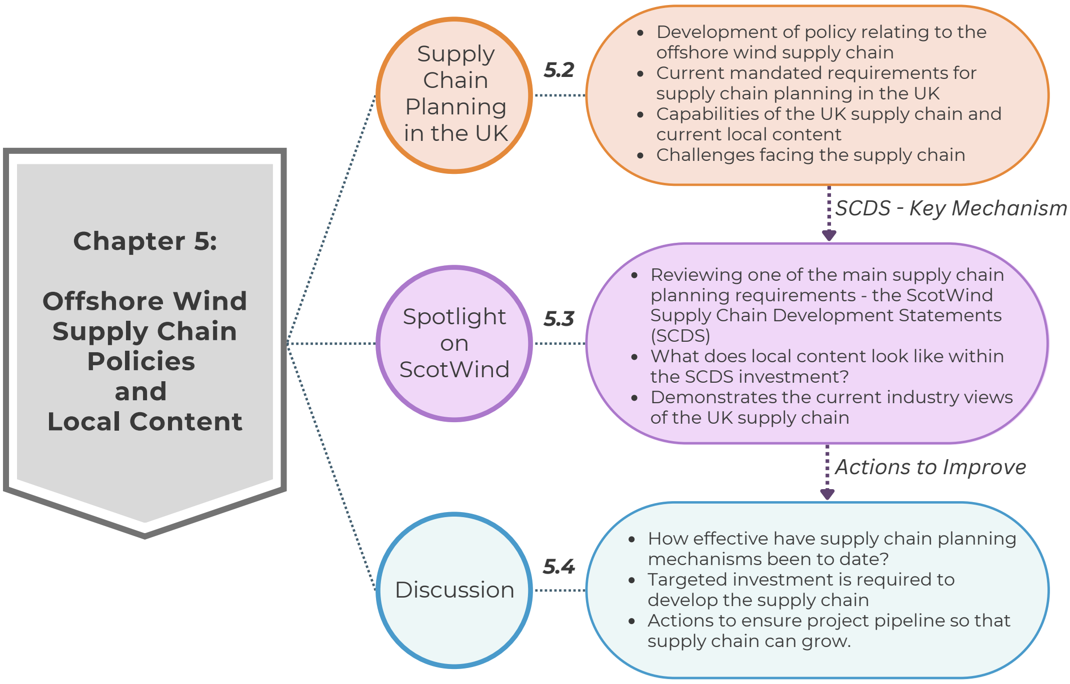

Figure 5.1: Chapter 5 structure and highlights

supply chain planning in the UK, covering its evolution to date and a look to the future. This leads into a focused analysis in Section 5.3 of one of the key mechanisms for supply chain planning in the UK, the provision of Supply Chain Development Statements in the ScotWind leasing round for offshore wind developments in Scotland. This assessment allows for a comparison to be made between the local content ambitions of twenty planned offshore wind projects and the UK 60% local content target for 2030, with a view to understanding how these results link to the policy landscape and future potential of the UK offshore wind market. The chapter is finalised by Section 5.4, which pulls together the analysis in the preceding sections, and presents a discussion on the key areas where policy action could be targeted to help the UK supply chain.

5.2 Supply Chain Planning in the UK

The development of the supply chain for offshore wind is essential if ambitious deployment targets, such as the UK goal of 50GW by 2030, are to be met (BEIS 2022a). This section presents a overview of supply chain planning in the UK, and is outlined as follows: firstly a review of the development of supply chain policy relating to offshore wind is undertaken in Section 5.2.1, which leads into an overview of the current offshore wind supply chain requirements in Section 5.2.2. Section 5.2.3 presents a summary of the current capability of the UK supply chain, while Section 5.2.4 analyses some of the key challenges facing the offshore wind supply chain when looking to the future.

5.2.1 Development of Supply Chain Policy

In the early years of the offshore wind industry in the UK, funding for new projects was provided through mechanisms such as the Offshore Wind Capital Grants scheme and Renewables Obligation[2]. At the time, the focus from government was on scaling up the industry to demonstrate that it could play a central role in reducing our reliance on fossil fuels for energy, and ultimately contribute towards the climate change goals that were becoming increasingly spotlighted. As such, growing the offshore wind supply chain in the UK was not a consideration within the policies governing these schemes. The remainder of Section 5.2.1 presents a discussion on how the focus on the supply chain changed in the years following these early mechanisms, with both government policy and studies from the wider industry discussed. A summary of the publications considered in this section is provided in Table 5.1 for reference, with each of the publications discussed in turn through Sections 5.2.1.1 to 5.2.1.8.

[2]See Chapter 2 for details on these schemes.

Table 5.1: Summary of supply chain publications, with location and publishing body

Publication	Year	Location	Body	Section
Scotland's offshore wind route map (OWIG 2010)	2010	Scotland	Industry	5.2.1.1
Offshore Wind Industrial Strategy (DECC & BIS 2013)	2013	UK	Government	5.2.1.1
UK offshore wind supply chain: capabilities and opportunities (BVG Associates 2014)	2014	UK	Industry[3]	5.2.1.3
Clean Growth Strategy (BEIS 2017b)	2017	UK	Government	5.2.1.4
Scottish Energy Strategy (Scottish Government 2017)	2017	Scotland	Government	5.2.1.5
Offshore Wind Sector Deal (BEIS 2019c)	2019	UK	Government	5.2.1.6
UK and Scottish content baseline and roadmap (BVG Associates 2021b)	2021	UK	Industry	5.2.1.7
Offshore Wind Industrial Growth Plan (RenewableUK 2024)	2024	UK	Industry	5.2.1.8

5.2.1.1 Scotland's Offshore Wind Route Map (2010)

In 2010 the Offshore Wind Industry Group (OWIG) published a route map for developing the offshore wind industry in Scotland (OWIG 2010). This noted the central role that the sector could play not only in helping Scotland (and the wider UK) to meet its renewable energy targets, but also as a key contributor in the transition to a low-carbon economy. The report discussed that investment in the supply chain would create jobs, with Scottish businesses able to develop and in turn support the growing installation of new offshore wind projects both at home and further afield. This was recognition that through the roll-out of these new energy generation plants, there was "the biggest opportunity for sustainable economic growth for a generation" (OWIG 2010, p6).

Though there was discussion about Scottish businesses being able to compete within the supply chain, local content was not mentioned within the route map other than one

[3] On behalf of BIS.

bullet point which stated the desire to “ensure the potential local content of the offshore wind industry is maximised and fully taken advantage of across local communities in Scotland” (OWIG 2010, p42). No definition on what may be included within ‘local content’ was provided. Nonetheless, recommendations for the supply chain included: targeting global companies dominant in offshore wind to invest in building Scottish plants; investing in port infrastructure; and focusing on developing capability in areas identified as supply chain bottlenecks.

One key point noted in the report was the “need to understand the timetable for development of individual sites and the procurement strategies that developers are intending to adopt” (OWIG 2010, p31) — a crucial notion reflecting that without a clear pipeline of projects (and thus potential business), a sustainable supply chain could not be developed. While the ambition behind gaining investment and attracting new companies to establish themselves is laudable, without a clear indication that these businesses could make enough sales to be viable long-term, this was unlikely to come to fruition.

5.2.1.2 Offshore Wind Industrial Strategy (2013)

At the UK level, the Offshore Wind Industrial Strategy was published in 2013, detailing the actions that businesses and the government should take to grow the industry and capitalise on the potential socio-economic benefits (DECC & BIS 2013). The overarching vision within the Strategy was stated as “Industry and Government work[ing] together to build a competitive and innovative UK supply chain that delivers and sustains jobs, exports and economic benefits for the UK” (DECC & BIS 2013, p5). The UK content in UK offshore wind farms at the time was estimated in the Strategy at around 30%. Here, local content was defined as the percentage of UK spend on both capital and operating expenditure of a project. The 30% estimate demonstrated the significant opportunity available — by increasing the level of UK content a large boost to the economy could be delivered through extra jobs and a rise in GVA. The strategy also recognised the necessity of demonstrating a pipeline of projects to instil confidence in the supply chain — greater visibility should encourage investment, in turn increasing the number of UK companies operating in the supply chain.

A number of actions were outlined in the Strategy for both government and industry, covering aspects from: increasing investment in innovation and lending for small to medium-sized enterprises; reducing financial risk by guaranteeing energy prices via Contracts for Difference (CfD), which was announced within the Electricity Market Reform programme in 2013 (DECC 2013a); and supporting apprenticeship programmes to develop the skilled workforce required to facilitate the growth of the sector. Ultimately, however, the main aim of the Strategy as a whole was to enable UK companies to compete globally on both cost and quality, with recognition that this would often mean direct competition with established businesses based abroad.

Existing capability in the UK supply chain was identified within the strategy, highlighting the relative strengths and gaps. The development stage of a project was identified as an area with high UK content, while aspects such as turbine manufacture were outlined as areas where new companies would struggle to compete with long-established businesses with high market share. However, it was noted that smaller UK businesses did feature within the ultimate supply chain for these manufacturers, and targeting this could be a way to increase UK content.

5.2.1.3 Offshore Wind Supply Chain: Capabilities and Opportunities (2014)

The brief analysis of the existing supply chain capability in the UK within the Strategy was followed up in 2014 with a dedicated report on the topic and the potential opportunities for the UK (BVG Associates 2014). This detailed assessment represented one of the first whole-project evaluations of the UK offshore wind supply chain, mapping the strengths and weaknesses to identify potential areas for improvement. However, it should be noted that the report made no recommendations on how to proceed or actually improve upon levels of UK content, it was intended solely as a basis of understanding the landscape as it stood. Additionally, 'local content' was not generally used as a metric throughout the report, where instead 'UK expenditure' was discussed. It is assumed that these terms could be deemed interchangeable, and where other reports may discuss the level of UK content in a project, the percentage of UK expenditure identified here is simply a proxy term describing the same metric.

The analysis in the report looked at six aspects of the supply chain — namely development, turbine supply, balance of plant supply, installation, O&M, and support services — and assessed each stage across six criteria: UK track record, market readiness for scale, investment risk, logistics, UK expertise, and size of the UK opportunity. Generally the report found that even for categories where there had been little track record of UK companies successfully supplying offshore wind in the past, there theoretically was expertise available by drawing on the experiences of other, more established sectors such as oil and gas.

5.2.1.4 Clean Growth Strategy (2017)

Government policy in subsequent years followed similar lines to the Offshore Wind Industrial Strategy, though there was limited new legislation specifically targeting supply chain development. The Clean Growth Strategy aimed to "maximise the UK industrial advantages from the global shift to a low carbon economy" (BEIS 2017b, p37). Within this Strategy, the supply chain of renewable energy was mentioned only passively when discussing widespread investment to generate growth. Though offshore wind was identified as a clean growth success story and British companies were stated as being experts in certain parts of supply, the primary reference to the sector was in reducing costs.

In summary, the Strategy did not identify any actions that government would take to develop the offshore wind (or wider renewable energy) supply chain to achieve the targeted clean growth. While understandable that the offshore wind supply chain in particular was not the focus in an all-encompassing report, given that the sector had previously been highlighted as a key technology in reaching the UK's climate change goals and as a source of economic benefit in the Offshore Wind Industrial Strategy, it could be expected that some actions towards growing the UK supply chain for the sector would have been included towards the aim of Clean Growth.

5.2.1.5 Scottish Energy Strategy (2017)

A few months after the release of the Clean Growth Strategy, the Scottish Government published the Scottish Energy Strategy which looked at the future towards 2050 (Scottish Government 2017). For offshore wind in particular, growing the Scottish supply chain was the main stated aim, with the goal to "renew [...] support for the development of an innovative and competitive supply chain in Scotland" (Scottish Government 2017, p45). Whilst no specific policies were outlined in the Strategy to this end, it was again recognised that there was significant economic potential in its development and benefits to be gained through growing the offshore wind sector. The case of floating wind was also highlighted as an area where Scotland could capitalise. In referencing Scottish marine innovation, the establishment in the North Sea of "the world's first floating offshore wind farm [...] place[d] Scotland on a strong footing" (Scottish Government 2017, p77), referring to the 2017 commissioning of the Hywind Scotland array off the coast of Peterhead (WindEurope 2017a).

5.2.1.6 Offshore Wind Sector Deal (2019)

It was not until the Offshore Wind Sector Deal Industrial Strategy was published in 2019 that any specific targets were set by government regarding the supply chain of offshore wind in the UK (BEIS 2019c). The Sector Deal aimed to build on the growth of the UK offshore wind industry to date, setting out a number of aims to continue to develop the sector. Key amongst these was the target for new domestic offshore wind farms to have 60% UK content through their project lifetime — a target that was set by the sector for the year 2030.

No specific definition of UK content was provided in the Deal, so it is assumed that this means that of the overall expenditure of a project, 60% should be spent in businesses based within the UK. At the time of the Deal, UK content in offshore wind was estimated by BEIS at around 50%. The target further specified the aim that within this lifetime percentage, UK content in the capital expenditure (CAPEX) phase should increase. This is recognition of the results of analyses mentioned previously, crucially that the CAPEX phase shows the lowest share of purchases locally — with the majority of the main components of an offshore wind farm sourced from foreign markets.

5.2.1.7 UK and Scottish Content Baseline and Roadmap (2021)

In 2021, the Scottish Offshore Wind Energy Council (SOWEC) commissioned a report from BVG Associates to investigate how businesses in Scotland (i.e. Scottish content) could contribute to the UK content target of the Offshore Wind Sector Deal (BVG Associates 2021b). An explicit definition of local content was not provided within the report, but it was noted that some content figures were derived from estimates of "where the project was delivered from" (BVG Associates 2021b, p7). The authors additionally recognised that in some cases this meant the data was not cost-driven. This definition of UK content is then at odds with what has been previously defined (if, indeed, previous publications defined it) and raises the question of how comparable UK/local content percentages may be across different publications. However, the authors do note that the advantage of their approach is not skewed by the expenditure of specific projects.

Within the report, a 2020 baseline of 48% UK content for UK projects was found, in line with the 50% estimated in the Sector Deal. Additionally, the average Scottish content in UK projects was found to be 18%, but for Scottish projects this was 44% — indicating that there is minimal Scottish content in offshore wind developments in the rest of the UK. Indeed, this was found to be the case, with less than 1% of Scottish content in non-Scottish UK projects. The level of Scottish or UK content was also found to vary across the different stages of project investment, with development expenditure

(DEVEX) and OPEX scoring highly on their percentage of local content while CAPEX and decommissioning expenditure (DECEX) presented much lower shares. When investigating at a more detailed level, the authors found that a large proportion of local content across the lifecycle of the development was in work such as project management, while manufacturing activities were mainly sourced from outwith the UK. For Scottish projects, operations and maintenance activities contributed the largest percentage of local content overall, higher than development spend. For projects in the rest of the UK (rUK), development activities showed the highest UK content.

Clearly this indicates some areas to target for improving levels of local content in the coming years, most specifically in the manufacturing of components to increase CAPEX shares. As such, the report models and recommends the key areas of focus within the supply chain to achieve the 60% local content by 2030. Within this, the most likely changes would be the establishment of new factories to build towers and blades for turbines, and more crucially for the fabrication of monopile or floating foundations (BVG Associates 2021b). Towers and blades for offshore wind turbines have been growing in size in recent years, with lengths for the blades of the GE Haliade-X turbines to be used at the Dogger Bank site reaching 107m (SSE Renewables 2021). In fact, a new manufacturing plant in Teeside has been established to fabricate these blades, and is estimated to bring 750 direct jobs and 1,500 indirect jobs to the region. Due to the size of these state of the art turbine parts, manufacturing plants have to increasingly be located in coastal regions close to ports due to the difficulties in transporting components of this magnitude by road or rail (Diaz and Guedes Soares 2020). For the case of foundations, the size of the structures is also a contributing factor for the establishment of new, local manufacturing plants (BVG Associates 2021b).

With these outlined developments, it is estimated that UK content could reach the targeted 60% by 2030, with 20% of turbine CAPEX sourced from UK plants (up from 7% currently) and foundations rising significantly to 66% UK content (also from 7%). Considering the special case of floating wind projects, the local UK content is estimated as 62% in 2030, with a different ratio between spends than for fixed base. The main difference is for installation, where almost half of the content can be sourced locally, and also decommissioning with a 90% UK share. These higher percentages than for fixed bottom turbines reflect that much of the installation work can be done onshore or in port to utilise the local supply chain, before the components are towed into place at the project site.

5.2.1.8 Offshore Wind Industrial Growth Plan (2024)

The most recent publication to present a thorough overview of the potential for the UK offshore wind sector, the Offshore Wind Industrial Growth Plan outlines a routemap for how to grow the capability of the domestic supply chain, increasing the market share in UK projects and also overseas (RenewableUK 2024). While growing market share is stated within the headline aim of the Plan, local content as a concept is not a focus and no mention is made of the 60% target. The term market share could be considered to be a proxy for local content in the context employed here, but no specific goal or level is set out within the Plan. Instead, the priority was building upon the UK's existing capabilities and success, and looking forward at where emphasis should be placed and what needs to be implemented to realise the potential of the sector. There was recognition that for the UK to retain its position as one of the world leaders in offshore wind the supply chain would have to be competitive, with growing exports a key area of focus.

Components throughout the offshore wind value chain were split into four categories within a 'Make or Buy' framework, reflecting the domestic capability and ability to compete and win contracts, with those scoring highly in both designated as areas where the UK should focus on making the component to capture the available market opportunity. This resulted in five areas where the report recommended that the supply chain prioritise development, each with various levels of current capability and maturity. Namely: advanced turbine technologies; industrialised foundations and substructures; future electrical systems and cables; smart environmental services; and next generation installation, operations, and maintenance. Within each of these priorities, potential investment and actions were outlined to enable the sector to meet goals within three programmes which were termed respond, expand and disrupt. For the first, these were actions proposed to respond to the immediate priorities of the sector, targeting supply constraints and ensuring capacity develops to support the UK industry. With 'expand', the aim was to leverage the UK's capability and record of delivery to begin targeting exports and addressing future capacity requirements in international markets. The final programme, 'disrupt', focused on employing the UK's strong history of research and development to innovate — placing it as a global centre for offshore wind.

Similarly to previous publications, the Industrial Growth Plan highlighted the need for direct investment to promote supply chain development, enabled by a growth fund from both private and public sources. The lack of certainty with regards to a project pipeline was highlighted as a challenge to securing investment, and a barrier to the development of the supply chain. Policy efforts at a government level, such as changes to the CfD subsidy scheme, will be required in order to reduce the financial risk on investing in offshore wind and its supply chain. However, the Plan was clear to note that investment alone would not be enough to generate a sustainable and competitive supply chain that persists after the initial funding. Beyond this targeted investment, the establishment of a new research and development entity was outlined as a way to facilitate and enable the required growth. The proposed Offshore Wind Innovation Development and Demonstration (WInDD) Hub aims to build upon the UK's demonstrated capability for design and existing success in areas such as deep-water ports and testing centres to drive innovation. Collaborative engagement across the supply chain of the five outlined priority areas, leveraging existing regional clusters which have previously helped to develop expertise, was highlighted as a crucial way that the UK can gain a competitive advantage.

Table 5.2: Summary of local content and targets in key supply chain publications

Publication	Local Content	Key Recommendations
Scotland's offshore wind route map (2010)	Desire to maximise, but no definition or target	Invest; Develop bottleneck areas; Understand timetable of project development
Offshore Wind Industrial Strategy (2013)	Definition: percentage of UK spend in CAPEX and OPEX	Demonstrate pipeline of projects; Invest; Enable global competitiveness
UK offshore wind supply chain: capabilities and opportunities (2014)	UK expenditure used, but not defined as local content	No policy recommendations
Clean Growth Strategy (2017)	No mention of local content	Supply chain not a focus
Scottish Energy Strategy (2017)	No mention of local content	Floating wind is a key area of opportunity
Offshore Wind Sector Deal (2019)	Sets target for the first time – 60% by 2030. No definition provided	UK content in CAPEX stage should increase
UK and Scottish content baseline and roadmap (2021)	No definition, but some figures derived from project delivery location rather than cost	Target new factories for towers, blades, and foundations; Floating wind presents opportunity for greater UK installation share
Offshore Wind Industrial Growth Plan (2024)	No mention of local content. Aim is to grow market share, but no target set	Focus on areas with greatest capability and ability to win; Establish innovation hub; Ensure project pipeline

5.2.1.9 Summary

Throughout the publications discussed in Sections 5.2.1.1 to 5.2.1.8, the offshore wind supply chain has become more emphasised as an area where economic benefit can be gained. Despite the growth of local content being one of the headline aims of the Offshore Wind Sector Deal in 2019, the metric has been ill-defined across the publications assessed in this section. A summary of the key points of each of these publications is provided in Table 5.2. From this, it is clear that other than from the Sector Deal, which does not provide a formal definition of local content despite setting a target, local content is generally only mentioned passively if at all.

However, other metrics which could be interpreted as local content are referenced throughout. From growing UK expenditure, to the aim for increasing market share in the most recent Industrial Growth Plan, what is clear from these publications is the common desire to develop the UK supply chain. While the language may vary, there is broad recognition that direct investment will be required, and that the guarantee of a clear pipeline of projects will encourage investment and provide opportunities for a competitive supply chain that can be retained long-term. Growing the UK share in the CAPEX stage was generally highlighted as the greatest opportunity, as it presents the overall highest spend and value. In more recent publications, floating wind has also been spotlighted as an area where the UK could hope to grow its market share — taking advantage of existing expertise in other industries and the development of the sector from its nascent state.

5.2.2 Current Offshore Wind Supply Chain Requirements

Currently the main funding mechanism for offshore wind in Great Britain is through the Contracts for Difference (CfD) scheme, which held its first auction in 2015. Offshore wind costs were seen to dramatically reduce through the first four allocation rounds (AR), with the strike prices of successful offshore wind projects reducing from around £120/MWh in AR1 to £38/MWh in AR4 in 2021 (all in 2012 prices) (Watson and Bolton 2023). As part of a bid into the CfD scheme, applicants whose projects meet certain criteria are required to submit a Supply Chain Plan (SCP). These must be approved by the Secretary of State for Energy Security and Net Zero (formerly the Secretary of State for Business, Energy and Industrial Strategy) in order for the project to qualify for entry into the auction (DESNZ 2023c). Projects of all technologies which are expected to have a generation capacity of 300MW or more have been required to submit a SCP since AR1. From AR5 onwards, there has also been the requirement for all floating offshore wind projects to submit, regardless of their capacity.

The SCP application involves the developer completing a questionnaire, the responses in which are then scored[4]. A project must score at least 60%[5] in each section of the questionnaire (50% for floating wind) in order to be approved by the Secretary of State (DESNZ 2023c). The scored sections include questions on green growth, infrastructure, innovation, and skills. From the introduction of the questionnaire in its current form in AR4, a section has been included for the developer to indicate the expected level of UK content through the DEVEX, CAPEX, OPEX, and DECEX stages of the project lifecycle. While the guidance document does not provide an explicit definition of UK content, a template is provided to aide in the calculation. This bases the final UK content percentage of each project component on the expenditure of the stage scaled by the capacity of UK suppliers to meet demand, and the probability of a UK supplier winning the contract in a competitive tender. Though a mandatory step in the questionnaire, the UK content section is not scored and does not count towards the approval or otherwise of the SCP. It is further noted that the details of the planned UK content will not be publicised, though a headline figure may be published by the government.

The Supply Chain Plans of successful applicants are published within three months of the signing of the CfD contract (DESNZ 2023c), though in earlier rounds the guidance stated that a full copy may be published two years after the contract award (BEIS 2018a). Developers are able to indicate any ‘commercially sensitive’ details or sections of their questionnaire and subsequent SCP that they would like to be redacted prior to publication. To date, only the SCP of eligible offshore wind projects from AR1 – AR3 have been published — accounting for ten projects out of the fifteen offshore wind

[4]The SCP questionnaire for AR6 wind projects of at least 300MW can be found on the UK Government website (DESNZ 2023c).

[5]Note: 60% here is a rating against the criteria of the questionnaire, it is not linked to level of local content.

projects of at least 300MW to bid successfully into CfD over rounds AR1 to AR5. As such, the details relating to the UK content question, introduced in AR4, are not yet available. However, within earlier SCP that have reached publication, UK content has been briefly referenced. For example, the SCP for AR3 offshore wind farm Seagreen Phase 1 states their aim to "maximise opportunit[ies] for UK suppliers to bid on the Project with an aspirational target of achieving a range of at least 50 – 55% lifetime UK content" (SWEL 2020, p6). It isn't clear from the information available regarding AR3 whether UK content was required to be calculated in the provision of the SCPs, or whether this ambition solely reflects industry sentiment at the time surrounding the targets of the Offshore Wind Sector Deal.

The other important mechanism for supply chain planning currently mandated within the UK was the requirement of a Supply Chain Development Statement (SCDS) from the bidders into Round 1 of ScotWind leasing, which concluded in 2022[6]. As touched upon in Section 2.3.3 of Chapter 2, ScotWind was the first offshore wind leasing round solely for projects in Scottish waters. Within the SCDS, developers had to outline their planned expenditure across four project stages and four geographical regions, as shown in the example in Table 5.3 (Crown Estate Scotland 2021b). Two of these tables were required, one for the 'Committed' expenditure and one for their 'Ambition' expenditure. These tables were then made public in an SCDS Outlook for each project, whilst additional information regarding expected full-time equivalent (FTE) jobs in each of the sixteen categories of Table 5.3, explanations on how these estimates were met, and a description of how the project met any other obligation were all required in the full SCDS Narrative which was retained confidentially by Crown Estate Scotland (Crown Estate Scotland 2020c).

Similarly to the UK content section of the Supply Chain Plans in the CfD process, applicants were not judged on where they planned to make their investments and these tables were not taken into account in the granting of leases to successful applicants.

[6]There is currently no analogue to the SCDS for offshore leasing within England and Wales, which is run by the Crown Estate — a separate entity from Crown Estate Scotland.

Table 5.3: Example of table from ScotWind Supply Chain Development Statement

	Planned Expenditure (£m)			
Project Stage	Scotland	Rest of UK	Europe	Rest of World
Development				
Manufacturing				
Installation				
Operations & Maintenance				

The aim of the SCDS was to demonstrate a pipeline of projects for Scotland that could stimulate the development of the local supply chain for offshore wind. By showing a plan for a number of projects in the coming years, it was hoped that this would encourage industry investment within Scotland to compete for the business of the new offshore wind farms. The Committed case in the SCDS was the expenditure that developers expected they could currently make in each of the project areas, indicating the current state of the market. The Ambition case instead demonstrated the investment they would hope to make if business conditions were to develop and, usually, more of the content of the wind farms would be sourced in Scotland.

Following the conclusion of ScotWind Round 1, seventeen projects were successful in being granted option agreements to develop on the seabed — with three further projects successful in the later clearing round (Crown Estate Scotland 2023b). The SCDS Outlook was released for each project shortly after the winning applicants were announced, containing the Committed and Ambition tables in the format of Table 5.3, with the total planned expenditure for the projects (in millions of pounds) allocated across the sixteen criteria. Other information contained within the SCDS Outlook varied across developers, with some providing more information on the project and others divulging mainly the tables. However, the standardised nature of the Committed and Ambition tables which were required in the SCDS allows for comparison of key details across the projects — most notably their planned levels of local content.

Comparing the SCDS provision of ScotWind with the SCP of the CfD scheme cannot be like for like, as each mechanism captures different data from prospective developers. Though all eligible projects through CfD now complete the same questionnaire, there is not an equivalent to the tables required in ScotWind which allows for comparison between projects. The data within the available SCP is of a more qualitative nature and presented as a report, generally not including much planned expenditure (or that which was included originally has been redacted before publishing). From a transparency standpoint, the early publication of expenditure and local content data in ScotWind is more open and inclusive than the system under CfD.

Additionally, this point can also be applied to timing. For the 300MW or more projects that successfully bid into AR4 which closed in July 2022, SCPs are yet to be published[7]. Considering the earlier rounds, for each of AR 1 – 3 there is a dedicated page on the government website compiling the SCPs of the successful projects over 300MW (DECC 2015b; BEIS 2018b; BEIS and DESNZ 2020)[8]. It is noted in the details for each of these webpages that the SCPs linked there are "shortened versions" of the original, submitted plans and may have been "subject to a limited amount of redaction". In each case, there is also a note that the government "will publish fuller versions of these plans in approximately 12 months once the projects have passed their milestone delivery date and when we expect that the majority of information is no longer commercially sensitive". Following a thorough search of the government website, updated SCPs for each of these ten projects could not be found — despite more than 12 months passing since the original publication dates. It is not clear whether these full, unredacted SCPs are available in the public domain — and if so, how a user may access them.

It should be noted at this point that the projects bidding into ScotWind and those applying for funding through CfD are at different stages in their project lifecycle. In

[7]At time of writing, April 2024.

[8]It should be noted that these were only found after a detailed search on the UK Government website using the keywords "CfD supply chain plan", which brought 17,156 results. These were not easily located through a search engine, as members of the public may be expected to use. There was no clear link on the website from information about each AR to the resulting SCPs as 'related content' — a user would have to specifically seek these out. This is clearly a process which puts added onus onto the individual, and is less transparent than the process could be.

ScotWind, they are at a much earlier, more speculative, stage and applying only for the right to develop the seabed. For the CfD a large amount of development work will already have been carried out to try and establish the project as viable, and they are looking for a funding guarantee on the energy they hope to ultimately sell. So, removing the issue around timeliness of publication of supply chain planning information, projects bidding into the two schemes vary in terms of commercial sensitivity and what they may be willing to publish. This could account for some of the perceived variation in the transparency of the data made public through ScotWind versus CfD.

Overall, the CfD Supply Chain Plans and ScotWind SCDS represent a positive step in legislating for early supply chain management. The proposed offshore wind farms from Round 1 of ScotWind outlined their ambitions at a very early stage of the development process. The reasoning behind the SCDS provision in the leasing round outlined the need for transparency from developers prior to the procurement stage of a project, with the aim that a potential pipeline of projects would be elucidated and provide incentive for the local supply chain to develop. The SCP required under CfD are produced at a later stage in the development of a project, and aren't made public until after the CfD has been signed — so it is less clear the effect this will have on forward-planning when compared with the ScotWind SCDS.

However, these SCPs have to be approved at a government level to be permitted to bid into CfD. As such, the purpose of the SCP is less to promote business investment and more for government to ensure that projects which hope to receive funding have a robust plan in place to ensure that their project comes to fruition. Indeed, this is the stated aim of the Supply Chain Plan process, specifically that it should "encourage competitive, productive and efficient supply chains" (DESNZ 2023c, p5). Yet, the delay in publication of SCPs and thus their availability to be seen by relevant industry stakeholders could impact upon this aim. If businesses cannot view these ambitions until late in the process, this does not help to illuminate the pipeline of potential work that they could capitalise on, thus minimising the forward-planning aspect of the SCP.

For both mechanisms, the supply chain plan provision is not solely a forward-looking, administrative exercise — both the CfD scheme and ScotWind have elements of ongoing monitoring embedded within them. For the SCP of successful CfD applicants, the Generator (as the project developer is referred) will undergo monitoring every two months until their ‘milestone delivery date’ — eighteen months after the signing of the CfD contract, when Generators must demonstrate project progress (BEIS 2021b). After this time, monitoring frequency will reduce to a six monthly basis. The monitoring involves assessing the progress against each of the SCP commitments, and requires evidence that Generators are on track to meet them or “can evidence substantial and sustained efforts” to meet them (DESNZ 2023c, p16). The latter point reflects that Generators will not be penalised for missing commitments for reasons outwith their control, so long as they can prove that they have attempted to do so.

After the milestone delivery date, a Generator can apply for a Supply Chain Plan Implementation Statement from the Department for Energy Security and Net Zero (DESNZ), which involves each commitment in their SCP being scored (similarly to the original questionnaire). The Generator must score at least 60%, or 50% for floating wind, to be issued with a Statement. Without the successful receipt of this Statement, the Generator will not receive their CfD payments and the contract may be terminated. The final element of assessment is the submission of a Post-build Implementation Report following project completion, where the Generator must demonstrate where they have met their commitments or otherwise. If a Generator has substantially not met their commitments, failing on a majority, they could be forbidden from entering into future CfD rounds.

The monitoring of the SCDS under ScotWind varies from the CfD system. Here, each of the projects must submit an updated SCDS every two years, and outline to Crown Estate Scotland, with evidence, the reasons for any variation since the previous submission (Crown Estate Scotland 2020c). Updated SCDS Outlooks will be published if accepted, with the complete SCDS Narrative again being kept confidential. When reaching the end of the project development stage, and applying for the seabed lease, developers are required to produce a Contracted Position Statement (CPS) which includes their actual expenditure during the development stage and future expenditure in other stages evidenced by final contracts with industry (Crown Estate Scotland 2021b). This CPS will be compared against the active SCDS, for each of the sixteen project stage and geographical location combinations, and Crown Estate Scotland will judge on the adherence to the commitments in each case. If the CPS does not match the SCDS commitments, then contractual remedies may be applied. The level of the contractual remedy will be based on the category with the largest discrepancy, meaning a penalty will apply even if the expenditure commitment was missed in only one stage and area. The contractual remedy varies from £50,000 if more than 90% but less than 100% of the expenditure is met, £100,000 for between 50% and 90%, to £250,000 for 25% to 50% (Crown Estate Scotland 2021b). If there is less than 25% of the commitment demonstrated, then the developer may not apply for the seabed lease. Outwith the adherence to the commitments, the CPS will only be accepted if the information within the statement is evidenced such that the results can be expected to actually arise as indicated (Crown Estate Scotland 2020c).

The aim of these contractual remedies, is to "provide an incentive" to developers to both produce realistic commitments in the first instance, but also to make effort to achieve the commitments when they come to develop the project (Crown Estate Scotland 2021b, p2). This aligns with the broader purpose behind the SCDS requirements, to provide visibility to industry stakeholders on a pipeline of upcoming projects in order to encourage supply chain development both in Scotland and further afield. With the provision of contractual remedies for unmet commitments, the hope is that industry can "regard the SCDS Outlook with a degree of confidence" (Crown Estate Scotland 2020c, p11). However, while this is a positive step, and one of the first clear attempts to add financial penalties for non-adherence in supply chain planning for offshore wind, the extent of the deterrent remains to be seen, and it is too early to say whether these remedies will be successful in practice. Consider, with one 10MW wind turbine estimated to cost around £10million, even the £250,000 largest financial remedy proposed for a missed commitment would account for only 2.5% of the cost of one turbine — and the smallest proposed site for ScotWind would see fifty of these 10MW turbines purchased (BVG Associates 2019)[9]. It would not then be outwith the realms of possibility to see a case where it makes better financial sense for a developer to change the location of the expenditure and pay the contractual remedy, if the saving they could make outweighs the payment required for breaking their SCDS commitment.

5.2.3 Supply Chain and Local Content in the UK Today

Having considered the changing policy landscape around supply chain planning and local content targets, this section touches on how this is accounted for by developers. The current capability of the UK offshore wind supply chain is also discussed.

For the majority of global offshore wind farms commissioned to date, the same large businesses tend to crop up repeatedly as suppliers. Developers are mostly free to choose for themselves which suppliers to contract for any given aspect of work, and as such have typically been incentivised by the lowest cost options (Van der Loos et al. 2022). Due to the high levels of capital expenditure required in offshore wind, developers to date have often been utilities companies — who have subsequently gone on to be the operators of their wind farms once operational (Poulsen and Lema 2017). Some developers in the UK market to date have included Equinor, Ørsted, and ScottishPower Renewables (BVG Associates 2019). As the 'lead firm' in a project, the developer controls the choices that are made in terms of shaping the supply chain (Poulsen and Lema 2017).

Different developers take different strategies on their contracting approach, with some preferring to follow a 'multi-contracting' model while others take the engineering, procurement, construction and installation (EPCI) route. The larger developers, and those with the most experience in the offshore wind sector, mostly utilise multi-contracting. With this, the developer holds the project management risk and contracts out to various supply chain companies for each element of the build (e.g. turbine

[9]See Table 5.8 in Section 5.3.1 for a list of ScotWind projects and their respective capacity estimates.

supply, cable installation) (BVG Associates 2021a). Under this model the developer retains oversight of the entire supply chain, and manages the interfaces between the contracted companies in-house. For the EPCI strategy, smaller or less experienced developers tend to contract out for fewer, larger work packages. For example, one of these contracts may be with the turbine original equipment manufacturers (OEM) who will supply, install, and provide O&M for the generating assets once operational. Under this model, the EPCI companies take a larger share of the overall project risk away from the developer but this comes with a greater financial cost than multi-contracting, as the developer is essentially paying to remove the liability from themselves. This approach also means that the developer has less oversight of the supply chain for their project, with the EPCI contractors making the decisions, and it may be more difficult to optimise the interfaces between the different contracts.

One area that is lacking in the academic literature is the impact that these differing procurement strategies may have on local content levels. This knowledge gap is a trend also identified by Poulsen and Lema (2017), who note that this is generally the case for studies on renewable energy supply chains across the board. In their research, the authors here assessed supply chain readiness for offshore wind developments and identified bottlenecks to progress in the European and Chinese markets — local content was not a consideration and was mentioned only in the context of requirements set out by national governments. One of the only additional studies identified on the subject of supply chain and local content, from Van der Loos et al. (2022), discussed how lead firms have a variety of requirements when sourcing their supply chain, and must take into consideration a number of potentially competing demands such as local content rules in the project region, availability of resource in the vicinity, and the costs of transporting parts from distant locales to name a few. The authors found that local content rules are likely to increase the shares of locally sourced suppliers, for both developers local to the jurisdiction and foreign developers. However, though local developers were more likely to use local companies in their supply chain even in the absence of regulations, the types of suppliers used were found to change when regulations were imposed. When pressed into choosing local content, lower value supply chain items were targeted compared to the case where the developer had free choice — the authors propose that when there is a requirement to increase levels of local content, the parts which could typically be sourced cheaply in other markets are encouraged to be purchased instead from domestic companies. In turn, higher value parts which a local developer may have otherwise sourced from a local supplier have to be purchased from foreign regions to offset the cost increase of the less complex components.

This is echoed in an alternate study from Bazilian et al. (2020) where this very phenomenon is cited as a recognised criticism of local content regulations in other industries. The authors here assessed the impact of these restrictions on renewable energy markets in Brazil, India and South Africa; reporting that the companies chosen to increase local content were typically those involved in activities such as project development, which were not renewable energy specific, or in the manufacturing of low complexity parts. This is of critical importance to understand, as the composition of the local content has been shown to impact on the level of economic benefit that is delivered from a project (Allan et al. 2020). As such, the implications of the study from Van der Loos et al. were that the imposition or otherwise of local content rules, should be dependent on whether the country wishes to increase output levels (and in turn stimulate employment) or develop the supply chain of higher value, complex parts (Van der Loos et al. 2022).

To date, some parts such as turbines are typically sourced from the same small group of OEM on repeat projects, while supply chain considerations such as where to hire vessels may be more likely to vary with project location and utilise local content — leading to the low levels of local content in CAPEX and higher levels in OPEX demonstrated previously (BVG Associates 2021b; Van der Loos et al. 2022). With regards to component suppliers, Siemens Gamesa are the current market leaders in offshore wind turbines with 66% of installed capacity, followed by MHI Vestas with 16% (ORE Catapult 2020). Other parts in the value chain of an offshore wind development are typically less biased towards manufacturers with such large market shares. Indeed, for components which are relatively standardised across the industry (e.g. offshore wind turbine foundations), there may be manufacturing plants in many regions all capable of producing the part — including in the country of origin of a given project (Van der Loos et al. 2022). However, this relative ease of fabrication means that there could be many firms bidding for the same contract, and suppliers from regions with lower costs may be able to undercut the local companies. As posited by Van der Loos et al., there are circumstances when a developer will support suppliers local to a project over those from the developer's own region or the global market, and vice versa, and this is typically dependent on the type of part that is being sourced. This may also tie into the previously mentioned procurement strategies. Were a developer to multi-contract to many individual companies and manage the project in house, it could be imagined that local content levels may be different versus the case where EPCI is utilised and large firms provide much of the work themselves. No studies could be found in the academic literature to assess whether this is indeed the case.

Looking forwards, for Scotland, a high-confidence pipeline of projects coming out of ScotWind should allow for confidence in supply chain investments that has been lacking in the past. Crucially, there exists a great opportunity for Scottish companies to gain a foothold in the floating market as early-movers and benefit when the sector grows in foreign markets (SOWEC 2021). There is a knowledge gap at present as to how offshore wind developers view the SCDS or SCP requirements and inherent local content emphasis within them, despite the industry collaborating with government to commit to the 60% target in the Offshore Wind Sector Deal. Whether developers see this as something beneficial to their business case, solely a social obligation to the country they hope to do business in, or more as an unavoidable roadblock on their way to building a new generating asset cannot currently be known — and the attitude one way or another may critically impact the delivered levels of local content and economic benefit going forwards. One potential positive either way is that research has suggested that even for UK developments with a 'passive approach' to local content, significant GVA and employment impacts can be seen (Allan et al. 2020). This research showed

Table 5.4: UK content in recent offshore wind farms[10](BVG Associates 2024b)

Stage	UK Share	Share of Total Spend
Development	1.8%	2.5%
Manufacturing: Turbine	5%	21%
Manufacturing: Balance of Plant	2%	13%
Installation & Commissioning	5%	14%
O&M	33%	43%
Decommissioning	2%	7%
Total	*48%*	*100%*

that the scale of these effects only increases with a rise in local content, so there are substantial benefits to be found in the UK with higher levels in the future.

Local content in recent UK offshore wind farms is estimated as approximately 50%, still a way off the 60% targeted for 2030 by the Offshore Wind Sector Deal in 2019 (BVG Associates 2024b). The share of different project stages as a percentage of total expenditure in recent UK offshore wind farms, and the UK share of each stage is shown in Table 5.4. Within the 48% UK content, the largest share, at 33%, is identified as the contribution from O&M activities — while O&M is 43% of the total spend. This shows that the majority of O&M in recent projects has been sourced within the UK. The large UK share of this stage makes sense, as O&M activities tend to be based at ports close to the wind farm site, to facilitate access. The development stage also shows the majority of the spend located with businesses in the UK, in alignment with previous studies. The area with the lowest UK investment share is in manufacturing, for both the turbine and the balance of plant. However, the 5% contribution to turbine expenditure primarily comes from the manufacture of blades — where most have been sourced within the UK. Both Siemens Gamesa and LM Wind Power, a subsidiary of GE, have blade factories based in the UK (BVG Associates 2024a).

The shares indicated in Table 5.4 again illustrate areas where gains could be made

[9]Note: Table values do not add due to rounding.

in UK content levels, in order to capitalise on the expected growth of the sector in coming years. The capability of the offshore wind supply chain to deliver this growth has been questioned beyond UK shores, as the market is expected to ramp up not just domestically but also at a European level and beyond. This will be touched on further in Section 5.2.4, where the challenges facing the supply chain will be explored.

5.2.4 Supply Chain Challenges and the Future

Having reviewed the development of UK supply chain policy to date, and assessed where the sector currently stands with regards to both supply chain planning and local content, the possible future development of offshore wind in the UK should now be discussed. In this section, the potential risks facing the sector as it aims to continue growing in installed capacity will be touched upon. Firstly, Section 5.2.4.1 lays out some of the key challenges to increasing local content; Section 5.2.4.2 outlines ongoing funding for the sector; Section 5.2.4.3 discusses the capability of the supply chain to scale up production to meet ambitious targets; and Section 5.2.4.4 presents a summary of two further offshore wind leasing rounds run in the UK — INTOG and Celtic Sea.

5.2.4.1 Local Content Challenges

Through the changes in policy discussed in the previous sections, and culminating in the current requirements surrounding supply chain planning for UK offshore wind, the emphasis on local content in the supply chain has increased in recent years. Though strategically speaking the plan for developing the UK supply chain and increasing levels of local content in offshore wind farms is a positive step, expected to deliver economic benefits in the form of jobs and GVA, it belies the fact that through the delivery of almost 15GW of offshore wind to date a successful UK supply chain has not been created for much of the lifetime expenditure of offshore wind projects.

Considering Scotland as an example, delays and cancellations of proposed projects between 2010 and 2020 meant that the offshore wind sector in the country did not develop as originally envisioned. In 2010, eleven sites or zones had been granted agreements by the Crown Estate[11] to develop the seabed in Scottish waters. These projects are given in Table 5.5. Of these eleven, only five are still active today — in various stages of completion. Reasons varied for the shelving of projects, with three stopped by the Scottish Government after strong public backlash to the sites and a review finding that the potential economic benefits did not outweigh the negative impacts foreseen (Marine Scotland 2011). The remaining three were cancelled or shelved by their developers, with financial or strategic planning cited as the reasoning. Of the projects which continued in some form, only three are so far (at least partly) operational — more than a decade after first gaining exclusivity agreements from the Crown Estate to develop the seabed.

This period of limited offshore wind commissioning in Scotland, while other regions saw expansion, gave foreign markets the opportunity to grow their supply chain and become embedded within the industry — making it more difficult for Scottish companies to compete when projects eventually started to be installed (SOWEC 2021). One high-profile example of this is the collapse of BiFab, a Scottish manufacturing company which fabricated offshore structures for the oil & gas and renewables industries. Though initially supported financially by the Scottish Government, after failing to win contracts to build the jacket foundations for new wind farm developments in Scotland, the government declined to provide further funds to keep the company afloat and it fell into administration in 2020 (Economy, Energy and Fair Work Committee 2021). This illustrates the issues that UK companies often have when bidding for work on domestic wind farms, in that developers can source the parts cheaper elsewhere and ship them to the UK (BVG Associates 2021b). Without a clear pipeline of work, the owners of BiFab did not wish to commit to the financial assurances required to meet the contract for the Scottish wind farm which they had won a tender for (Economy, Energy and Fair Work Committee 2021).

[11] At this time, Crown Estate Scotland was not yet a separate body.

Table 5.5: Planned Scottish offshore wind developments, as of 2010 (OWIG 2010)

Name	Current Status	Information	Reference
Solway Firth	Cancelled	Public acceptance, socio-economic impacts	Marine Scotland (2011)
Wigtown Bay	Cancelled	Public acceptance, socio-economic impacts	Marine Scotland (2011)
Kintyre	Cancelled	Public acceptance, environmental impact, future investment	Marine Scotland (2011)
Islay	Cancelled	Financial	The Telegraph (2014)
Argyll Array	Cancelled	Financial, shark habitat, challenging conditions	ScottishPower Renewables (2013)
Beatrice	Operational	Commissioned 2019	Offshore Wind Scotland (2024)
Inch Cape	Development	—	Offshore Wind Scotland (2024)
Neart na Gaoithe	Under Construction	—	Offshore Wind Scotland (2024)
Forth Array	Cancelled	Strategic decision	Renewables Now (2010)
Moray Firth	Operational/ Under Construction	Moray East commissioned 2021, Moray West under construction	Offshore Wind Scotland (2024)
Firth of Forth	Operational/ Development	Seagreen 1 commissioned 2023, Seagreen 1a & Berwick Bank in Development	Offshore Wind Scotland (2024)

This again ties in with the desire through the ScotWind SCDS and CfD Supply Chain Plans to elucidate a pipeline of work which will increase confidence for investors and bolster UK companies within the offshore wind supply chain. Concluding the case of BiFab, in February 2021 InfraStrata, the owner of the Harland & Wolff shipyards in Belfast, purchased two out of the three BiFab sites which had been placed into administration, with the hope that they would be able to compete for the newest rounds of offshore wind farm contracts (BBC News 2021). Recently, Harland & Wolff have announced proposals for £270million investment into the two former BiFab sites to develop them as renewable energy hubs (Harland & Wolff 2024). These plans are being supported by the SOWEC and would see the site in Methil, Fife, expand its capability to build offshore wind turbine foundations while the Arnish location, on the Isle of Lewis, would receive investment to develop the port at Stornoway into an offshore wind hub.

When deciding to stop additional financial support for the struggling BiFab, the Scottish Government cited EU state aid rules as justification (Economy, Energy and Fair Work Committee 2021). The UK Government also declined support under the same rationale. This illustrates additional difficulties for UK companies, as competing businesses in other European countries and beyond are found to be state-owned or heavily subsidised, enabling them to bid more competitively. This is something which until now UK governments have been unwilling or unable to do, despite other EU companies spending much more on industry support whilst still adhering to the State Aid rules. However, one touted ‘benefit of Brexit’ is that the UK is now free to set its own laws on subsidies and bailouts, while still operating within World Trade Organization (WTO) rules (The Guardian 2021). There have been calls for future policies on subsidies and local content levels to be aligned, and focused on ensuring that UK companies can be successful in bidding for future work on domestic wind farms as the pace of new developments is accelerated towards 50GW capacity by 2030 (Economy, Energy and Fair Work Committee 2021). However, in 2022 the EU challenged the inclusion of local content requirements in the UK CfD scheme as discriminatory under WTO rules, with the UK ultimately acceding to remove requirements from the scheme to end the contest (M. Feng 2023). This demonstrates one aspect of the difficulty facing the UK to achieve the desired increase to local content levels in offshore wind. Without the ability to mandate its inclusion in new developments, there is a need to rely on developers choosing this voluntarily or costs of UK manufacturing reducing significantly enough that they can compete directly with parts sourced from foreign markets.

5.2.4.2 Funding

Considering costs of offshore wind, strike prices of successful project bids into CfD show a clear reduction in the years since AR1, as demonstrated in Table 5.6[12]. In AR4 of the Contracts for Difference scheme, offshore wind reached record low strike prices with successful projects bidding at £37.35/MWh, down from an average of around £120/MWh[13] in AR1 (DECC 2015a; BEIS and DESNZ 2022). However, in the time since the conclusion of the AR4 auction in 2022 the prevailing market conditions have changed significantly. Following the Russian invasion of Ukraine, gas prices (already high following the economic recovery from the Coronavirus pandemic) skyrocketed and caused knock-on effects to power prices worldwide (IEA 2024). Combined with high levels of inflation, this has caused significant pressures in the offshore wind supply chain (GWEC 2023). These price increases have led to a reassessment of projects worldwide, and in the UK resulted in developer Vattenfall announcing in July 2023 that they were stopping development of the Norfolk Boreas offshore wind farm (The Guardian 2023). The project had been successful in receiving funding through CfD AR4 at the record low strike price of £37.35/MWh but, citing a 40% rise in costs, the company deemed the project to no longer be financially viable at that price.

This global supply chain crisis has highlighted concerns that not only would other projects be experiencing the same challenging conditions that led to the Vattenfall decision, but that the future progress of the sector was also at risk. The fifth allocation

[12] The changing strike prices across AR 1 – 3 were detailed earlier in this thesis in Section 2.3.3.
[13] All strike prices are in 2012 prices.

Table 5.6: Average CfD strike prices for offshore wind. (Source: DECC (2015a), BEIS (2017a), BEIS (2019b) and BEIS and DESNZ (2022))

Allocation Round	Strike Price (£/MWh)	Capacity (MW)
AR1 (2015)	114 – 120	1,162
AR2 (2017)	58 – 75	3,196
AR3 (2019)	40 – 42	5,466
AR4 (2022)	37	6,994

round of CfD was held in September 2023, with industry unease leading into the auction that the £44/MWh administrative strike price (ASP) set for offshore wind did not reflect the prevailing market conditions and challenges — with this price a reduction from the £46/MWh set for AR4 (BVG Associates 2023). On the completion of the auction round, it was announced that no offshore wind projects bid for the desired 4GW of capacity it was hoped would be awarded (ORE Catapult 2023). With the previous success of the CfD scheme for offshore wind, this was clearly a blow to the UK Government and an additional challenge for the target of reaching 50GW of offshore wind by 2030.

The UK Government has proposed reforms for the upcoming sixth and seventh CfD auction rounds (AR6 and AR7). For AR6, the ASP for offshore wind has been increased from £44/MWh to £73/MWh — an increase of 66% on the AR5 value (DESNZ 2023a). The ASP for floating wind has also been raised, from £116/MWh in AR5 to £176/MWh. It is hoped that these increases will enable offshore wind to once again be economically viable under CfD, capturing the reality of higher prices across the supply chain and the increased risk of project financing for offshore wind[14]. In a change from AR5, offshore wind has also been placed into its own funding pot (Pot 3) while all other established technologies are in Pot 1. The UK Government has set challenging offshore wind capacity targets for 2030 and this separation demonstrates

[14]The results of AR6 were announced in September 2024, with almost 5GW offshore wind capacity awarded. Around 1.6GW was from projects previously awarded CfD reapplying for higher strike prices, which achieved £54.23/MWh. The new capacity was successful at £58.87/MWh, while one floating wind project bid at £139.93/MWh (DESNZ 2024a).

the ambition for the highest possible quantity of projects to be successful in AR6 and contribute towards this goal — particularly given the failure of AR5 from an offshore wind standpoint, and the potential setback in reaching the target that it represented.

Considering AR7, due in 2025, a consultation process is ongoing between government and the offshore wind industry in relation to the inclusion of new non-price factors in the CfD scheme. The proposed 'Sustainable Industry Reward' aims to expand on the provision of low-carbon power that has been delivered through the deployment of offshore wind, by rewarding future projects that make additional efforts surrounding sustainability. These non-price factors would provide a higher level of reward to developers who commit to taking "meaningful action to increase the economic, environmental and social sustainability" (DESNZ 2023b, p7). Interestingly, it is proposed that this mechanism could be in place of the current SCP provision in CfD. Though limited detail is provided to this point within the consultation, the economic, environmental, and social aspects referred to previously do relate to the supply chain of the project — so there is the understanding that much of the work when applying to the potential Sustainable Industry Reward would then be duplicated in any SCP.

5.2.4.3 Supply Chain Capability

The rising supply chain prices and subsequent issues described in Section 5.2.4.2 only represent one facet of the challenge facing the offshore wind supply chain. The UK has set the ambitious target of 50GW of offshore wind by 2030 (with 5GW of the still nascent floating wind), which is a substantial scale up of the 14GW installed to date — a further 36GW in only six years. There is clearly both a huge opportunity and significant challenge for the supply chain to meet this demand. Of course the UK target does not sit in isolation, with other regions worldwide also setting demanding installation targets for the industry which means increased competition for a limited supply pool.

To this end, WindEurope produced a report in 2023 which presented a review of the wind energy supply chain and the challenges it faces to meet capacity goals (Rystad Energy 2023). The report highlighted recent increases in costs for power, shipping, and raw materials, as well as the inflationary impact on prices across the value chain as an ongoing challenge for the wind industry. It also touched upon potential geopolitical issues relating to materials, with China the main producer of most of the raw materials and components within wind energy. Russia is also a significant producer of materials such as aluminium and nickel, with their export under sanction from countries worldwide. The European reliance on foreign markets for the import of components and materials in the offshore wind supply chain was thus flagged as an area of concern for potential future disruptions. Individual components were also considered more closely, with turbine rotors, monopile and floating foundations, and vessels all highlighted as areas for urgent and significant capacity expansion.

Within the UK, a recent review into the capability of the domestic supply chain highlighted both challenges and opportunities across the project lifecycle for offshore wind (OWIC and OWGP 2023). Similarly to previous studies and reviews, areas such as the development stage and cabling were hailed as strengths — contributing to the roughly 50% local content in the newest UK offshore wind farms. In component terms, the turbines themselves were generally highlighted as areas for concern — with limited capability available locally for towers and nacelles, and the threat of current rotor manufacturing losing out as future blade lengths increase beyond the scale of existing factories.

5.2.4.4 INTOG and Celtic Sea Leasing

To date, ScotWind has been the only offshore wind leasing round which has required any detailed supply chain planning at this stage of project development. In the years since ScotWind, two further leasing rounds in the UK have either been run or planned — the Innovation and Targeted Oil and Gas (INTOG) leasing round for projects in the North Sea off of Scotland in 2022 – 2023, and the upcoming Crown Estate Leasing

Round 5 which is targeting floating wind in the Celtic Sea. This section discusses both of these rounds, and how supply chain planning is embedded within.

The INTOG leasing round was formulated after the success of ScotWind in attracting bids for commercial scale offshore wind in Scotland. There was recognition that beyond these large scale projects, smaller, more innovative projects should also be given the chance to apply for seabed rights and help to develop the future of the offshore wind industry (Marine Scotland 2022). Additionally, the role that offshore wind could play in decarbonising the oil and gas industry was recognised, through the potential for electrifying oil and gas infrastructure. To that end, the INTOG leasing round was established, split into two parts: ‘IN’ for innovation projects with a capacity up to 100MW; and ‘TOG’ for projects targeted at reducing emissions from the oil and gas industry by supplying installations in the North Sea with renewable energy, removing the need to power them with diesel or natural gas (Marine Scotland 2022).

In 2023, twelve successful bidders were announced — with five innovation projects offered Exclusivity Agreements and seven for targeted oil and gas. Exclusivity Agreements allow the developer to start development work in their area, while the Sectoral Marine Plan for INTOG is developed by the Scottish Government[15] (Crown Estate Scotland 2023a). All twelve of the proposed projects in INTOG are for floating wind technology, with a combined capacity of 5.4GW (Crown Estate Scotland 2023a). The locations of the INTOG projects are shown in Figure 5.2, with the sites designated by their project ID, and a summary is provided in Table 5.7 which details the name, developer and project details of each applicant. Within the INTOG round, regions of seabed that featured in the earlier Sectoral Marine Plan and ScotWind leasing round were excluded, and are shown as grey cross-hatched areas in the figure. Additionally, TOG projects could only be proposed within a designated zone, shown in blue hatching in the figure (Marine Scotland 2022). Of the innovation projects, four are located off of the East-North East coast of Scotland, while one (project 5) is planned for the West coast region.

[15] The final plan is expected in Spring 2025.

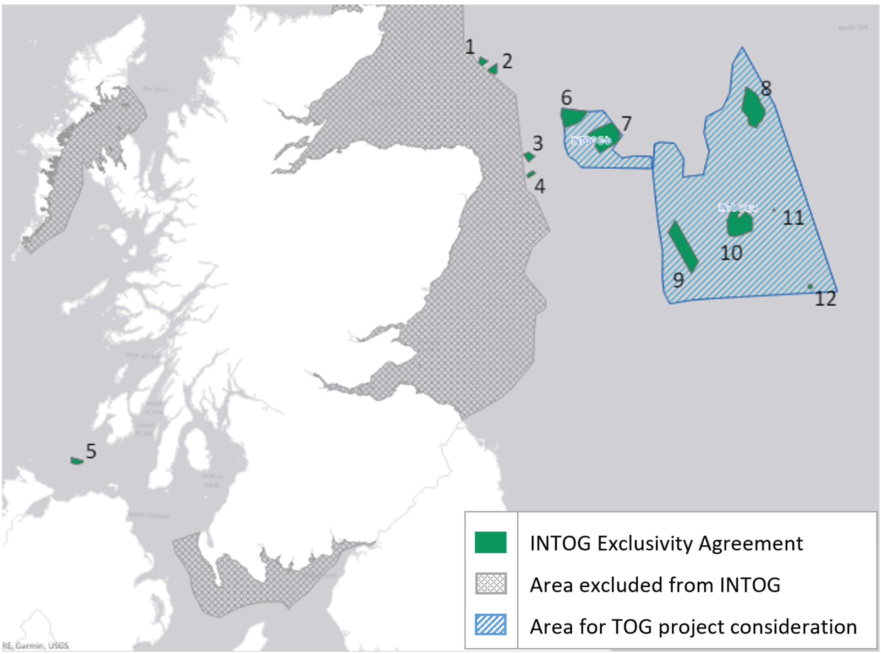

Figure 5.2: Locations of INTOG leasing round projects (Adapted from Crown Estate Scotland (2023d))

At this early, speculative stage of the development of the potential INTOG projects, no formal supply chain planning has yet been required in the receipt of Exclusivity Agreements. Once the INTOG Sectoral Marine Plan is complete, the projects will have the opportunity to apply for option agreements, to allow them to continue development work and eventually apply for a seabed lease, if their planned development is taken forward in the Plan (Crown Estate Scotland 2023a). At this stage, developers will be required to submit a Supply Chain Development Statement (SCDS). While no information is available on the exact data that will be required in the SCDS, other details supporting this provision appear to be in line with the SCDS mechanism in ScotWind. For instance: the full lifecycle of the project must be included, SCDS Outlooks must continue to be updated as development progresses, and discrepancies between final SCDS commitments and actual progress may result in the application of a contractual remedy.

While it is too early in the development of the INTOG projects to assess their impact on the offshore wind supply chain, it is promising that the supply chain planning

Table 5.7: INTOG projects and details (Source: Crown Estate Scotland (2023d) and Crown Estate Scotland (2023e))

ID	Project	Lead Applicant	IN/TOG	Capacity (MW)
1	Sinclair	Bluefloat Energy/ Renantis	IN	100
2	Scaraben	Bluefloat Energy/ Renantis	IN	100
3	Salamander	Simply Blue Energy	IN	100
4	Flora	BP Alternative Energy Investments	IN	50
5	Malin	ESB Asset Development	IN	96
6	Green Volt	Flotation Energy	TOG	560
7	Aspen	Cerulean Winds	TOG	1008
8	Beech	Cerulean Winds	TOG	1008
9	Cedar	Cerulean Winds	TOG	1008
10	Cenos	Flotation Energy	TOG	1350
11	Culzean	TotalEnergies	TOG	3
12	Judy	Harbour Energy	TOG	15

procedure established with ScotWind is going to be extended here. Further cementing the aim of the ScotWind SCDS to demonstrate a pipeline of projects and instil confidence to invest in the UK and Scottish supply chain, these INTOG projects add more potential capacity for companies to bid for. Across the projects, and more specifically the five 'IN' designated projects, the opportunity they present to help develop the nascent floating wind supply chain has been highlighted. For instance, the Sinclair and Scaraben projects are now planned as the first stage in the delivery of the ScotWind Broadshore project, intended to test the floating wind technology in the project area before expanding to commercial scale (BlueFloat Energy 2023). Likewise the Salamander offshore wind farm notes that alongside taking the risk out of future floating wind projects by testing out the technology on a smaller scale, this also gives the local supply chain the chance to ramp up for potential larger capacity projects (Simply Blue Energy 2024). The Flora project is also noted as an "exciting first step" to building the developer's floating offshore wind portfolio, with its innovation further expected to be integrated into a future hydrogen hub in the Aberdeen region (bp 2024, p1).

These ambitions align well with the INTOG initial plan which stated that the smaller scale of these projects "provide[s] an excellent opportunity" to develop the floating wind supply chain, with their size meaning that they may be developed sooner than the larger ScotWind projects (Marine Scotland 2022, p22). Ramping up the supply chain gradually by targeting these smaller capacity projects could lead to a more sustainable industry than if many contracts were required in a short timeframe when multiple, large ScotWind projects could be competing for a limited supply chain at similar times. Ultimately this would be positive for the sector long-term, increasing the depth of companies who are competitive in the market and producing a better equipped supply chain to minimise the risk of bottlenecks and delays.

Considering the future of offshore wind in the rest of the UK, the Crown Estate is currently[16] preparing for Leasing Round 5, offering seabed leases for floating offshore wind farms in the Celtic Sea. Commercialising floating wind for the first time in the England and Wales regions, up to 12GW capacity is planned to be made available in the round (The Crown Estate 2023a). As yet, there is no clear indication that supply chain plans will be required by bidders into the round in a similar manner to ScotWind and INTOG, or the CfD auctions. However, a number of other commitments are outlined in the bidder requirements. Firstly, bidders must identify their preferred ports and commit support to develop them. The Celtic Sea area does not currently have port infrastructure to support commercial scale offshore wind, so it is a crucial point of note that this will need to be remedied at the earliest possible stage to allow the planned capacity to be developed (LumenEE 2024). The other major commitment setting Round 5 apart is that bidders must outline how their project will create both social and environmental value, leaving communities and the natural environment better than they found them. These commitments will be monitored and enforced throughout the life of a successful project. The additional value brought to these Round 5 projects through these commitments could tie in with the proposed Sustainable Industry Reward

[16] As of April 2024.

in AR7 of the CfD auction.

While no further commitments surrounding supply chain planning are required, developing the supply chain for floating offshore wind is embedded throughout the plans for the leasing round. For instance, it is made explicit that a “stepping-stone approach” can be used to build a project in phases, allowing for capability in the supply chain to ramp up gradually (The Crown Estate 2023a, p9). Additionally, The Crown Estate has planned an initial £10million investment alongside DEVEX from successful bidders to accelerate UK supply chain projects, with the potential for a further £40million over time. The focus throughout the Round 5 details on developing the supply chain does raise the question as to why no formal supply chain plan is expected to be required from bidders — especially when a previous leasing round placed this as a key facet, albeit based in Scotland not England and Wales. Given the 60% local content target from the Offshore Wind Sector Deal, it is also perhaps surprising that there is no specific mention of UK content within the information available for Round 5. Though the challenges around mandating levels of local content were discussed in Section 5.2.4.1, the supply chain planning mechanisms in both ScotWind and CfD do still outline the need for expected local content to be provided by applicants. The initial tender for the Celtic Sea leasing round is not planned to open for bids until late 2024, with the final auction expected in 2025, so it remains to be seen if the requirements on potential developers are updated nearer to the time with any more focus on supply chain planning to increase visibility across the industry.

5.2.5 Policy and Supply Chain Summary

Through the development of the UK offshore wind industry, the emphasis on local, UK content and growing a domestic supply chain has changed. From the early years of the 2010s, when the installed capacity was beginning to grow at pace and the role of the technology in delivering both economic benefit and clean energy was becoming more acknowledged, the development of a UK supply chain was not an element of focus in government policy. Despite no specific legislation to that regard, industrial strategy did recognise the potential that existed in expanding manufacturing capability on British shores. In general, much of the early strategy detailed the importance of transparency, and how a pipeline of projects should both instil confidence in the market and encourage businesses to invest and contract for offshore wind. The Offshore Wind Sector Deal in 2019 set the first mandated target for local content, with an aim of 60% in new offshore wind projects by 2030 — rising from a base estimate of 50%.

The current requirements for supply chain planning in UK offshore wind developments are largely contained in two mechanisms — the Supply Chain Plan when applying for funding through CfD, and the Supply Chain Development Statement that was required from bidders into the ScotWind leasing round. These two mechanisms have been a significant step towards the transparency that was recommended in the publications discussed in Section 5.2.1, with both having at least some of the data contained within them made public — demonstrating the planned investment by developers. The provision of both of these plans has also delivered an element of accountability around supply chain planning for offshore wind. Whilst the success of a ScotWind bid or CfD application is not predicated on the information contained within the plans, contractual penalties may be applied to a developer if they do not meet the stipulations that they initially set out. It remains to be seen how successful these enforcement mechanisms may be — both in terms of the penalty actually being applied and in the deterrent they present in discouraging a developer from reneging on their initial commitments. For instance, the penalty may be lower in monetary terms than what can be saved by changing where they source a particular part — so the penalty becomes only a fine and does not cancel out the saving they make elsewhere. Both the SCP and SCDS monitoring regimes do create the potential where a project could be prevented from continuing, if their developer has significantly failed to meet their commitments. This for the first time does then introduce an incentive for accurate supply chain planning and for efforts to be made to adhere to this.

Whilst the future of the offshore wind supply chain offers a huge opportunity when considering the aims to scale up installed capacity, both in the UK and worldwide, there is also a significant amount of risk facing the industry. As discussed in Section 5.2.4, in addition to considerable price rises due to inflation and geopolitical pressures, there is growing concern about bottlenecks in the supply chain with many projects competing for limited resource (GWEC 2023). This links closely with the increased emphasis on the supply chain in general and with growing focus on transparent supply chain planning at the early stage of project development. Only when there is a clear possibility of being able to realistically compete for contracts will investment in the supply chain materialise. From a UK standpoint, this investment should then lead even passively to increased levels of local content in new offshore wind projects, but — crucially — could also lead to businesses being able to export and compete for work in new projects in foreign markets. This type of competitive supply chain is key if the industry is to be sustainable, with retention levels within the UK economy crucial for long-term economic benefits to be delivered.

5.3 Spotlight on ScotWind

Throughout the discussion on the development and current status of supply chain planning for offshore wind within the UK in Section 5.2, it was evident that the focus on the topic has changed over the years. Currently, there are two formal supply chain planning mechanisms employed within the UK offshore wind sector, as part of the CfD subsidy scheme and ScotWind seabed leasing. These represent the first attempts to mandate advance supply chain planning for the industry, and have been an attempt to increase transparency to the wider sector on the procurement intentions of project developers.

In this section, a high-level analysis of the data contained within the Supply Chain Development Statement (SCDS) Outlooks of ScotWind projects is presented. As outlined in Section 5.2, this is one of the main mechanisms for supply chain planning in UK offshore wind to date, with planned expenditure information made publicly available for the twenty projects which were successful in the leasing round. With expenditure information as part of the CfD Supply Chain Plans generally withheld by government for confidentiality reasons, the information within these SCDS Outlooks represents the largest source of UK supply chain planning data currently available. It provides an opportunity to assess the current landscape surrounding the state of the industry in the UK from a developer standpoint — as where they expect to procure their components indicates the likely business that is currently feasible locally. As such, in this section a review of the data from these SCDS is presented, to investigate how the proposed investment by developers varies across the projects, focusing on criteria such as fixed versus floating wind and local content levels. This assessment is compared with present targets for the industry, such as that for 60% local content in new projects by 2030, to provide an overview of the current 'state of play' and possible future trajectory.

The remainder of this section is laid out as follows: first a brief outline of the SCDS data used for the analysis is discussed in Section 5.3.1. The analysis itself, which looks at the aggregate investment of the twenty proposed projects, as well as variation between the projects and project stages, is presented in Section 5.3.2. The discussion is summarised in Section 5.3.3, drawing together the main conclusions of the analysis.

5.3.1 Data

In this section, the data which was used for this analysis is outlined. Through ScotWind leasing Round 1, twenty projects were successful in being granted 'Option Agreements' to develop new offshore wind projects in Scottish waters. These included an initial seventeen projects, plus a further three who were granted approval in the clearing round for sites around Shetland. The twenty successful projects and their respective developers are listed in Table 5.8.

As part of the application process for the seabed lease, prospective developers were obliged to submit a Supply Chain Development Statement along with their bid, as detailed in Section 5.2.2. Within this they were required to outline their planned expenditure in four project stages (development, manufacturing & fabrication, installation, and operations[17]) in each of four geographical regions (Scotland, rest of UK, EU, rest of the World). This had to be provided in two cases — one was their 'Committed' spend, and one their 'Ambition'. Projects were not ranked or scored on the information contained within their SCDS when granting an Option Agreement. However, if the application was successful then contractual remedies may be applied in the future if the project spend does not adhere to the commitments outlined in the SCDS (Crown Estate Scotland 2021b).

The information utilised for the analysis here was obtained from the publicly available SCDS Outlook of each of the twenty successful projects (Crown Estate Scotland 2023e). For conciseness, these will simply be termed 'SCDS' going forwards — though it is noted it is solely the publicly available Outlooks that have been consulted, not the original, full SCDS Narratives submitted with the bids to Crown Estate Scotland. The planned (committed and ambition) expenditure of each project across the four stages and four geographical locations was the primary data of interest, but project details such as developer, capacity, and technology type were also considered throughout the analysis where this was provided.

Seventeen of the twenty projects submitted an updated SCDS in July 2023. The analysis discussed in the following sections considers data from the original twenty SCDS from the time of the project bids in 2021, in order to perform comparisons with the three projects that have not yet been required to submit an update.

5.3.2 Analysis

This section discusses the results of analysing the data contained within the SCDS of the twenty successful ScotWind projects. These projects, shown in Table 5.8, have a planned operating capacity of 27.6GW. Thirteen of the projects plan to use solely floating wind technology, whilst six outline a fixed-bottom approach, and one site aims

[17]Spend in the first six years of operation of the wind farm.

Table 5.8: ScotWind projects (Crown Estate Scotland 2023e)

Project No.	**Project Name**	**Project Developer(s)**	**Capacity [MW]**	**Fixed/ Floating?**
1	Morven	bp, EnBW	2907	Fixed
2	Ossian	SSE Renewables, Marubeni, CPI	2610	Float
3	Bellrock	Blue Float Energy, Renantis	1200	Float
4	CampionWind	Shell, SPR	2000	Float
5	Muir Mhor	Vattenfall, Fred. Olsen Renewables	798	Float
6	Bowdun	DEME, Qair, Aspiravi	1008	Fixed
7	Ayre	DEME, Qair, Aspiravi	1008	Float
8	Stromar	Ørsted, Renantis, Blue Float Energy	1000	Float
9	Caledonia	Ocean Winds, EDP, Engie	1000	Fixed
10	Broadshore	Blue Float Energy, Renantis	500	Float
11	MarramWind	SPR, Shell	3000	Float
12	Buchan	BayWa r.e., Elicio, BW Ideol	960	Float
13	West of Orkney	Corio, Total, RIDG	2000	Fixed
14	Havbredey	Northland Power, Arcus, Worley	1500	Float
15	Talisk	Magnora ASA, Technip FMC	495	Mixed
16	Spiorad Na Mara	Northland Power, Arcus, Worley	840	Fixed
17	MachairWind	SPR	2000	Fixed
18	Arven South	Ocean Winds, EDP, Engie	500	Float
19	Arven	Mainstream Renewable Power	1800	Float
20	Stoura	ESB Asset Development	500	Float

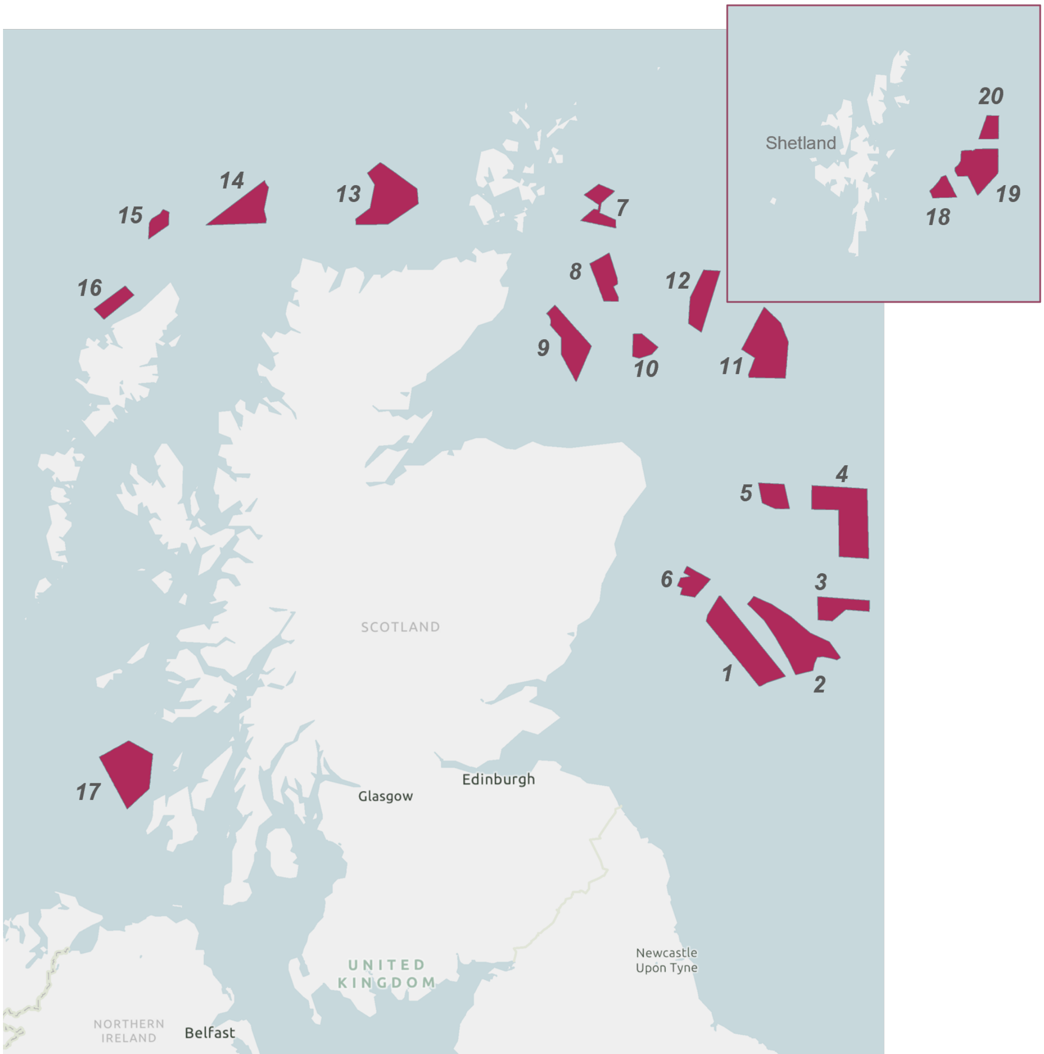

Figure 5.3: Locations of ScotWind Round 1 projects (adapted from Crown Estate Scotland (2023c))

to use a mixture of both methods. The water depth and distance from shore of each of the projects varies. Seventeen of the proposed sites are located around the coast of mainland Scotland and three are off the coast of Shetland, as shown in Figure 5.3. These sites are all contained within the Plan Option areas set out in the Scottish Government Sectoral Marine Plan for Offshore Wind Energy which detailed the framework for the ScotWind leasing round, as discussed in Chapter 2 (Scottish Government 2020c)[18].

The remainder of this section is split into two parts. The first, Section 5.3.2.1

[18]See Figure 2.6 and discussion in Section 2.3.3.

Table 5.9: 'Committed' spend of ScotWind projects by project stage and area

Stage	**UK [£m]**	**EU [£m]**	**RoW [£m]**	***Total* [£m]**
Development	3,318	291	20	**3,628**
Manuf. & Fabrication	23,828	19,947	7,493	**51,268**
Installation	7,278	4,933	466	**12,677**
Operations	7,568	1,130	107	**8,805**
***Total* [£m]**	**41,991**	**26,300**	**8,087**	**76,378**

Table 5.10: 'Ambition' spend of ScotWind projects by project stage and area

Stage	**UK [£m]**	**EU [£m]**	**RoW [£m]**	***Total* [£m]**
Development	3,642	302	10	**3,954**
Manuf. & Fabrication	34,934	17,797	3,515	**56,246**
Installation	9,843	3,533	346	**13,722**
Operations	8,382	577	77	**9,035**
***Total* [£m]**	**56,801**	**22,208**	**3,948**	**82,957**

considers the overall investment from ScotWind, breaking down the planned spend by project stage and location for both the committed and ambition expenditure of the aggregated twenty projects. The second, Section 5.3.2.2, takes a more detailed look at the individual projects and how their investment and UK content vary, and also analyses differences based on specific characteristics such as distance the wind farm is sited from shore or the region of origin of the project developer.

5.3.2.1 Overview of All Projects

This section reviews the data from the successful ScotWind Round 1 Supply Chain Development Statements, considering the investment from all projects combined.

The combined 'Committed' expenditure of the twenty projects, with units in millions of pounds (£m), is shown in Table 5.9; whilst the spend for the 'Ambition' case is displayed in Table 5.10. In the committed case, a spend of £76bn is expected if all projects were to progress to completion — with £42bn of this to be spent in the UK (£29bn in Scotland). This increases to a total of £83bn in the ambition case, with £57bn in UK spend (£42bn Scotland)[19]. The largest share of investment is shown to be in the manufacturing and fabrication stage, where £24bn is expected to be spent in the UK and £51bn will be spent in total. This spend is many times larger than each of the other project stages, and accounts for two thirds of the overall committed spend up to the end of six years of operation.

A comparison of the regional shares for the committed versus ambition spends is displayed in Figure 5.4, where the percentage of expenditure expected in each location is shown. This demonstrates that, in both cases, the largest share of the expenditure is expected within Scotland. However, under the committed spend of all projects combined, only 55% is expected in the UK when combining the Scotland and rUK percentages. Thus, the UK share of ScotWind expenditure falls short of the 60% local content target set out in the Offshore Wind Sector Deal for 2030 (BEIS 2019c). Whilst overall UK content does rise to 68% when considering ambition, these values indicate that there is a discrepancy between what the industry expects is possible for building new offshore wind sites in the coming years and the aims set out in national legislation.

It is also instructive to look at the differences in planned UK expenditure across the four project stages outlined in the SCDS. Once again considering all twenty projects combined, Figure 5.5 shows the UK (Scotland + rUK) percentage share for each stage, under both the committed and ambition cases. This shows that — for the committed spend — the Development stage is expected to have the highest local content, with 91% planned within the UK, followed by Operations (86%) and Installation (57%), while the lowest percentage is predicted for Manufacturing and Fabrication at only 46%. For the ambition spend, the UK shares across all four project stages increase — with local content in the manufacturing and installation stages most affected and rising to 62%

[19]Some projects provided only their UK spend, whilst suppressing non-UK expenditure for confidentiality. As such, a higher ambition spend perhaps indicates the increased UK share in these projects, not necessarily an increase in absolute spend across all projects.

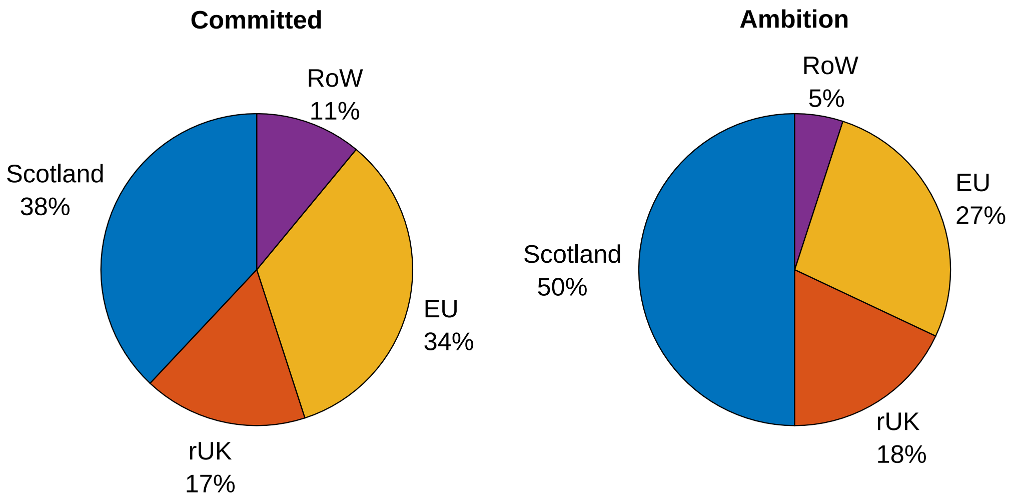

Figure 5.4: Location shares for 'Committed' and 'Ambition' ScotWind spends

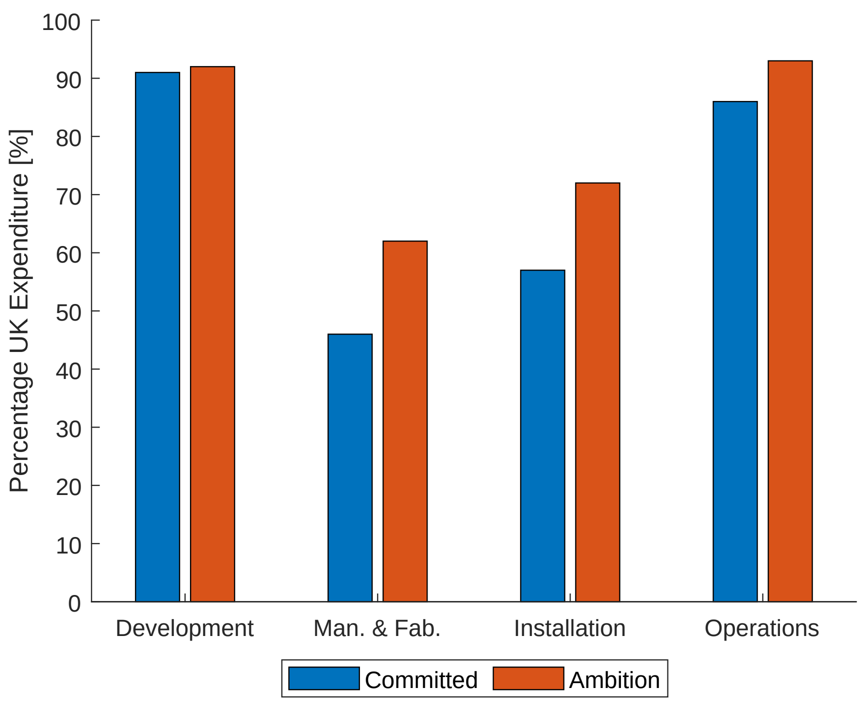

Figure 5.5: Percentage UK expenditure in ScotWind by project stage

and 72% respectively. This represents a significant additional investment into the UK, especially within manufacturing, as whilst the overall UK share is still lower than for other stages it is a share of a much larger expenditure.

The committed values reflect the current, and expected, capacity that is available within the UK supply chain for each stage. This is broadly in terms with the example used in Allan et al. (2020) which outlines the local content of the East Anglia wind farm. Here, development features 90% of UK content and up to 80% UK content in operating expenditure. When considering manufacturing there is variation across components — the supply of turbines and cables both have local content of less than 30%, with foundations sourcing approximately 50% from the UK. Whilst this is clearly not an exhaustive list of the manufactured components in an offshore wind farm, these values would indicate a slightly reduced UK share than the 46% calculated from the data within the SCDS for ScotWind.

However, it is noted that the values used in the Allan et al. (2020) analysis date to 2014 and represent a wind farm which uses 7MW turbines on jacket foundations. The turbines expected for the ScotWind projects are all significantly larger (15MW+), reflecting the progress in the technology in the intervening years. Additionally, the majority of the sites are expected to implement floating foundations rather than the more traditional fixed-bottom approach followed by East Anglia. There is an expectation that a higher percentage of floating foundations will be manufactured in the UK than has historically been the case for jacket or monopile foundation options (BVG Associates 2021b). Therefore it is to be expected that a higher share of UK manufacturing is predicted for these future projects than was previously seen.

Though there has been improvement seen in the UK supply chain to date, these proposals demonstrate where emphasis should be placed to further its development. In order to capitalise on the expenditure proposed under the ambition case, there is a requirement for more manufacturing capability across the board — but key areas for improved UK capacity identified within the SCDS include the fabrication of cables and wind turbine blades (Crown Estate Scotland 2023e). Development and operations already show healthy levels of planned investment to the UK economy, so the target should be on improving the share within the manufacturing and installation stages — with a focus on manufacturing. A few percentage points of improvement on this stage, which represents by far the largest outright expenditure, would provide a much greater boost to the UK than a few extra percent in the development stage.

5.3.2.2 Analysis at Individual Project Level

Thus far, only the combined investment of the twenty projects have been considered. However, the projects have been proposed by varying developers, all of whom will have different levels of experience and ideas for their supply chain sourcing. As such, it is important to also look at the details at an individual project level. Nine criteria are considered, and are discussed through the following subsections, (a) to (i).

(a) UK versus non-UK content: Figure 5.6 presents the percentage breakdown in committed spend of each project, showing the UK and non-UK content in each stage of their project (development, manufacturing/fabrication, installation, and operations). The projects are shown in order of their proposed level of UK content, from highest in the top left to lowest in the bottom right. The target set out in the Offshore Wind Sector Deal of 60% UK content in new projects by 2030 is marked for reference.

The graph shows that, other than the four projects which have withheld non-UK expenditure[20] and thus show 100% of their spend in the UK, only two have committed to UK content of over 60%. This indicates that the 55% total UK content calculated for all of the ScotWind projects combined (as discussed in the previous section) is being skewed by the four which have outlined only their UK shares. Excluding these four sites from the calculation, the UK content for the committed spend of the remaining sixteen proposals is 49%, and rises to 63% with the ambition spends.

(b) UK and non-UK spend per project stage: Looking in more detail at the UK and non-UK spend, each of the four life-cycle stages are shown in more detail in Figure 5.7. Here, the percentage of the total project spend in that stage by each of the

[20] Three of these projects explicitly stated they were suppressing non-UK values for confidentiality. The fourth makes no mention within the SCDS that this was done, but this is assumed to be the case.

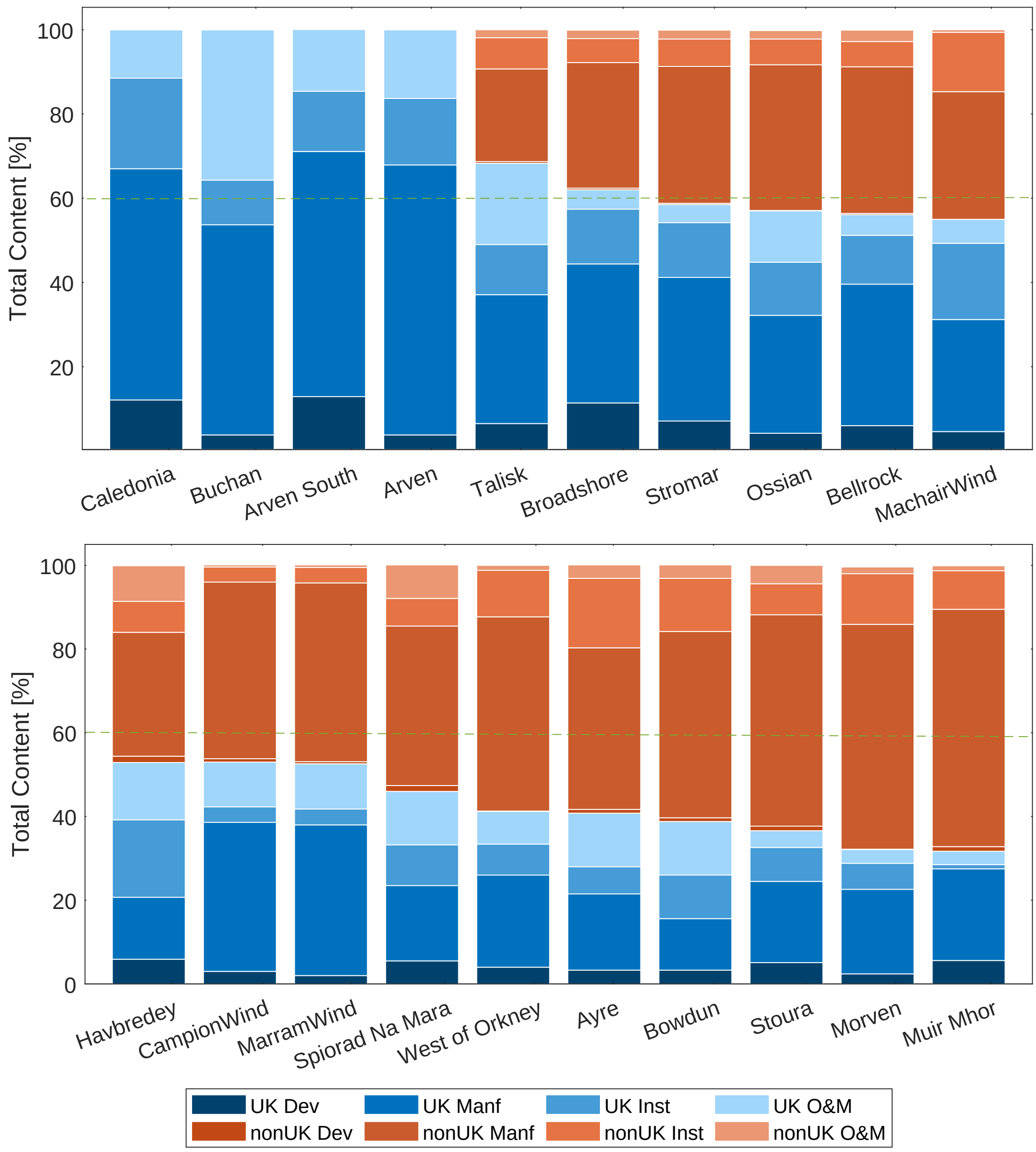

Figure 5.6: ScotWind projects showing percentage spend on each stage in UK and non-UK regions, ordered by level of UK content. 60% UK content marker shown.

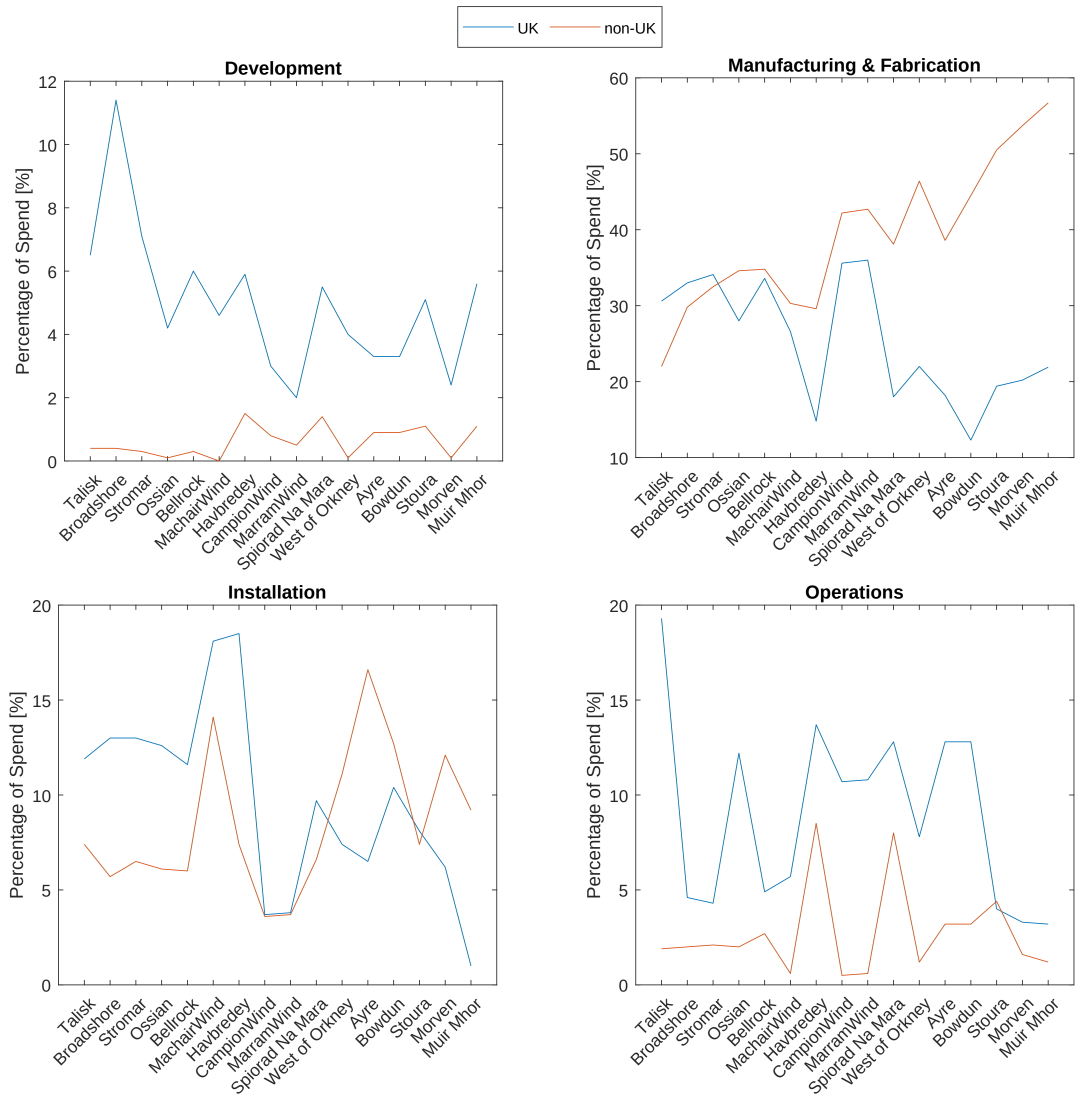

Figure 5.7: UK and non-UK content in each project stage, ordered by level of total UK content (excluding four projects which withheld non-UK spend)

ScotWind projects can be seen — excluding the four projects which published only UK expenditure. Again, the data is ordered by the total level of UK content in the project: left to right, from highest to lowest.

The graphs show that manufacturing spend is driving the increasing levels of non-UK content. While the three other stages show more variation between UK and non-UK content across all projects, non-UK manufacturing expenditure has a clear upwards trend as the level of total project UK content decreases. Whilst it has already been discussed that manufacturing is both the highest outright spend from the SCDS and the stage with the highest non-UK spend overall, this further demonstrates that this is the sector where the largest gains could be made in efforts to increase local content.

(c) Operations stage: The data in these plots also demonstrates variation between the different projects on the share of total expenditure they intend for each project stage. For instance, in the operations stage, non-UK spend is relatively consistent for all bar two of the projects — these two indicate roughly 8% of total expenditure on non-UK operations, whilst the remainder are all around 4% or lower. These two projects, Havbredey (project 14) and Spiorad Na Mara (project 16), also have corresponding rises in their UK operational spend, showing that they are anticipating higher operational costs overall than most other projects. Both projects are planned in the waters around the Western Isles of Scotland and have the same developers, with Havbredey planning to utilise floating platforms and Spiorad Na Mara using fixed bottom technology.

From the information available in the SCDS, it cannot immediately be said whether the higher than average operational expenditure (with higher non-UK content) is due to developer preference or based on the conditions expected for running the wind farm upon commissioning. However, for comparison, the Talisk wind farm (project 15) is located in the same geographical region and outlined a total operations expenditure of a similar percentage — albeit with the majority of the spend committed to the UK. When considering these three projects together, it could be concluded that the higher operational spend percentage is related to the siting location of the wind farms; but the share of UK to non-UK spend is dependent on decisions made by the project developer.

(d) Installation stage: While not as pronounced as for manufacturing, non-UK spend in the installation stage is also driving reduction in overall UK content. The projects with lower total UK content are generally spending more on installation in non-UK markets than within the UK. The seven committing the highest UK content all demonstrate higher UK than non-UK installation spend, the next two have an almost even split, whilst of the seven projects with the lowest UK content only two are committing more than half of their installation spend in the UK.

In the most recent detailed analysis of the UK supply chain for offshore wind, 'offshore services' was identified as the largest potential opportunity for the UK supply chain in financial terms — encompassing installation and O&M activities (OWIC and OWGP 2023). As such five out of the sixteen projects (almost one third of projects) focusing their installation spend outwith the UK, and two more opting for essentially a 50:50 split, demonstrates that this area of the sector may not yet be strong enough to compete with non-UK businesses in certain aspects. While it would not be expected that all the business would be retained in the UK, this discrepancy with the aims of the sector does indicate that there is scope for improvement. On the other hand, one estimate for installation and commissioning UK content in recent offshore wind farms is 36% (BVG Associates 2024b). So while some ScotWind projects may fall short of the ambition, a 52% average UK content share in installation across the sixteen projects demonstrates an improvement on the current state of affairs.

(e) Project capacity: Continuing to look at an individual project level, Figure 5.8 demonstrates the correlation between the capacity of each planned wind farm and its committed spend. As one would expect, higher capacity is proportional to higher spend — a larger capacity wind farm will likely be a larger footprint and purchase more turbines, assuming that all projects will target similar sized turbines. However, it can also be seen that for the same or similar capacities, projects utilising floating technology are generally more expensive than those employing more traditional fixed bottom approaches. This is demonstrative of the relative nascency of floating technology, and a recognition of the more challenging offshore site work that is required for deeper waters. To account for the correlation between capacity and expenditure, subsequent graphs will instead look at expenditure per unit capacity (£bn/GW) to remove the dependency on the size of the wind farm.

(f) UK content and spend per unit capacity: Considering local content levels, Figure 5.9 shows the variation of UK content percentages with spend per GW. For

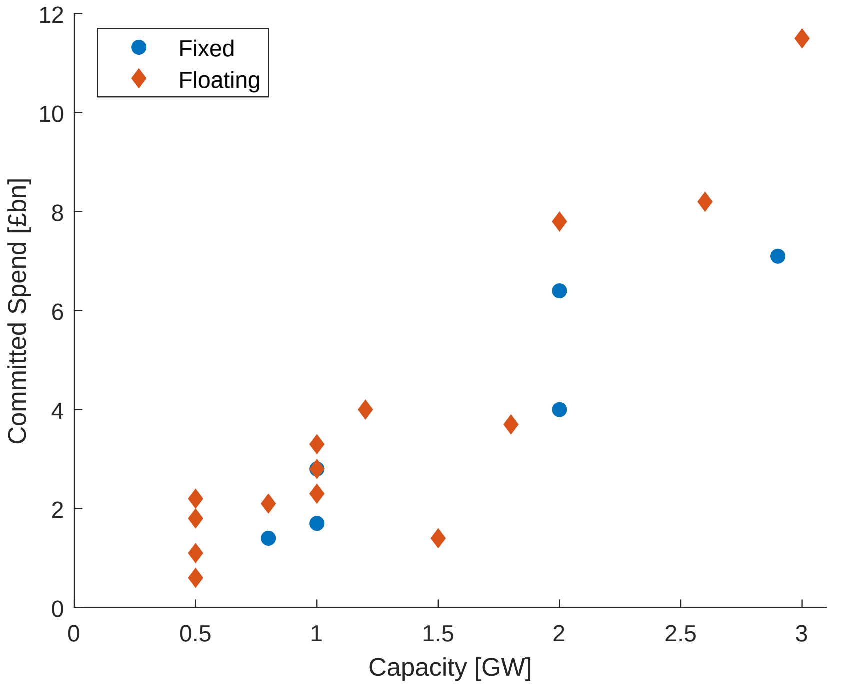

Figure 5.8: Wind farm capacity vs committed expenditure of the ScotWind projects

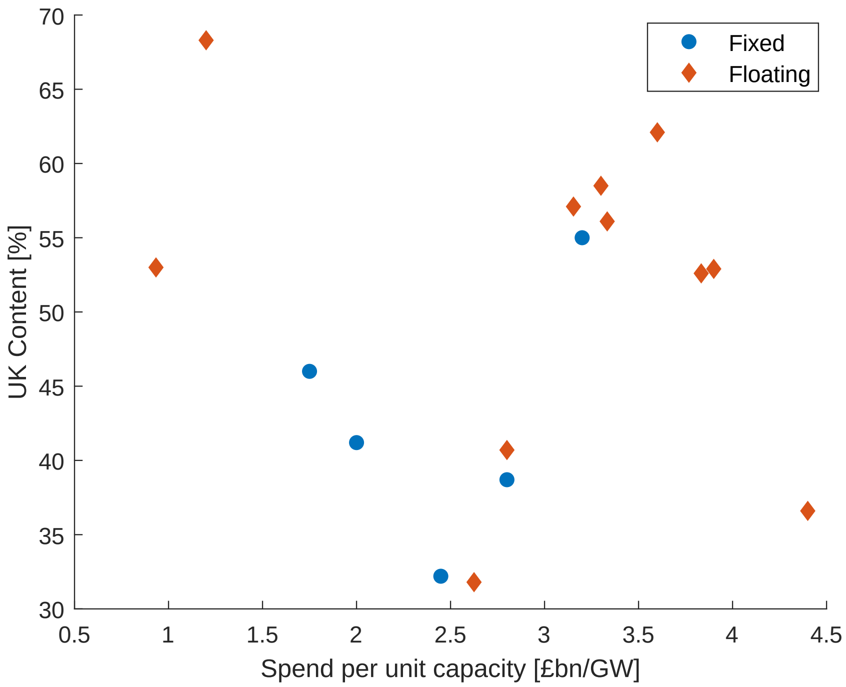

Figure 5.9: UK content in each ScotWind project vs Spend/GW (excluding four projects which withheld non-UK spend)

the projects intending to use fixed-bottom technology, there is no trend in increasing spend having an impact on UK content. However, only five projects are included in this category (as one fixed wind farm which has not divulged non-UK spend is excluded) so there are limited data points to show a pattern. With regards to the floating projects, whilst there are some outliers which have either a low spend/GW but high UK content or high spend/GW but low UK content, in general the UK content of the projects increases as expenditure per unit capacity increases. Whilst the exact reasons for this cannot be specified, it is indicative that there is a disconnect between the desire to keep costs low and to source within the UK.

This point does raise the question of incentive to source within the UK. If prices are generally higher domestically than when sourcing from foreign markets, without a contractual obligation to do so then why would a developer sign contracts with UK businesses? Neither the ScotWind SCDS nor the SCP within the CfD auctions mandate certain levels of UK content, they only desire that accurate estimates and commitments be made. Whilst the 60% local content target from the Offshore Wind Sector Deal was set in conjunction with the industry, and high levels of UK content could constitute good PR for a company, the fact remains that the cost of a product will likely be the driving factor behind developer decision making. One potential argument for sourcing from the UK could come down to considerations around security of supply and bottlenecks in the global supply chain as other markets also ramp up toward their renewable energy targets. An increase in cost for certain contracts could be viewed as an acceptable trade-off if it guarantees that the project can meet its milestones and begin generating energy quicker.

(g) Distance from shore: One further driver of spend that has been assessed is how far the site is located from land, with the spend/GW of each project shown in Figure 5.10 as a function of distance from shore. Considering the fixed projects first, excluding one outlier (MachairWind, project 17 — marked on the figure for clarity) there is a general correlation that the further the wind farm is situated from shore the higher its expenditure will be. While there are again a limited number of fixed projects to

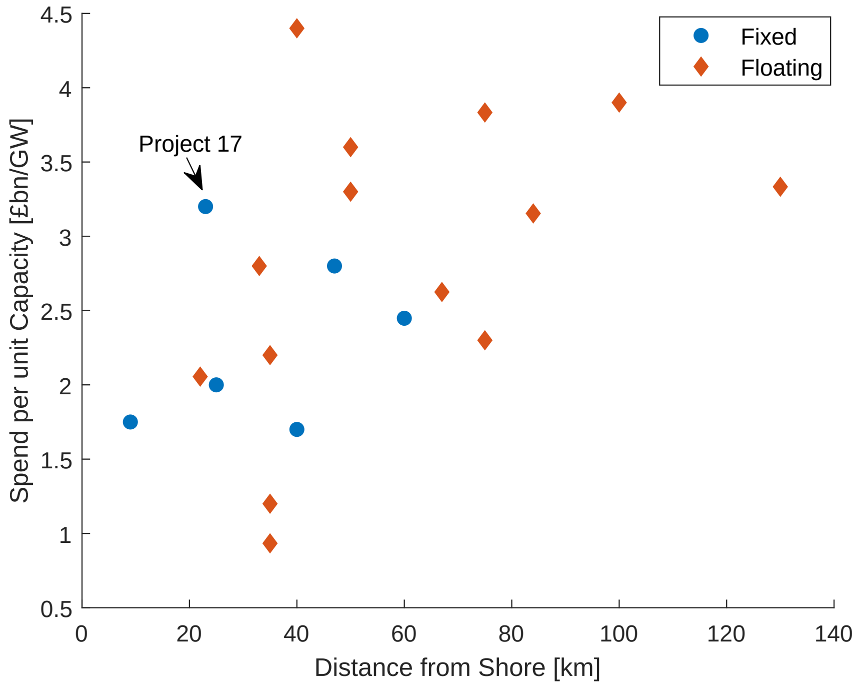

Figure 5.10: Variation of spend/GW with distance from shore of ScotWind projects

ascertain a definite pattern, we would intuitively expect a distant site to cost more due to complexity of installation and transferring crews a greater distance.

For the case of MachairWind, with a high comparative spend for its distance from shore, this project also had the highest UK content of all the fixed projects. Interestingly, this potential site was the only successful applicant in the round which won the right to the seabed in a plan area on the west coast of Scotland. Contrary to the increasingly congested waters on the east, there are currently no operational wind farms in this area — with only one other consented in the INTOG leasing round for a much smaller, floating project (Crown Estate Scotland 2023e). A previously planned offshore wind farm in this region, the Argyll Array, was abandoned in 2013 with challenging ground and wave conditions cited as factors (ScottishPower Renewables 2013). At the time, the developer noted that future technological improvements and cost reduction could improve the financial viability of a project in this region. These aforementioned challenging conditions could be the driving force behind the higher spend for this project. Indeed, when referring back to Figure 5.7, MachairWind has the highest share of its overall spend dedicated to installation — 32% of total project expenditure is committed to this stage, with the next highest project predicting 26% — potentially demonstrating an increased cost to install foundations on harder ground.

For the remaining, floating wind farms there is also a correlation in Figure 5.10 between distance from shore and spend — albeit with a wide scatter around the trend. In general, it can be said that an offshore wind farm situated further from shore is likely to exhibit higher costs than an equivalent project located closer to shore. Other variation is difficult to pick out or attribute to a specific cause, with factors such as developer strategy or nature of the site contributing to differences between projects. Nevertheless, one project of note is Stoura (project 20), which has the highest spend per unit capacity, and is an outlier to the trend with a location only 40km from shore. One of the three Shetland projects which were granted option agreements in the clearing round of ScotWind (along with projects 18 and 19), Stoura has the third lowest UK content of the group — though both of the other Shetland projects withheld their non-UK spend. When considering this point, it cannot be said with any certainty how they would compare with the spend per unit capacity of Stoura. It may be that when including the withheld, non-UK spend that these would also have a high spend per unit capacity and would join Stoura as outliers in Figure 5.10, being situated 35km and 22km from shore respectively. Due to the withholding of data on these projects, the reason for Stoura's high spend per unit capacity cannot be ascertained as any geographical factor would also apply to the other two projects.

(h) Developer location: The developers of the twenty ScotWind projects vary, with a combination of standalone companies and consortia bidding into the round. These developers cover a range of business types, from established renewable energy generators to oil and gas majors; and a range of geographical locations, with established companies from the UK, Europe and beyond all successful in the leasing round. With such a range of developer locations not within the UK, it is interesting to consider whether this has played a part in the distribution of committed UK content across the projects. This is shown in Figure 5.11, where the developers have been categorised based on where

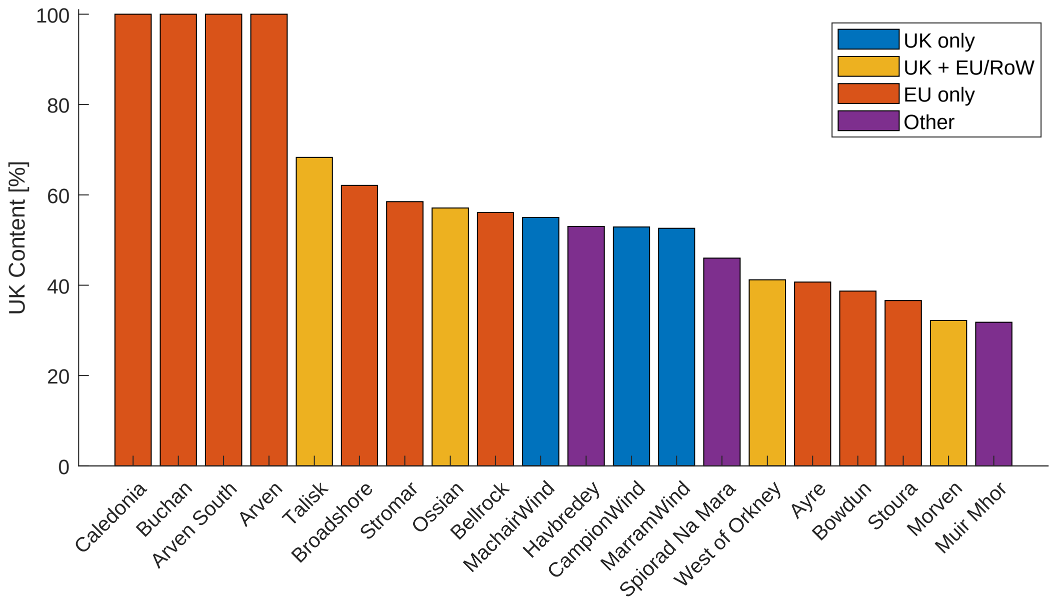

Figure 5.11: Location of ScotWind project developer and UK content

the business is headquartered across the UK, EU and rest of world (RoW) — the locations considered in the ScotWind SCDS. The projects have been split into four: those with UK based developers, consortia with at least one UK developer combined with any other location, EU headquartered, and any remaining which are RoW only or a combination of RoW and EU have been grouped into 'other'.

From Figure 5.11, organised by project UK content from left to right, there does not appear to be any real correlation between developer location and UK content. The four projects which erroneously show 100% UK content are included to indicate their developer location, but do not tell us anything meaningful about their true local content. For the remainder, the UK only projects are clustered around the mid-way point, though they share the same developers amongst them and UK shares may be more representative of their decision making than telling us anything about attitudes of the wider pool of UK developers. Looking to consortia featuring a UK company there is a more widespread distribution of planned UK content, which indicates a lack of correlation between a UK based developer and the level of UK content. Only Muir Mhor (project 5) consists of solely RoW developers, whilst the remaining two classed as ‘other’ are a combination of RoW and EU. Though encompassing the project with the lowest local content, there are too few of this classification to meaningfully say how this situating of developers impacts UK content — if indeed there is any correlation to be seen. The lack of a clear relationship in the other categories would seem to indicate that UK content may not have any link to the location of the developer.

(i) Planned additional investment: Looking beyond solely the planned expenditure of the ScotWind wind farms, some projects have also outlined their intention to support the UK supply chain and help in its development. For instance, the West of Orkney wind farm has recently sponsored an offshore wind research and innovation programme delivered by the European Marine Energy Centre, where up to £1million in funding has been made available (EMEC 2023). Whilst the first call for proposals was focused on metocean challenges for the West of Orkney site, future calls are expected to relate to projects supporting the supply chain in scaling up and bringing new technology to market. Meanwhile, the CampionWind, MarramWind and MachairWind projects have each confirmed £25million in supply chain stimulus funds, investing in infrastructure and helping to support Scottish businesses to expand (CampionWind 2022; ScottishPower Renewables 2024). This funding is in addition to the direct investment in the supply chain outlined in the respective SCDS.

On a related note, other projects have committed investment to skills and STEM outreach with the aim of training the next generation of workers for offshore wind. Examples include the developer of the Bowdun and Ayre offshore wind farms donating a training vessel to the University of the Highlands and Islands, and those of the Caledonia project funding scholarships for undergraduate students from the Moray and Aberdeenshire areas to study in a field related to offshore wind (Thistle Wind Partners 2023; Ocean Winds 2022).

5.3.3 Summary of ScotWind Assessment

As of April 2024, all twenty of the ScotWind projects are still undergoing development and expected to start generating electricity from 2030 onwards. Despite the challenging conditions facing the industry in the past couple of years, the overall progression of offshore wind in Scotland seems on track. With a planned combined investment of £76bn, £42bn of which is earmarked for the UK, there is significant scope for supply chain companies to compete for contracts with the ScotWind projects.

As an exercise in supply chain planning, the ScotWind SCDS offer a good indication to businesses across the sector of a healthy pipeline of projects. Particularly in the case of floating wind, the fourteen projects planning use of this technology mark a very steep increase in capacity from the level of floating wind currently installed. The industry will need to ramp up quickly in order to facilitate these projects. To that regard, it is then positive that the potential investment has been made apparent to the supply chain — and will ideally stimulate external investment. By extension, the earmarked additional funding that has been offered by some of the developers to help build the local supply chain should, as well as helping with the progress of their own project, also be beneficial to the wider industry both in Scotland and further afield.

What has been highlighted by the analysis of the SCDS Outlook data, is that on the whole there is a disconnect between the UK content that the developers deem is realistic for these projects and the 60% target that has been set within the Offshore Wind Sector Deal. The most critical evidence from the SCDS which offers an explanation as to why this might be, is that there does seem to be a correlation between higher expenditure (per GW) and UK content — with the graph in Figure 5.9 showing that, for the floating projects, UK content commitments rise with increasing spend per unit capacity. It then follows that costs associated with sourcing within the UK are higher than sourcing from other markets. This higher cost is the main barrier to raising levels of local content in line with the 2030 target.

Considering other project specific data, there do not seem to be any other criteria which have a close link with local content levels or is driving it. Whilst there is expenditure variation, with projects in some Plan Areas exhibiting higher costs than in others, within similar geographic conditions there is often wide variation in planned local content. The conclusion to be drawn from this, is that the main driver in UK content commitment is developer preference. Amongst the developers, this does not appear to be clearly driven by where the developer is based, and so other company-specific attitudes that cannot be easily ascertained appear to make the most impact.

5.4 Discussion

The previous sections have shown that through the CfD and ScotWind processes there have been attempts to incorporate more formal supply chain planning into the early stages of offshore wind farm development across the UK. However, the question remains as to what impact these mechanisms had or will have on local content levels. In 2013, the Offshore Wind Industrial Strategy estimated local content at around 30% in UK offshore wind farms, and this rose to around 50% by the time of the Offshore Wind Sector Deal in 2019 (DECC & BIS 2013; BEIS 2019c). In the intervening time, none of the publications discussed in Section 5.2 put anything legislative in place to mandate supply chain planning and, in terms of support for the supply chain, did not go beyond general aims to invest and studies identifying areas of weakness. Despite this, a notable increase in local content was still seen in wind farms commissioning in this period, so could it be inferred that formal mechanisms are not actually needed?

While it is true there was no mandated planning over the period between 2013 and 2019, there were still developments in the background in this time. It is hard to say for certain which aspects contributed to the increase in local content levels, but this may have been stimulated through increased investment in the supply chain as outlined in, for instance, the Offshore Wind Industrial Strategy or the Clean Growth Strategy (DECC & BIS 2013; BEIS 2017b). Additionally, though no wind farms which gained funding through the CfD scheme were operational by 2019 and included in the 50% local content estimate in the Offshore Wind Sector Deal, its commencement in 2015 and associated supply chain planning guidance may still have influenced the wider industry at the time. Since 2019, from the limited published data on more recently commissioned UK offshore wind farms, the local content level has stagnated at around 50%. While the time taken to develop a wind farm through to the operational phase can be long, these projects will likely have been influenced both by the increasing focus on local content as a general sentiment and what was formalised by the Sector Deal. The lack of significant improvement[21] from the 50% estimate in 2019 does then indicate that something new is required, which is where the increasingly detailed CfD SCP and the ScotWind SCDS can play a role.

When discussing the implementation of these planning mechanisms and their impact on local content in offshore wind, it is important to remember that the legislation behind them does not, and cannot, mandate a level of local content due to World Trade Organization (WTO) rules[22]. It follows, then, that these policies are essentially setting good practice guidelines for the industry on local content — with guidance that the desire is for more content to be sourced from the UK. By increasing the transparency, and visibility, of supply chain planning by developers through the publishing of SCP and SCDS, the aim is that the industry will organically develop and the market will then choose more UK content of its own accord. The view that developers take of government mandated supply chain planning requirements may also play a role here, impacting on the potential local content and economic benefit that can be achieved. However, it has been previously discussed, and shown by Allan et al. (2020), that even a passive approach to local content can bring a boost to GVA and employment.

To reach the target of 60% local content by 2030, the SCP and SCDS mechanisms cannot be relied upon alone. The remainder of this discussion section touches on some key areas where support or policy action could be targeted to help develop the

[21]The period since the Offshore Wind Sector Deal has, of course, been influenced by external factors such as the Coronavirus pandemic, delaying the development of many projects.

[22]As discussed in Section 5.2.4.1.

UK supply chain, and ultimately assist in meeting the goal of 50GW of offshore wind by 2030 with higher levels of local content across the sector. Two main factors are proposed, with investment into the domestic supply chain the focus of Section 5.4.1; and the matter of a realistic project pipeline in Section 5.4.2. The latter is further split into three categories, namely: project approvals and grid connection in Sections 5.4.2.1 and 5.4.2.2 respectively, and improvements to port infrastructure in Section 5.4.2.3.

5.4.1 Supply Chain Investment

Arguably the most crucial element in the drive for increased levels of local content in UK offshore wind farms is the development of the domestic supply chain, where a greater number and diversity of businesses should naturally lead to an increase in competitiveness and market share for UK companies (RenewableUK 2024). Investment has been casually mentioned in government strategies and plans for a number of years, but there has been very little in the way of concrete policy action or commitments. Ultimately, an appropriate description for the position of the government to date has been to follow a market-based approach, where the aim is that business will organically develop to serve the needs of industry — but a more systematic approach between government and industry will be required for future growth (OWIC and OWGP 2023). While UK content is well represented in the development stage of offshore wind projects, with estimates of 72% in recent projects and 91% of development spend across the ScotWind projects committed to the UK[23], it has long and repeatedly been shown that domestic capability is lacking in other stages, with manufacturing in particular an area where much improvement could be made. As such, there is clearly a disconnect between market incentive for investment and the desire for more local content; and without specific, and targeted, investment it will be difficult for the sector to ramp up. If the 60% target is to be met by the end of the decade, the landscape is going to have to change — and change quickly.

[23] Estimates from BVG Associates (2024b) and ScotWind SCDS (Crown Estate Scotland 2023e).

While developers are increasingly open to investing outwith their direct supply chain — as evidenced in Section 5.3.2.2 where some ScotWind developers have committed a combined £51m extra into skills training, metocean research, and supply chain stimulus funds — relying too heavily on these sorts of altruistic investments is not sustainable. If market financial conditions were to change, it could be expected that additional funding of this nature would be one of the first cuts made by a private business to reduce expenditure. In many cases, government is better placed to provide assistance, especially in larger scale projects such as port infrastructure — an area that has consistently been highlighted as in need of investment since 2010[24] (OWIG 2010).

Regarding direct investment into supply chain businesses, it is key that any investment is made into the most appropriate areas. In certain project stages there are well established companies which are deeply embedded within the global offshore wind supply chain, and it would be incredibly difficult for a new business to compete here — for instance, Siemens Gamesa and Vestas in turbine manufacture. However, with sufficient levels of innovation in the UK, and appropriate support, this may not be impossible (RenewableUK 2024). Additionally, there are examples of these incumbent, multinational companies investing in bases or factories within the UK. The literature review in Chapter 3 of this thesis touched upon studies of local content requirements (see Section 3.3), with the general finding that subsidiaries of foreign suppliers have often been the main route for increasing local content levels in developing markets (Hansen et al. 2020). While the ultimate headquarters of the business may not be based in the UK and as such their investment is sometimes the focus of criticism, facilities like these can still bring jobs and economic benefit to the UK.

There are plenty of other opportunities where focusing investment could encourage growth, with the development of floating wind technology an obvious example. It has been highlighted that the UK has the expertise to become a dominant force in the nascent sector, as discussed in Section 5.2.3, and dedicated effort now to be early adopters of the technology will help to not only develop the industry here, but also

[24]Improvements to port infrastructure are discussed in more detail in Section 5.4.2.3.

enable the UK to export that experience to foreign markets (SOWEC 2021; OWIC and OWGP 2023). Returning again to the literature review of Section 3.3, early adopters have previously been found to be more successful at developing, and maintaining, local content, so this could be a key avenue for meeting the UK target of 60% (Scheifele et al. 2022). It is promising that the INTOG leasing round opened the opportunity for more small scale floating wind projects to get approved, and essentially work as a testing ground for bigger projects in ScotWind and Celtic Sea to follow.

Generally speaking, targeted assistance for the domestic supply chain would be expected to help its development, and ensure that companies can compete fairly for contracts on new offshore wind projects in the UK. This way, higher local content should be achieved organically without mandating shares and falling foul of WTO rules. However, this will only work if there is a market for the supply chain to deliver into. Government must keep up the progress on leasing and approving new offshore wind farms and, importantly, ensure that conditions are such that the projects actually come to fruition.

5.4.2 Project Pipeline

Returning to the ScotWind SCDS discussed in Section 5.3, across the projects the UK content commitment varied between 32% and 68%; with an overall UK content of 49% when all committed expenditure was combined[25]. Whilst ambition spend was also outlined for each project, the committed expenditure represents what developers viewed was possible at the time of the ScotWind application. Coming after the Offshore Wind Sector Deal, these figures generally fall far short of the 60% target set for new projects by 2030. In order for the ambition figures to materialise, the supply chain in the UK will have to develop from its current state. It was discussed earlier in this chapter, as highlighted in publications from as early as 2010, that demonstrating a clear pipeline of projects is crucial for the development of a successful supply chain. The delays

[25]Excluding four projects which withheld non-UK spend.

and cancellation of a number of Scottish projects throughout the 2010s undoubtedly influenced the supply chain in Scotland, with BiFab[26] a prime example of a business failing when contracts dried up. The ScotWind SCDS then should be viewed as a positive step. The plans have been requested from developers at the very earliest stage of development and published freely for the wider industry to see, allowing investors a view on the potential market that could be available in the coming years. This is one area where there could be an advantage to the ScotWind method as compared to the CfD SCP which is produced at a much later stage of project development.

Even with this forward view, risk remains that not all of the ScotWind projects will come to fruition, especially when market constraints and external drivers such as inflation are taken into account. This remains a danger for businesses hoping to serve the ScotWind projects; though considering the wider 50GW target for the UK, enough projects may be going through the development phase in the UK as a whole to offset any loss in the ScotWind capacity. However, it has been shown that Scottish content is not well represented in offshore wind farms in the rUK market — meaning there could be additional risk to Scottish businesses if projects in Scottish waters do not come to pass, compared with businesses based in England and Wales (BVG Associates 2021b).

Beyond elucidating a pipeline of projects, there are other actions that could be taken to assist the UK supply chain and, by extension, increase levels of local content in UK offshore wind farms. Chiefly, ensuring that projects actually progress through to operation. Whilst there are external factors to this that cannot be controlled (for instance, the global financial situation or policy actions taken by other countries), there are elements where policymakers and those in charge of infrastructure in the UK can influence matters. The remainder of this section details three key aspects of project development which have frequently been highlighted as bottlenecks to the progress of the sector, and are areas where effort should be focused to ensure that the collective goals of government and industry can be met. Firstly, improvements to the project approvals process are discussed in Section 5.4.2.1, before matters relating to connecting

[26] As discussed in Section 5.2.4.1.

to the electricity grid are outlined in Section 5.4.2.2. The discussion is concluded by Section 5.4.2.3, which reviews the readiness of UK port infrastructure for the expected scale-up of capacity.

5.4.2.1 Project Approvals

Consent approvals have previously been highlighted as one of the main barriers to deployment of offshore wind due to the speed of the process (OWIC 2024). A crucial aspect required before a new project can break ground, the time taken to grant approval averaged around four years in 2023 (NIC 2023). While it is clearly important for due diligence to be performed during the consenting process, with many considerations requiring attention, the timescale for decision making is putting the UK's ambitious capacity goals at risk. For instance, delays in the approvals process in early 2024 meant that the proposed 4.1GW Berwick Bank wind farm in Scotland and the 717MW Sheringham and Dudgeon Extensions combined project were unable to bid into AR6 of the CfD scheme which closed to applications in April 2024 (BBC News 2024; Planning Inspectorate 2024). The almost 5GW of capacity of these projects could have represented a positive step towards the target of 50GW by 2030, with the projects now having to wait until AR7 or beyond before applying for CfD funding.

This issue was one of those highlighted by the Offshore Wind Industry Council in their report on Policy and Legislative Barriers to Offshore Wind Consenting (OWIC 2024). The report argued that the lack of coherence between the elements of offshore wind consenting should be remedied in order to optimise the consenting process, with the misalignment of the consenting and CfD processes one of the issues spotlighted. A study by the National Infrastructure Commission (NIC) on the consenting process for Nationally Significant Infrastructure Projects in the UK also highlighted inefficiencies in the system — with co-ordination of environmental assessments between multiple offshore wind farms in a similar area presented as one way to streamline the process (NIC 2023). Outside of the UK, the EU Renewables Directive sets out that all renewable energy permitting should be carried out within two years, with improvements in permitting times seen across EU member states since its revision in 2023 (WindEurope 2024b). Though the British Energy Security Strategy (BEIS 2022a) stated the aim to reduce the time of consent approvals from four years down to one, no specific legislation has yet been put in place in the UK to enshrine the time limit in law. If improvements are not seen, following the example set by the EU could encourage consents to be granted quicker and ultimately help to meet the 2030 capacity and local content goals.

5.4.2.2 Grid Connection

A further consideration to raise on the subject of ensuring that projects progress through to the operational phase relates to challenges with the electricity grid, with grid access highlighted as one of the biggest challenges to the growth of renewable energy across Europe (WindEurope 2024a). The National Grid in the UK was the first integrated national grid in the world when it was established in 1935, transmitting the power generated in Britain's network of coal-fired power stations to centres of demand (National Grid 2024b). By the 1950s, the electricity demand of the UK was exceeding what the original grid could deliver, and a series of upgrades began to be carried out which saw the installation of 275kV and 400kV cabling to carry power across the country. Much of the infrastructure which was built during this period is still existing today, with limited development or investment in the decades since.

The energy landscape today is significantly different from that in the 1950s, with large, centralised power stations making way for a de-centralised energy system increasingly made up of renewable energy sources like wind and solar. Much of the UK's wind energy capacity must be harnessed from areas such as the North Sea off the coast of Scotland, and then transmitted great distances by cable to the main population and demand centres such as London. Currently, this means that the majority of that power generated in the north of GB has to be transmitted south through only two on land 400kV cables across the Scotland-England border. This limited transmission capability means that bottlenecks frequently occur on days when there is high wind generation, with wind operators often required to curtail their output so as not to overload the grid. The National Energy System Operator (NESO) must balance supply and demand on the grid at all times, and they make constraint payments to generators who are asked to curtail their output behind a grid constraint[27]. Additionally, they must also pay generators to come online and meet demand beyond the constraint point. From an economic standpoint this behaviour comes with a cost to NESO[28], estimated at £1.4bn for the financial year 2023 to 2024 (NESO 2024). Paying for fossil fuel generation at times when there is plentiful renewable generation is also contrary to net zero goals and the transition to cleaner energy sources. The issue of grid capacity and curtailment is not exclusive to wind generation, but the characteristics of the technology do mean that it is highly affected. With around 15GW offshore wind currently installed in the UK, and the target of 50GW by 2030, it is clear that these problems will only get more severe as more capacity comes online — without even considering other generating technologies in the scenario[29].

There is one additional, but intrinsically linked, point to consider on grid issues; that is, the challenges around securing a grid connection. Highlighted as the main barrier to renewable energy deployment by WindEurope (2024a), the issue in the UK is exacerbated by the ageing and at-capacity grid. With limited capability for new grid connections to be approved, the queue of projects (not exclusively renewables) waiting to join the transmission network is estimated to reach 800GW by the end of 2024 (ESO 2024). This backlog means that there are projects which may be ready to generate in the coming years but have been offered grid connections in the mid-2030s. Work is ongoing between NESO and Ofgem, the GB energy regulator, to reduce this bottleneck and ensure that projects which are ready to generate will be given priority for grid connections ahead of so-called 'zombie' projects — those which are taking up

[27]The level of payment is correlated to the capacity they are asked to reduce and the value of generation payments lost during the curtailment period.

[28]These costs are ultimately passed onto consumers as network costs on their energy bills.

[29]While not explored here, options for long-duration energy storage (such as batteries or pumped hydro) offer a possible way to offset the impact of excess energy generation on the grid.

space in the queue but will not meet any grid connection date they are offered (ESO 2024). The proposed changes to the system will follow a “First Ready, First Connected” approach, with attention also given to how a project meets certain strategic criteria such as technology type or location.

While this will help with the volume of projects in the queue for grid connection, wholesale improvements and extensions to the grid will also be required if there is to be hope of realising offshore wind capacity goals. If the capability of the transmission network is not improved upon, reducing the lengthy waits for grid connection and frequency of curtailment for operational projects, much of the incentive for new developments to progress will be lost. This will have a knock-on effect to anything which is reliant on the development of these projects — employment, investment, and the supply chain which has developed on the understanding that projects will come to fruition. Therefore, to guarantee local content in new developments and the resultant benefits to the UK economy, grid investment and upgrades must happen at pace and at scale. Some green shoots of progress can already be seen, with National Grid committing to £60bn investment by the end of March 2029 (National Grid 2024a). The ‘Great Grid Upgrade’ project is expected to support 55,000 new jobs by the end of the decade, and facilitate the transmission of the 50GW of offshore wind targeted by the government (National Grid 2024b). Progress will not be easy, given the scale of infrastructure intended to be added and updated, and the possible public backlash to the construction of new cabling and pylons, but it is a necessary step to transform to an electrified energy system.

5.4.2.3 Port Infrastructure

A final key area of development to enable the full potential of the UK offshore wind sector is the matter of port infrastructure. Ports play a key role in both the manufacturing and O&M stages of a project (OWIG 2010). Due to the size of many offshore wind farm components, it is often more suitable for their manufacturing and assembly to be carried out near the coast and with accessible ports because of the difficulty in transporting them by road or rail. Components may also be assembled in port and then transported to the project site for deployment, to minimise the work carried out off-shore (Akbari et al. 2017). Once the wind farm is operational, a port is required within sailing distance of the project site to enable transfer of crew and parts for maintenance purposes (Crown Estate Scotland 2020a).

It was highlighted even in the earliest supply chain publications discussed in Section 5.2 that suitably capable ports and harbours would be required in order to maximise the UK supply chain and the growth of offshore wind generation (OWIG 2010). Well over a decade later, the lack of appropriate port infrastructure remains a key barrier to developing the sector to meet the 2030 installation targets and the wider net zero transition goals of the UK. For instance, it has repeatedly been emphasised that floating offshore wind has a crucial role to play in decarbonising the UK energy sector, but concerns have been raised that there are currently no UK port facilities which have the requirements for facilitating a commercial scale project (Crown Estate Scotland 2020a; RenewableUK 2023). Floating wind offers a benefit over its fixed-bottom counterpart in that much of the assembly and integration of the turbine and foundation substructure can be done close to shore, in port, and then towed to the project site — minimising the scale of work required at locations with deep water and far from the coast. However, this requires suitably deep-water ports, and for substantial amounts of land to allow for heavy cranes and the manufacture or storage of components.

If the sector hopes to scale to meet 2030 targets and beyond, significant improvements, and potentially new developments, need to be initiated through the impending years. Progress has already started to be made from a policy standpoint, with the Celtic Sea leasing round (discussed in Section 5.2.4.4) the first for England and Wales to feature an aim on supporting the expansion of the domestic offshore wind supply chain — with port infrastructure a particular focus (The Crown Estate 2023a). As no ports in the region of the expected Celtic Sea wind farms are currently capable of meeting the requirements for the projects, as part of the seabed leasing round The

Crown Estate will require prospective bidders to specify their preferred ports and commit to invest in their development. The aim with this condition is to ensure that early investment will be targeted to develop facilities which would have a role to play in the growth of the UK offshore wind industry, and signal further opportunities for investment into the wider supply chain. Further investment into UK ports has already been committed by the government via the Floating Offshore Wind Manufacturing Investment Scheme (FLOWMIS), which granted up to £160 million to support the growth of port infrastructure, while additional funding is targeted via the UK & Scottish National Infrastructure Banks in the form of guarantees (RenewableUK 2024). While these commitments are a good start, there must be follow through on the longer term aims for the development of port infrastructure. Appropriate facilities can be an enabler for growth in the rest of the supply chain, and for the deployment of offshore wind on the scale required for net zero, so action should be taken as quickly as is feasible to ensure that the opportunity available is not missed.

5.5 Conclusion

In recent years, the emphasis on developing the UK supply chain for offshore wind has grown, with increasing awareness of the potential economic benefit that can be delivered by higher levels of local content. Throughout this chapter, it has been shown that the policy landscape regarding the supply chain of offshore wind has transitioned since the early days of the sector when the main aim was to grow the installed capacity and demonstrate how the technology could help move UK electricity generation away from fossil fuels. When the industry developed through the 2010s, there was consensus across both business and government that investment in the domestic supply chain was key if the sector was to continue to grow and that a clear pipeline of projects should be demonstrated in order to encourage businesses to invest.

With around 50% UK content in new offshore wind projects today, improvement needs to be seen across the supply chain in the coming years to meet the government target of 60% local content by 2030. From a policy standpoint, the Supply Chain Plan and Supply Chain Development Statement mechanisms that have been implemented in recent years are some of the first attempts to enshrine supply chain planning in law, and aim to increase transparency by illustrating the potential expenditure of new offshore wind projects in development. While there is no mandated level of local content for developers to source under the mechanisms, there is accountability as contractual penalties may be applied if committed local content levels in the original plans are not adhered to.

Ultimately, to grow both local content and the installed capacity of offshore wind, a holistic and multifaceted approach is required. Direct government investment into the supply chain is likely needed to establish new businesses and enable them to compete for contracts on the wider market, with floating wind technology a key area where gains could be made. However, investing into the supply chain without ensuring there are enough projects to compete for is doomed to fail. A pipeline of projects must keep being demonstrated, but key to this is also ensuring that proposals actually progress through development and come to fruition. Avoidable delays in the consenting or grid connection approvals process and failure to effectively develop port infrastructure will hamper progress, and make it increasingly difficult to meet not only the local content and offshore wind capacity targets for 2030, but the wider net zero goals.

Chapter 6

Economic Analysis of ScotWind Investment and Impact of Delays

6.1 Introduction

The ScotWind leasing round, completed in 2022, resulted in twenty successful offshore wind projects being granted Option Agreements to develop seabed areas in Scottish waters. With a proposed installed capacity of nearly 30GW, and a combined potential investment to the UK of £42bn[1], there is scope for significant impact to the UK economy if these projects all come to fruition. These projects were discussed in detail throughout Section 5.3 of Chapter 5, as the Supply Chain Development Statement (SCDS) supplied by the projects during the leasing round represents one of the key mechanisms for supply chain planning in the UK to date. The focus in the previous chapter was on details such as the local content commitments of the projects, and analysis of the spread in investment across lifecycle stage and location, with a view to understanding how the commitments made by the ScotWind projects aligned with the UK Government targets for local content and supply chain development.

[1] In 2021 prices.

Extending from the previous discussion, the aim of this chapter is to analyse the potential economic impact of investment into the UK supply chain from the growth of the offshore wind sector. The proposed investment of the ScotWind projects will be used to represent the change in demand on the economy that could be expected as the UK scales up the offshore wind sector to meet its target 50GW of installed capacity by 2030. Applying an ex-ante economic analysis, the possible GVA and employment impacts of the investment will be assessed, considering both direct and indirect effects on sectors across the entire UK supply chain. Furthermore, given the challenging conditions facing the offshore wind sector globally, as discussed in Chapter 5, the possibility of project delays and the potential difference this could make to the economic benefit achieved by the UK are also captured by the analysis.

The remainder of this chapter is outlined in Figure 6.1 and presented as follows: firstly, this introductory section is completed by a review of the salient academic literature on the economic modelling of renewable energy investment in Section 6.1.1, and a brief outline of the novelty of this work in Section 6.1.2. An overview of the input-output methodology followed for this study is then provided in Section 6.2, detailing how the proposed ScotWind investment was treated as a demand shock into the UK economy to determine the potential impact to GVA and employment. The data utilised within this study is outlined in Section 6.3, where the attribution of the proposed spend across the sectors of the economy and through time are also discussed. Section 6.4 follows, with the results of the analysis presented across four distinct scenarios which assess the possible differences in economic impact between project stages and if investment were to be delayed. The chapter is concluded by a summary in Section 6.5.

6.1.1 Literature Review

It has previously been demonstrated, through a literature review of the economics of the energy sector in Chapter 3 and in support of the Structural Decomposition Analysis (SDA) work in Chapter 4, that IO analysis has been widely employed in the study of

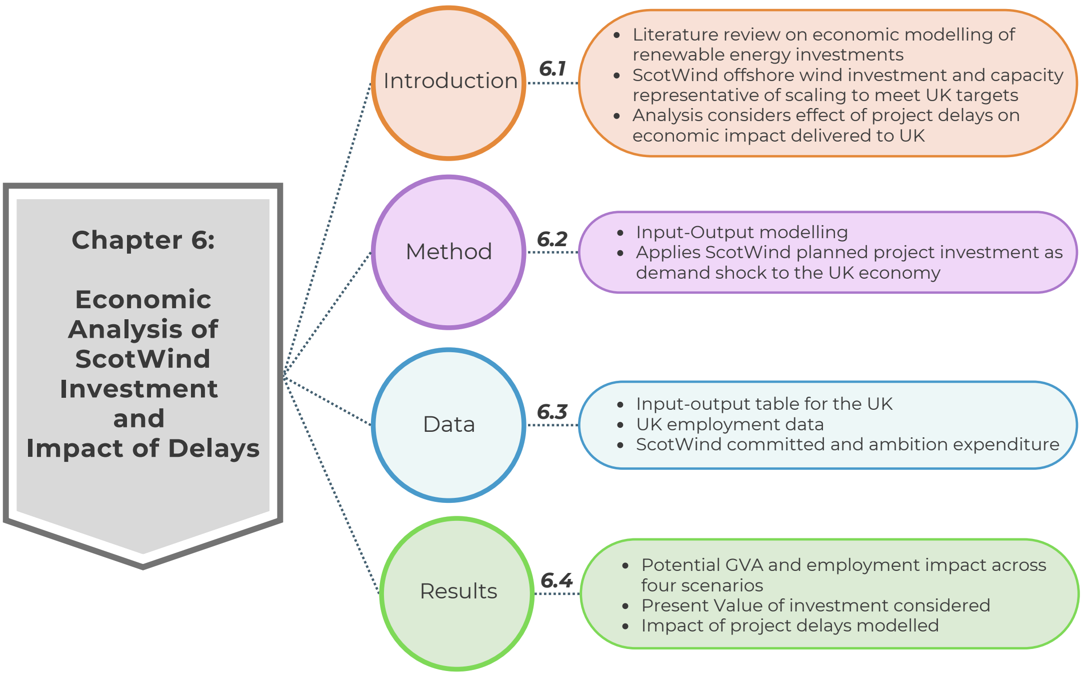

Figure 6.1: Chapter 6 structure and highlights

the impacts of offshore wind energy. One area where it is of particular use is in the consideration of the potential impact of a new investment into the economy, for instance to find the impact of a wholesale development of a particular industry or on the smaller scale of an individual project.

The benefits of employing IO analysis for these sorts of assessments is that the method allows for the macroeconomic impacts across all industries to be modelled, through the inter-sectoral relationships embodied in the structure of IO tables. When expenditure is made into a given industrial sector, or range of sectors, the effects of this investment are not isolated to that sector. In order to create their output, all sectors require inputs from a range of other sectors across the economy, who - in turn - require inputs from others. Due to the interconnectedness of the economy, it is not only direct impacts that are seen in the sectors receiving new investment, there are also knock-on, indirect effects across many other sectors. This is oft highlighted as one of the main advantages of utilising IO to assess economic impacts to metrics such as GVA or employment (e.g. Garrett-Peltier (2017), Henriques et al. (2016)), and was the basis behind a recommendation in a study from the International Energy Agency (IEA) for its use in the analysis of employment impacts of renewable energy generation (IEA-RETD 2012). IO allows for the total potential impact to the economy to be assessed throughout the supply chain, and is illustrative to policymakers in demonstrating the true benefits of investment and also where support should be placed to maximise the achievable benefit.

However, there are drawbacks to the IO methodology. Firstly, the underpinning assumptions of IO could represent a shortcoming in the method, depending on the aims of the analysis[2]. Under IO, the main assumptions are that: technical coefficients (representative of the pattern of inputs to a sector) are fixed; there are no supply constraints (meaning that any additional demand can be fulfilled); and there is no substitution of inputs (Markaki et al. 2013; Allan et al. 2014b). Furthermore, the lack of disaggregation of the energy sector in typical IO tables means that there are challenges in analysing the impact of changes within the electricity sector, or in a specific technology such as offshore wind (Duarte et al. 2017; Allan et al. 2021). While this is crucial to note, it is not a consideration for the study within this chapter where the investment is allocated as a demand shock across sectors within the supply chain.

Computable General Equilibrium (CGE) modelling is often proposed as an alternative method to IO, as it allows for restrictions in the supply chain and for the input mix to change when the level of output required is altered (Allan et al. 2014b; Connolly 2020). However, while CGE analysis could overcome some of the drawbacks of the IO method, and could equally provide information at a sectoral level, it is recognised that there is a higher burden of data and computational analysis with the technique versus the comparatively simpler data requirements of IO (Garrett-Peltier 2017). Considering the relative advantages and drawbacks of the two methods, covered in more detail in Appendix A.3, IO was chosen as the preferred method for this study. While both methods and data are compatible with the desire to assess the sectoral supply chain

[2] Appendix A.1.3 provides a summary of the challenges and assumptions of IO in more detail.

impacts of the ScotWind project investment, the relatively lower computational burden for IO and the ease of presentation of the method to industry and policy stakeholders drove the selection.

Many papers have utilised the IO method to model the impact of the potential expenditure of renewable energy developments, considering it as an exogenous shock to the economy, represented as a change in demand. For instance, Garrett-Peltier (2017) performs a comparison of the employment effects from energy efficiency improvements, various types of renewable energy developments, and fossil fuel generation in the USA; creating vectors with exogenous demand change allocated to the sectors in US IO tables which would be expected to see investment in each of the cases. Similarly Markaki et al. (2013) create a vector of the spending expected under a number of ‘green' investments in Greece — such as renewable energy projects (e.g. on- and offshore wind, solar PV, hydro), building energy efficiency improvements, or low carbon transport. They also treat the expenditure, for both the development and operation stages, as a change in final demand into the existing economic structure, ultimately calculating the change in output and employment under different deployment scenarios. While both of these studies assessed the impacts from renewable energy developments in general, there have also been studies which focus specifically on the offshore wind sector. For example, Connolly (2020) considers the regional case study of offshore wind in Scotland, and notes how an exogenous change in final demand due to expenditure in the development, construction, and operation of offshore wind projects would stimulate changes in sectoral output across the economy — which could be analysed through the interconnectedness of IO methodology.

The same or similar methods have been widely applied in the field of renewable energy economics, with the connecting theme the benefit of using IO to assess sectoral impacts — and the importance of considering more than just the direct effects of investment. Some research has focused on the possible impact of the large-scale deployment of a specific technology such as wind energy (e.g. Faturay et al. 2020; Varela-Vázquez and Sánchez-Carreira 2017); while others considered the broader case of a wholesale development of clean energy per government policy (e.g. B. Luo et al. 2024; Lochot et al. 2024); or the narrower case of the impact of a specific project (e.g. Schallenberg-Rodriguez and Inchausti-Sintes 2021). The studies have spanned many geographical regions, with the aforementioned case studies covering the USA, Spain, Canada, France, and a regional assessment of Gran Canaria. The push towards clean energy is a global effort, with literature featuring similar methodologies also focused beyond the European and North American regions for countries in Asia and Africa (e.g. K.-Y. Wu et al. 2021; Lehr et al. 2016). With regards to the metrics assessed, there are analyses which focus on the economic impacts of renewable energy deployment such as GVA and employment (e.g. Henriques et al. 2016; Keček et al. 2019), while others extend the method to changes in emissions (e.g. Allan et al. 2020; Lochot et al. 2024).

One final consideration across some relevant studies found in the literature, is how the investment into the economy (and, by extension, the change in demand) will develop across the lifecycle of an offshore wind project. Separating temporary and permanent activities (i.e. CAPEX and OPEX), Varela-Vázquez and Sánchez-Carreira (2017) calculated the resultant employment from growing the offshore wind industry in Spain, in each year of their study. Similarly, Connolly (2020) separated the investment from the development of the Scottish offshore wind industry into DEVEX, CAPEX, and OPEX, sharing the expenditure across the years of each stage. For the CAPEX costs this involved splitting the total investment with a percentage allocated for each year, while the OPEX was set as a cost per MW for each year of operation. Schallenberg-Rodriguez and Inchausti-Sintes (2021) also split into project stages, for their case of a floating wind development in Gran Canaria, sharing the total investment across the CAPEX, OPEX and DECEX stages of the project lifecycle. Each of these studies produced a vector for the exogenous shock to the economy in each year of investment, calculating the impact per year through their respective projects. However, while both the sectoral and temporal impact was considered in each case, none of this research considered the present value of these investments — reflecting that money spent into the economy now is preferred, and is ‘worth’ more than the same expenditure in the future. When considering the lifetime of an offshore wind farm project, more than 30 years in the case of these studies, it could be argued that the same investment in absolute terms will vary in its value to the economy as time progresses.

6.1.2 Novelty

In this chapter, a case study of the potential economic impact of the investment from ScotWind is presented, with this work representing three novel contributions. To start, this is, to the author's knowledge, the first detailed economic study of the ScotWind projects in the academic literature. These twenty proposed offshore wind farms are expected at a cost of £76bn over their lifetime[3], with £42bn committed to be invested in the UK. Furthermore, the potential capacity of the combined projects is just below 28GW. As of December 2023, the UK had 15GW of operational capacity and a further 8GW in construction, with a government target of 50GW installed by 2030 (The Crown Estate 2024). As such, an analysis of the ScotWind projects could be viewed as representative of the possible impact from reaching the 2030 targets. By specifically focusing on the case of offshore wind development, this study is of interest to policymakers who have situated the technology as key in the UK's transition towards net zero.

Secondly, the investment data used for the case study is real, planned expenditure as outlined directly by each of the projects in the SCDS Outlooks they submitted to Crown Estate Scotland at the time of the leasing round. This data is publicly available, and the use of expenditure data that has been specifically committed by the proposed projects marks a departure from investment estimates employed by previous studies. In these cases, information may have been gained from an existing project which is then scaled to the required capacity, or by utilising average prices that have been aggregated by industry publications (e.g. Allan et al. (2020)). Monetary data in such transparent terms as with ScotWind is not typically available for other proposed developments or on such an aggregated scale, with its use in this case study a departure from the

[3] Up to and including the first six years of operation, per the expenditure outlined in the SCDS.

usual estimations. Assumptions are still made on the split of the spending across the sectors of the economy, and on the timing of the investment, as with other publications. However, the outright monetary value that will be introduced as the demand shock is based on planned industry investment with no qualifying assumptions.

Of increasing relevance to the development of offshore wind projects in the UK is the issue of project delays, with many factors combining to make this a pertinent topic for study. Firstly, there are bureaucratic factors such as delays for project approvals, with projects often waiting many years before they can commence construction, and the growing issue of the queue for grid connection — both discussed in Section 5.4.2. Additionally, the global supply chain landscape has changed significantly in the last few years, with inflation dramatically increasing costs and higher demand for limited manufacturing capability causing many bottlenecks (see Section 5.2.4 for more detail on challenges facing the supply chain). Despite these problems becoming increasingly prevalent in the offshore wind industry, both in the UK and further afield, the possible effect of these types of issues on the economic impact that could be achieved through offshore wind investment have not, to the author's knowledge, been modelled in the literature.

To that end, this chapter proposes the case where the investment for the ScotWind projects is spread over time — with the demand shock calculated for each year of expenditure. While other studies have calculated annual effects or the impacts per project stage, as discussed in the previous section, the novel extension within this work was to employ discounting to the annual shock so that the present value of the investment and impacts could be considered. This has allowed for an additional case to be modelled featuring the key contribution of this case study, which is an assessment of the impact of project delays on the economic benefit achieved within the UK as a result of the ScotWind investment.

The overall aim of this chapter is to analyse the potential sectoral impacts of the expected UK investment by the ScotWind projects, with the key contribution of demonstrating to policymakers the possible scale of economic impact that could be expected through developing the offshore wind sector to reach the 2030 targets. The interconnectedness of the supply chain is inherent in the IO model, allowing for effects across all sectors of the economy to be calculated. It is crucial for policy to understand the broader impacts of offshore wind investment, beyond solely the effect to the electricity sector and those industries which will see direct purchases throughout the lifetime of the ScotWind projects. Additionally, it demonstrates where emphasis should be placed to ensure that benefits are maximised, and highlights the importance of reducing delays — not only to reach installation targets and reduce reliance on fossil fuels sooner, but also to maximise the value of the impacts generated.

6.2 Method

This section presents the methodology followed in carrying out the case study, utilising IO modelling to assess how GVA and employment may be impacted by new offshore wind expenditure in the UK. The aim of this case study was to assess the potential economic impact of the UK investment proposed through the ScotWind projects. In simple terms, the ScotWind expenditure in UK businesses represents a change in demand on the economy. To meet the new demand, industries must increase their output — with this change in output requiring more employment to fulfil the orders and also stimulating a rise in GVA. In addition to assessing the possible GVA and employment impact throughout the period of investment, the effect of project delays on the level of economic benefit that may be realised was also analysed.

6.2.1 Input-Output Method

An Input-Output table details the intermediate sales, value added elements and final demand across all sectors of the economy in a given year. The remainder of this section outlines the IO methodology applied within this work, by treating the investment from

ScotWind as a 'shock' into the system contained within the IO table, and how the resultant impact of this investment on metrics such as employment and GVA was calculated.

In IO accounting, discussed in detail in Chapter 4, the output of the economy, $\mathbf{x}$, can be calculated via the matrix product of the Leontief inverse matrix, $\mathbf{L}$, and the vector of final demand, $\mathbf{f}$. As $\mathbf{L}$ captures fixed relationships between sectors, this product can also be used to calculate the change in output which is required to fulfil a change in final demand:

$$\Delta\mathbf{x} = \mathbf{L}\Delta\mathbf{f} \tag{6.1}$$

The investment from ScotWind takes the form of a vector[4], and represents a change in demand on each sector of the economy. Utilising this change in demand as $\Delta\mathbf{f}$ in equation 6.1, the change in output required from each sector to respond to the demand shock was calculated.

When considering the investment from a large-scale development such as an offshore wind farm (or series of offshore wind farms, as is the case here) the demand shock would not be expected to hit the economy as one lump sum, or even all within one calendar year. Furthermore, as the expenditure is spread over a number of years, the *present value* of the investment in each year will vary (Kumar 2016):

$$\Delta\mathbf{f}_{\text{t-PV}} = \frac{\Delta\mathbf{f}_{\text{t}}}{(1+r)^t} \tag{6.2}$$

Where $\Delta\mathbf{f}_{\text{t}}$ is the demand shock in year t (t = 0, 1, 2 etc.), r is the discount rate, and $\Delta\mathbf{f}_{\text{t-PV}}$ is the present value of the change in demand in year t, discounted to year *0*. The change in output triggered by the change in demand will also vary through time, as the investment is discounted for each subsequent year, and can be represented as:

[4] The creation of this vector is detailed in Section 6.3.2.

$$\Delta \mathbf{x}_{\text{t-PV}} = \mathbf{L}\, \Delta \mathbf{f}_{\text{t-PV}} \tag{6.3}$$

Where $\Delta \mathbf{x}_{\text{t-PV}}$ is the present value of the output in year t. While equations 6.2 and 6.3 allow for the calculation of the present value of each year of investment and the resultant change in output, it was also important to consider the cumulative impact of the demand shock over the lifetime of the ScotWind projects. Equation 6.3 can be extended to reflect the total change in output up to year n as:

$$\Delta \mathbf{x}_{\text{tot}} = \sum_{t=0}^{n} \Delta \mathbf{x}_{\text{t-PV}} = \sum_{t=0}^{n} \mathbf{L}\, \Delta \mathbf{f}_{\text{t-PV}} \tag{6.4}$$

Where $\Delta \mathbf{x}_{\text{tot}}$ is the present value of the total, cumulative change in output caused by the investment throughout the life of the ScotWind projects. It was assumed throughout the study that the production ratios contained within the Leontief inverse matrix would not change with time, following from the underlying IO assumption of fixed technical coefficients. While this is a simplifying assumption, most of the sectors receiving investment from the ScotWind projects are mature and unlikely to change their input structure significantly over the timeframe of the expenditure.

The IO method can be extended beyond solely the calculation of change in output, to a measure of metrics such as employment. Using this example, an employment-output coefficient (e_i) for sector i may be calculated as:

$$e_i = \frac{E_i}{x_i} \tag{6.5}$$

Where E_i represents the employment (i.e. number of jobs) in sector i, and e_i is then the number of jobs required to produce one unit of output from the sector. It follows that the change in employment ($\Delta\mathbf{E}$) due to a change in demand can be calculated through:

$$\Delta \mathbf{E} = \mathbf{e}\Delta \mathbf{x} = \mathbf{eL}\Delta \mathbf{f} \tag{6.6}$$

Where $\mathbf{e}$ is the vector of employment-output coefficients. From this, the change in employment in each year of investment can be calculated by substituting $\Delta\mathbf{x}$ as set out in equation 6.3, and the cumulative impact via equation 6.4. Similarly, the change in GVA was measured by calculating GVA-output coefficients from the initial IO data, and other metrics such as income or emissions could be treated in the same manner.

Only Type I effects were considered within the case study, i.e. direct and indirect effects. Direct impacts are seen only in sectors which receive the investment shock, while indirect effects are those which develop through purchases made by the sectors receiving the change in final demand. For example, the construction sector would be expected to see an increase in demand from the ScotWind projects. To create their output, the construction sector requires input from the plastics manufacturing sector, which in turn requires input from the petrochemicals sector, and so on. Whilst the plastic manufacturing and petrochemicals sectors do not receive direct investment from the ScotWind projects, in order to create the construction output, they *indirectly* increase their output. The total impact of the ScotWind investment is then the summation of the direct and indirect impacts across all 100 sectors within the IO table describing the economy.

Given the scale of the investment expected through ScotWind, and the general scaling up of the offshore wind sector to meet UK targets, it is likely that non-trivial induced impacts could be generated. These Type II effects, driven by changes in household income which is then spent back into the economy, have not been considered in this chapter and households were kept exogenous as part of final demand[5]. In this work, the focus was on the impact to the offshore wind supply chain and how spend in the development of new large-scale energy generation projects may impact industrial

[5]This is in line with the methodology followed by the ONS, where only Type I multipliers are produced (ONS 2022c).

production within the wider UK economy. As such, the analysis has not been extended to induced effects. This aligns with the stance taken in key policy publications such as the Clean Growth Strategy or Offshore Wind Sector Deal, which focused on the potential for direct jobs and the indirect employment and value that could be created through the supply chain when considering large scale investment to the renewable energy sector, but did not consider induced effects (BEIS 2017b; BEIS 2019c).

6.3 Data

Within this section, the three data sets utilised for the case study are outlined, namely: an input-output table for the UK; employment data for each sector corresponding to the IO table; and the project spend outlined in the SCDS of the successful ScotWind projects — each discussed in Section 6.3.1. The spending per sector, and how this was attributed across the economy, is presented in Section 6.3.2. Section 6.3.3 demonstrates the process followed for allocating the spending to each year of investment, while Section 6.3.4 closes by combining all of these aspects and defining the scenarios considered within the case study.

6.3.1 Case Study Inputs

The economic data that formed the basis of the GVA and employment metrics for the analysis was derived from the 2018 industry-by-industry IO table for the UK[6] (ONS 2022d). IO tables detail the sales and purchases between all sectors of the economy, value-added inputs like labour costs and taxes, and final demand from actors such as government and households. This table was also utilised for the analysis in Chapter 4, with detail on the aggregation of the table sectors discussed in Section 4.3. The resultant table covered 100 industrial sectors, listed in Table B.1 of the appendix, using

[6]The latest year of data available at the time of the study, as tables are published with a delay. Data up to 2021 is now available, though the ONS has advised that both 2020 and 2021 were non-typical due to the Covid-19 pandemic and should not be used to represent the usual UK economy.

the SIC 2007 classification to separate and group different types of economic activity.

Employment information for the UK was also gathered, in order to calculate possible employment impacts due to changes in the economy. A data set with job numbers for 2018 was utilised for consistency with the IO table — ensuring that employment levels were representative of the industry at the time (ONS 2022a). The published data contained information on full-time, part-time and total employment at a GB and UK level, with GB values provided down to a five-digit SIC code and UK values to three-digits. For confidentiality purposes, certain sectoral aggregations had their employment numbers withheld for the full-time versus part-time split. As such, the total employment value at the UK level was selected for the case study — comprising both employees and self-employed people, and both the public and private sector. In order to match the sectoral breakdown of the IO table, for a small subset of the sectors it was necessary to instead utilise the five-digit employment numbers provided in the GB table as the UK table was not disaggregated to the required level. This means that the employment figures used in the analysis presented within this chapter were slightly lower than the total employment for the UK in 2018 from the original dataset, though accounted for 99.991% of the overall total. After performing these steps, the result was a vector of total employment for each of the 100 sectors contained in the IO table.

The final input data to the case study analysis was the expenditure outlined by the twenty projects successful in ScotWind leasing Round 1, which was previously discussed in Chapter 5. The projects each submitted a Supply Chain Development Statement which outlined their committed and ambition expenditure across four main project stages and geographical regions[7] (Crown Estate Scotland 2023e). This planned expenditure was used as the input data to the case study analysis, with the investment representing a 'shock' to the economy which, in turn, would be expected to stimulate impacts in the GVA and employment seen in the UK. While the projects submitted updated versions of their SCDS in 2023, with slight changes in the planned investment

[7]See Section 5.2.2 for further detail on the SCDS requirements, and Section 5.3.1 for a high-level analysis of the planned expenditure of the projects.

for certain projects, the original SCDS submitted at the time of the original bids are used here — in line with the analysis presented in Chapter 5.

6.3.2 Sector Spend Allocation

The planned level of investment into the economy was taken from the SCDS of the twenty ScotWind projects, where the total project spend was outlined across four project stages (development, manufacturing, installation, and operations and maintenance[8]) and four geographical areas (Scotland, rest of UK, Europe, rest of World). For the purposes of this case study, the Scotland and rest of UK expenditure was combined into the overall spend in the UK as a whole. In order to assess the possible impacts of the investment, first, it was necessary to understand where across the economy the purchases would be made; and secondly to attribute this spend across the sectoral breakdown outlined in Section 6.3.1 such that it could be incorporated with the economic data from the IO table and the employment by sector.

6.3.2.1 Determining SIC Sectors for ScotWind Spend

The BVG Associates (2019) *Guide to an Offshore Wind Farm* details many of the stages and elements of an offshore wind farm and provides examples of suppliers for each aspect, as well as some illustrative costs for a representative 1GW offshore wind farm in the UK, comprising one hundred 10MW turbines. To determine which sectors would be expected to receive investment through ScotWind related purchases, the key suppliers suggested for each main project element in the *Guide to an Offshore Wind Farm* were matched with their business sector from the Companies House register (Companies House 2024). Businesses registered in the UK must file their accounts with Companies House, with information relating to the company available to search on the public register. Part of the filing involves the company divulging the nature of their business and selecting the five-digit SIC code that best reflects their activity. By

[8] O&M spend in the first 6 years of operation.

searching some exemplar suppliers for the main wind farm elements from the *Guide to an Offshore Wind Farm* on the Companies House register, appropriate sectors — in the same format as the IO data — could be ascertained for each project stage.

6.3.2.2 Allocating ScotWind Spend to Relevant Sectors

With the relevant SIC sectors established, the final step was to estimate the UK spend in each of these sectors by combining the indicative costs for each project element from the *Guide to an Offshore Wind Farm* with an appropriate UK share. As a basis, local content percentages for multiple offshore wind farm components proposed by Allan et al. (2020) in their assessment of how varying levels of local content in offshore wind farms affect the resultant economic and environmental impacts in the UK were used. In this study, both a low and high local content percentage were presented for each element, based on the supply chain plan of an installed UK project. The high percentage was aligned with a 52% lifetime total for UK content, broadly similar to the roughly 50% predicted for the aggregated ScotWind projects[9], so this was chosen as a starting point for the determination of possible ScotWind spend as the more representative of the two.

To ascertain how the ScotWind investment would be shared amongst the SIC sectors determined for each of the Development, Manufacturing, Installation, and Operations and Maintenance stages, the elements within each stage were compared with the representative local content levels taken from the Allan et al. (2020) study. For instance, from the *Guide to an Offshore Wind Farm*, procurement of wind turbines for a project accounts for around 60% of total manufacturing spend. However, it was discussed in Chapter 5 that the UK has little manufacturing capability for wind turbines, and this is evidenced by the 29% local content figure for turbine supply in the study used for reference here (Allan et al. 2020). Turning this example into a simple monetary form to demonstrate more clearly, if manufacturing spend is £100, then £60 of this

[9]See Section 5.3.2 for detailed analysis on the ScotWind project expenditure.

would need to be spent on turbines. However, only 29% of this £60 would be within the UK — while the remainder would go to businesses located elsewhere. This would leave approximately £17 being spent on turbine components within the UK, across all sectors which share the manufacture of these parts. Considering the representative costs of each component of a turbine, and the relevant sectors identified from company reporting of key suppliers, 89% of this example £17 would be attributable to sector C28[10], or around £15. As a result, when distributing the total ScotWind UK manufacturing spend to industry sectors, 15% was assigned to sector C28 to account for turbine manufacture. Considering each project element with this method in turn, a percentage allocation by SIC sector for each ScotWind stage was established and is shown in Table 6.1.

The same process was repeated to determine the sectoral percentage allocation for the 'Ambition' expenditure of the ScotWind projects, with the resultant values also presented in Table 6.1. For the ambition spend, it was assumed that the same sectors would receive investment as for the committed spend but with different ratios where necessary, reflecting the change in investment illustrated in the SCDS. For the Development, Installation, and O&M stages, the percentages for the ambition spend were kept the same as for the committed case. Whilst the absolute spend in the UK changed, the sector split for each stage was assumed to be unaffected. For instance, the Installation stage would still see spend on only construction and vessels — such that the relevant sectors receive the same relative percentage, but of a higher investment. The main change between the committed and ambition cases in the SCDS was in the investment into UK manufacturing, increasing from 57% of UK spend to 62% (Crown Estate Scotland 2023e). Through a review of the information provided in the SCDS on the ambition spend of the ScotWind projects, those projects which divulged specific plans detailed that were the local supply chain available, they would aim to source more of their foundations and floating wind structures from the UK market, utilise local vessels, and purchase elements such as cabling or turbine parts domestically. These

[10] C28: Manufacture Of Machinery And Equipment nec.

Table 6.1: ScotWind spend allocated to SIC sector – Committed and Ambition

Development		
SIC	Industry Sector	Com. *(Amb.)* [%]
M70	Activities of head offices and management consultancy	50 *(50)*
M71	Architectural, eng. activities; technical testing, analysis	25 *(25)*
M74	Other professional, scientific and technical activities	25 *(25)*

Manufacturing		
SIC	Industry Sector	Com. *(Amb.)* [%]
C25o.	Manufacture of fabricated metal products	20 *(17)*
C27	Manufacture of electrical equipment	15 *(18)*
C28	Manufacture of machinery and equipment nec.	15 *(12)*
C30.1	Building of ships and boats	10 *(11)*
C32	Other manufacturing	10 *(7)*
F	Construction	30 *(35)*

Installation		
SIC	Industry Sector	Com. *(Amb.)* [%]
F	Construction	75 *(75)*
H50	Water transport	25 *(25)*

Operations and Maintenance		
SIC	Industry Sector	Com. *(Amb.)* [%]
C33o.	Rest of repair; Installation	55 *(55)*
D35.1	Electric power gen., transmission and distribution	25 *(25)*
H50	Water transport	8 *(8)*
M70	Activities of head offices and management consultancy	3 *(3)*
M71	Architectural, eng. activities; technical testing, analysis	3 *(3)*
M74	Other professional, scientific and technical activities	3 *(3)*
N77	Rental and leasing activities	2 *(2)*
P85	Education	1 *(1)*

qualitative details were used to inform slight adjustments of the percentage spend in the sectors involved in the Manufacturing stage, with sectors relating to these elements receiving a boost and changing the ambition ('Amb.') percentages presented for the Manufacturing stage in Table 6.1.

These percentages were combined with the total UK spend in each of the four project stages to create a vector with the absolute investment due to the ScotWind projects into the 100 SIC sectors present in the IO table and employment data.

6.3.3 Spend per Year

To assess the potential economic impact of the UK investment by the ScotWind projects, four scenarios were analysed. Three of these utilised the combined £42bn committed expenditure of the projects, while the final considered the £57bn pledged in the UK under the ambition case (both in 2021 prices). To account for the spread of investment across different time periods, discounting was employed to convert the spend to its present value, capturing how impacts will vary through the lifecycle of the projects[11]. The effect of delays on the potential economic impact of the projects were also considered, to demonstrate whether this would make a material difference to the changes seen in the economy.

For a large-scale infrastructure project such as an offshore wind farm, the investment made through the life of the project will be spread across a timeframe spanning many years. As discussed in Section 6.2.1, these costs were discounted to their present value using (Kumar 2016):

$$\text{Present Value} = \frac{I_t}{(1+r)^t} \tag{6.7}$$

[11]While the project stages are discounted based on an estimated development timescale, this is not considered on an individual project basis. More than half of the projects did not divulge an expected project delivery date, so these have not been accounted for.

Where I_t is the investment in a given year, t, and r is the discount rate. The discount rate was assumed to be 3.5%, as set out in *The Green Book* for the appraisal of public projects (HM Treasury 2022). Discounting does not relate to adjusting costs for inflation, and instead represents the societal preference to receive value now rather than at a later date — with the discount rate also defined by HM Treasury as the social time preference rate. Previous studies (e.g. Allan et al. (2011)) have argued the use of alternative rates in discounting, such as the return on investment or weighted average cost of capital to better reflect costs for private businesses. The case study performed here aims to look at the potential impact of the ScotWind expenditure on the wider economy of the UK, as opposed to the cost for individual companies, and so the 3.5% social time preference rate was deemed to be most appropriate for this analysis.

To determine a timing estimate for the ScotWind investment, 2033 was taken as the representative operational year for the group of projects — based on the latest planned operational date[12] outlined in the SCDS (Crown Estate Scotland 2023e). The total investment for the ScotWind projects was assumed to be spread from year *0* to year *15*, as shown in Figure 6.2, with 2023 as year *0*. This includes six years of operational expenditure, in line with the SCDS, which only provided O&M spending for this time[13]. Each stage was assumed to begin after the previous stage was complete, and the total investment outlined for each stage in the SCDS was further assumed to be evenly split across the years spent on the stage.

In reality, there would be some overlap of expenditure, for instance some manufacturing procurement would be carried out whilst the development stage was ongoing, and some years would see a greater spend within a stage than others. However, the assumptions made here allowed for the impact of each stage to be seen more clearly, and not be clouded over by investment of a different stage that may be made in parallel. This would most notably be expected were cross-over between the development and manufacturing stages to be allowed as, with 8% and 57% of total ScotWind spend

[12] Of those projects which provided a date.

[13] The operational stage would be expected to continue beyond six years, or year *15* here, but the ScotWind expenditure provided in the SCDS covers only the first six years of O&M.

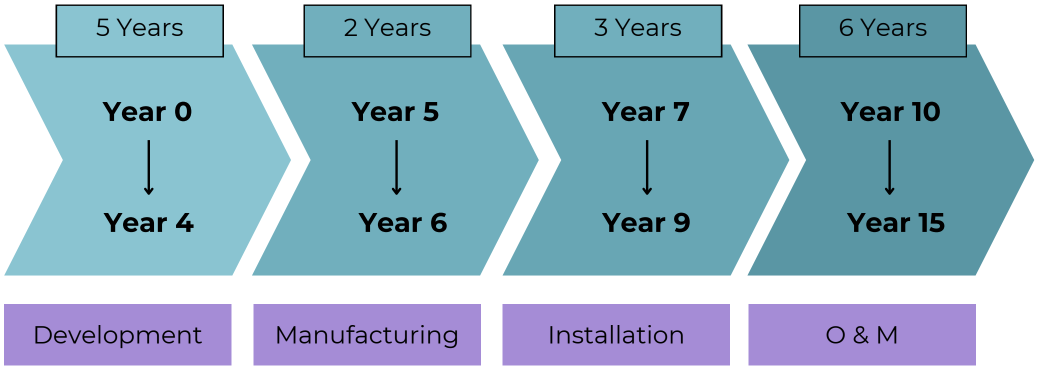

Figure 6.2: ScotWind stage estimated timings

respectively, any impact due to manufacturing activity could be sufficiently large as to hide the nuances of GVA or employment effects caused by development spend. Clearly there are some drawbacks to this method, as delaying investment until the previous stage is complete means that later spend will be more impacted by discounting. Nonetheless, for the purposes of the case study, an indicative response from the economy can still be determined.

Lastly, the impact of any delay to the investment was modelled. Under the initial assumption, all of the projects would be developed at the same rate and delivered at the same time. However, a more likely scenario is that some projects will experience delays which will put their expected investment further into the future. While there are many reasons for project delays (e.g. supply chain limitations, long waits for project approval), which would all lead to different spend profiles across the twenty projects, the purpose of incorporating some element of delay into the case study analysis was to demonstrate whether the expected impact on metrics such as employment or GVA within the UK would be materially changed when a project delay was incorporated. To account for this in the modelling, 50% of the total project spend for the ScotWind projects was delayed by five years. Here, the delayed expenditure was assumed to have the same sectoral spread as the non-delayed spend, though not starting until year *5* of the timeline indicated in Figure 6.2. It should be noted that this is not the same as delaying 50% of the projects, only £21bn of the overall investment. Across the

ScotWind SCDS, only eight of the projects specified a delivery date (with a range of 2027 to 2033). To avoid making assumptions on possible delivery times of particular projects or, for example, any likely difference between development of the fixed and floating technology types, the five years and 50% expenditure were selected purely as a representative estimate so that the impact of delays could be demonstrated. In reality, project investment and delivery dates would be spread across many years.

6.3.4 Scenarios

Combining each of the data sets and considerations detailed throughout this section, four scenarios were developed for analysis within the case study. These covered both the committed and ambition expenditure outlined in the ScotWind SCDS, and incorporated discounting of the spending through time and the potential impact of delays. The scenarios were as follows:

Scenario 1: The first, simplest scenario modelled the potential impact of the committed ScotWind investment if it were to be spent all in one year (year *0*) as a lump sum. This scenario provided a base level of impact which allowed for comparisons to be made with the results of other scenarios when varying factors were introduced.

Scenario 2: Assumed the ScotWind committed spend, with expenditure spread through the project lifecycle per the timeline indicated by Figure 6.2.

Scenario 3: Assumed the ScotWind committed spend, with 50% of the total expenditure following the timeline set out in Figure 6.2, while the remaining 50% was delayed by five years. The delayed 50% followed the same timings as for Scenario 2, but starting in year *5* and ending in year *20*.

Scenario 4: Assumed the ScotWind ambition spend, with expenditure spread through the project lifecycle per the timeline indicated by Figure 6.2 (i.e. Scenario 2 with ambition levels of investment).

Different assumptions could be made within any of these scenarios (e.g. differing lengths of time or delays) but the aim here was not to calculate an absolute impact for the ScotWind projects, only an indication of its possible scale and how this would be affected by delays. The analysis was intended to look more at the broad trends of where impacts may be seen across the economy, and the variation between the direct and indirect impacts in terms of scale and industrial sector. As such, the results should be taken as an illustration, indicative of what could possibly be achieved, not as the true outcome in terms of GVA or employment.

6.4 Results

This section presents the results of the analysis of each of the four scenarios outlined in Section 6.3.4, producing the potential change in output, GVA, and employment that could be expected from the investment committed by the ScotWind projects. The base case of a lump sum investment, Scenario 1, is discussed in Section 6.4.1; while Scenario 2, with the expenditure spread through time and the present value of the investment considered, is covered in Section 6.4.2. The direct and indirect impacts of the investment under Scenario 2 are analysed in Section 6.4.3, demonstrating how impacts are spread across the sectors of the economy. Section 6.4.4 presents how the economic benefit that could be gained through the ScotWind investment may be impacted were delays to affect the projects. Finally, Section 6.4.5 discusses how the GVA and employment effects may differ when considering the ambition spend of the projects.

A summary of the results is shown in Table 6.2, with the total change in output, GVA, and employment generated by the ScotWind investment in each of the scenarios. The present value of the investment in each case is also shown. It should be noted that in the case of employment, the figures provided for Scenarios 2, 3, and 4 are the change in employment that would be generated when considering the present value of the change in output. It is recognised that, for Scenarios 2 and 3, the 'undiscounted'

Table 6.2: Summary of output, GVA and employment results per scenario[14]

Scenario #	PV Spend (£bn)	$\Delta\mathbf{x}$ (£bn)	$\Delta\mathbf{GVA}$ (£bn)	$\Delta\mathbf{E}$ (1000 jobs)
Scenario 1	42.0	75.6	32.6	518.7
Scenario 2	33.3	59.7	25.9	416.7
Scenario 3	30.7	55.0	23.8	383.8
Scenario 4	45.3	82.1	35.3	562.1

jobs would match the employment change generated under Scenario 1 — where no discounting is taken into account. The discounted job figures are provided here, and discussed in the following sections, to illustrate the impact of delays on the economic benefit that could be delivered. The discounted employment for Scenario 4 (generated by ambition spend) is also presented in the table, to allow for comparison with Scenario 2 (the committed spend). The full results, with the calculated impacts for all 100 sectors contained within the IO table, are detailed in Table C.1 in Appendix C.

6.4.1 Base Case

Considering first Scenario 1, the case where all of the investment is spent as a lump sum with no element of time taken into account, the change in output ($\Delta\mathbf{x}$) across the 100 sectors of the economy due to the £42bn committed ScotWind expenditure was £75.6bn. Combining the 100 sectors into 19 industry sections[15], as summarised by Table 6.3, impacts were seen within each section. This is shown in Figure 6.3. The section which would be expected to exhibit the largest change in output was Section C (manufacturing), with Section F (construction) the second largest, accounting for 37% and 26% of the total change in output respectively. Both of these sections received direct investment in the calculation, but indirect impacts were also seen in sectors where no initial investment was made. Across the economy, 25% of the change in output generated was in sectors which received no direct purchases. For example, Section G

[14]Output and GVA in 2021 prices, consistent with publication year of SCDS.

[15]The full table of SIC sectors and corresponding section can be found in Table B.1 in Appendix B.

Table 6.3: SIC industrial sections of 2018 UK IO table

SIC Section	Description
A	Agriculture, forestry & fishing
B	Mining and quarrying
C	Manufacturing
D	Electricity, gas, steam, air conditioning supply
E	Water supply, sewerage, waste management, remediation activities
F	Construction
G	Wholesale and retail trade; Repair of motor vehicles, motorcycles
H	Transportation and storage
I	Accommodation and food service activities
J	Information and communication
K	Finance and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support service activities
O	Public administration and defence, compulsory social security
P	Education
Q	Human health and social work activities
R	Arts, entertainment and recreation
S & T	Other

(wholesale and retail trade) accounted for just below 5% of the total change in output, though none of the ScotWind purchases were made into the sectors of Section G. This demonstrates the importance of the knock-on effects of the initial investment, as non-trivial impacts are produced due to the interconnectedness of the sectors of the economy. Wholesale and retail trade, in particular, is an important sector within the UK economy, as all 100 sectors within the IO table aggregation use it as an input (including self-purchases by Section G). The relative shares of direct and indirect impacts of the ScotWind investment are explored in more detail in Section 6.4.3.

The Type I GVA and employment impacts under Scenario 1 are presented in Figures 6.4 and 6.5 respectively, with a total increase in GVA of £32.6bn and employment increasing by almost 519,000 jobs across the economy. The industrial sections experi-

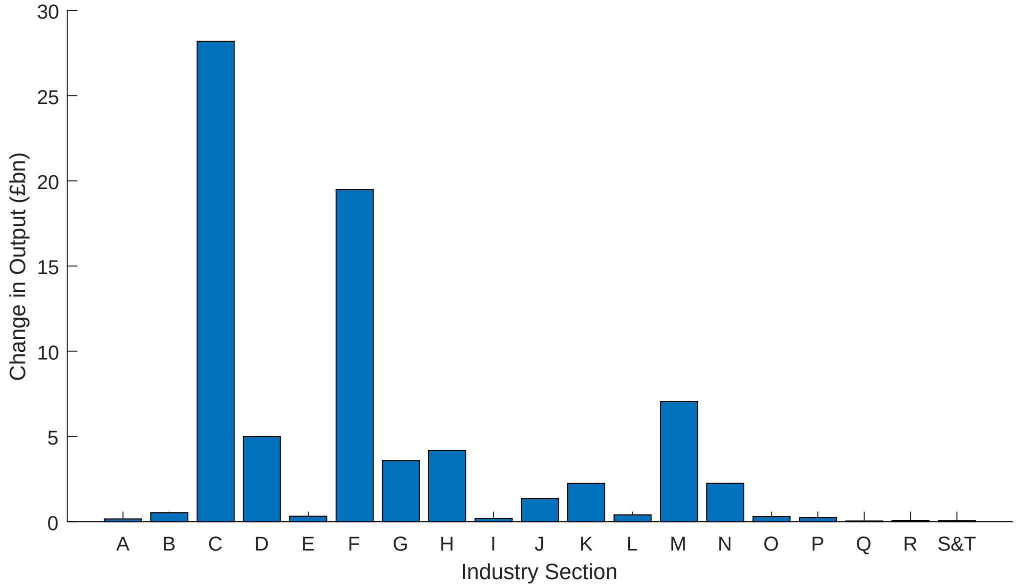

Figure 6.3: Change in output ($\Delta\mathbf{x}$) per industry section – Scenario 1

encing the most pronounced effects generally tracks the distribution seen in Figure 6.3 for change in output, as would be expected given they were calculated via the GVA-output and employment-output coefficients, but the scale of the impact per section (and per sector) varies between the metrics. This is reflective of the different labour intensities of each section, as some sectors of the economy require more jobs to create each unit of output than others. The most notable case of this from Figures 6.4 and 6.5 is for Section M (professional, scientific and technical activities) — with 9% of the change in output, 11% of the change in GVA, but 16% of the change in employment. Considering the initial ScotWind expenditure, 30% of the total committed spend was on construction in Section F while less than 10% was spent into Section M (mostly in the development stage) — but the resultant increase in number of jobs required in both cases is similar.

The same phenomenon can also be observed in the relationship between the bars for Sections F (construction) and G (wholesale and retail trade). These sections accounted for 23% and 6% of the total change in GVA respectively, broadly in line with the 26% and 5% shares of the total change in output. However, they accounted for 18% and 9%

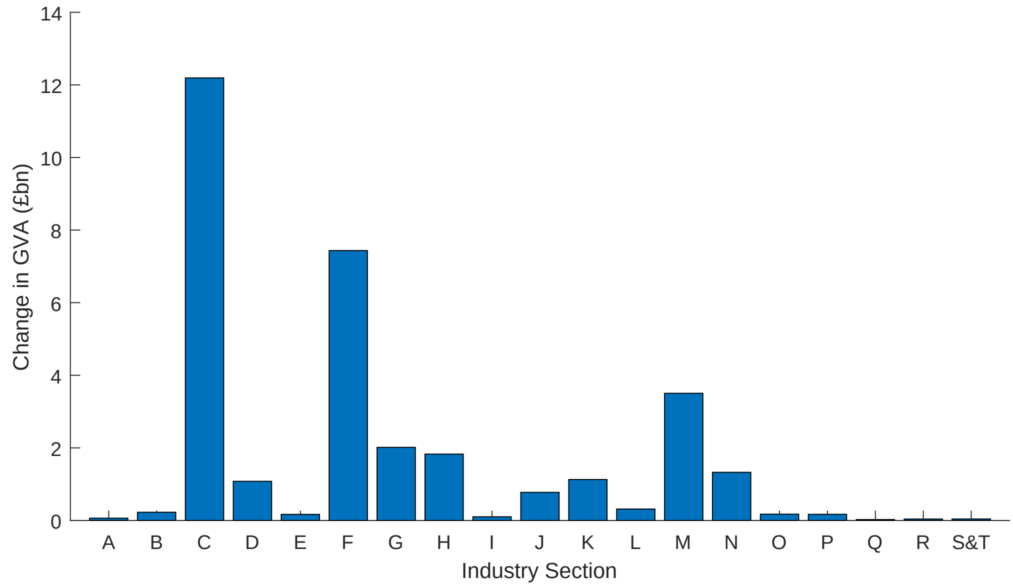

Figure 6.4: Change in GVA (ΔGVA) per industry section – Scenario 1

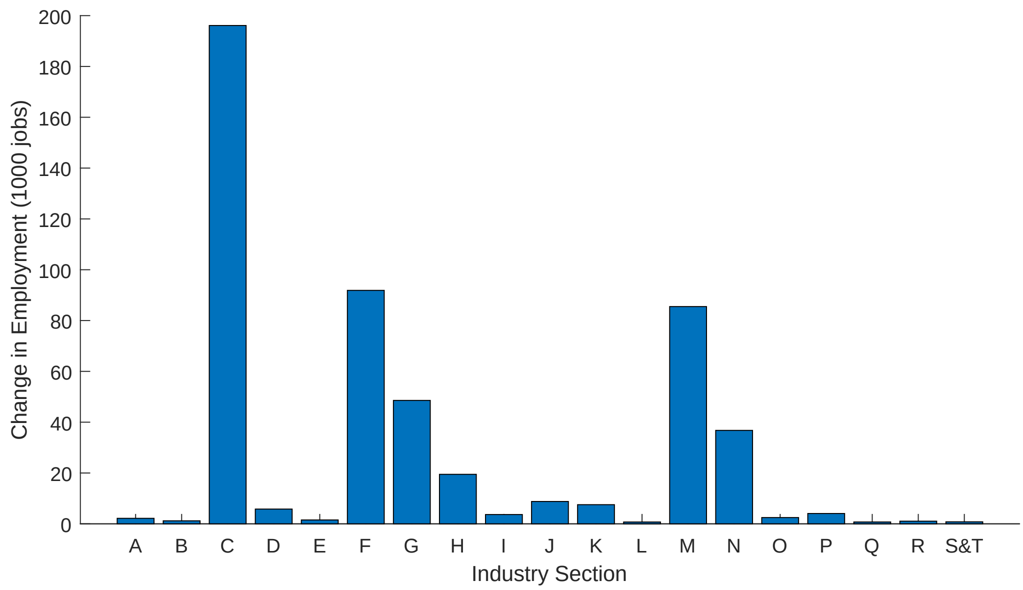

Figure 6.5: Change in employment ($\Delta\mathbf{E}$) per industry section – Scenario 1

of the total change in employment respectively. The labour intensity of Section G was almost three times as great as that for the construction sector[16], leading to a significant share of the employment supported by the ScotWind investment being generated in a section which received no direct impact. Aggregating across all 100 sectors, 28% of the change in GVA was generated in sectors outwith the direct ScotWind supply chain, and 31% of the employment. These are a significant share of the total economic impact, demonstrating clearly that investment in offshore wind can generate substantial production in industries which may not be classed as in the supply chain.

Clearly, the results demonstrated for GVA and employment through this scenario are large — as the investment committed to the UK under ScotWind is significant, and represents the wholesale development of the sector over a 15 year period. For context, consider firstly the UK investment of £42bn. Compared to the 2018 UK IO table, this represents a 1.1% increase of the total output of the economy for the year. For GVA and employment, the Scenario 1 results are around 1.6% and 1.7% of the 2018 totals respectively. While only a rough indication, the alignment of these values indicates that the scale of the impacts is broadly in line with the change in investment into the economy. Furthermore, the GVA result for Scenario 1 demonstrates a change of around £1.18bn/GW for the period covering up to and including 6 years of operation. By comparison, the recent UK Offshore Wind Industrial Growth Plan indicates that the sector contributes in the region of £2–3bn GVA per GW of installed capacity (RenewableUK 2024). It is assumed that this value covers the entire operational lifetime of a project, though it is unclear whether Type I or Type II impacts are being considered. Regardless, by order of magnitude the change in GVA generated under Scenario 1 within this chapter is in general alignment with the figure presented in the recent Plan. However, there is a discrepancy in the jobs figures presented, as the Plan indicates employment of around 120,000 direct and indirect jobs by 2035 with 45GW of offshore wind installed. Though not explicit, it is indicated that these figures have been extrapolated from a survey of businesses who identified as part of the offshore wind supply chain. This

[16]Based on the UK IO table and employment data of 2018, as discussed in Section 6.3.

misalignment reinforces the point made in Section 6.3.4, in that the results presented within this chapter should be taken as indicative. Value to industry stakeholders can still be gained from comparing the generated impacts through time, project stage and across Scenarios, demonstrating the broad trends that could be expected from the ScotWind investment.

6.4.2 Present Value: Impacts Over Time

As discussed in Section 6.3.4, whilst Scenario 1 can provide some indicative results on sectors of interest and a general idea of what impacts could be expected from the ScotWind investment, an extension to reflect the spread of the expenditure and increase in demand over time is more representative. Considering the previously outlined Scenario 2, the total change in output generated across the 100 sectors of the economy was found to be £59.7bn; a 21% reduction on the change in output from Scenario 1. The change in output of each industry section under Scenario 1 versus Scenario 2 is shown in Figure 6.6. The percentage change between scenarios was not constant across each sector and section of the economy, as some sectors saw more discounting of the investment they received since their purchases were not expected until later in the project lifecycle. For example, Section M (activities of head offices etc.) saw the lowest percentage change between Scenarios 1 and 2 of any sector; while Section D (electric power generation, transmission and distribution) saw the highest percentage change — these results follow from the majority of the Section M spend occurring in the development stage of the ScotWind investment, while the only direct spend into Section D did not occur until the O&M stage.

Considering the impact per year of the ScotWind project investment, Figures 6.7 and 6.8 present how the overall change in GVA and employment developed through time. At the end of the investment, in year *15*, the total, cumulative change in GVA across the UK economy was calculated at £25.9bn while the total change in employment

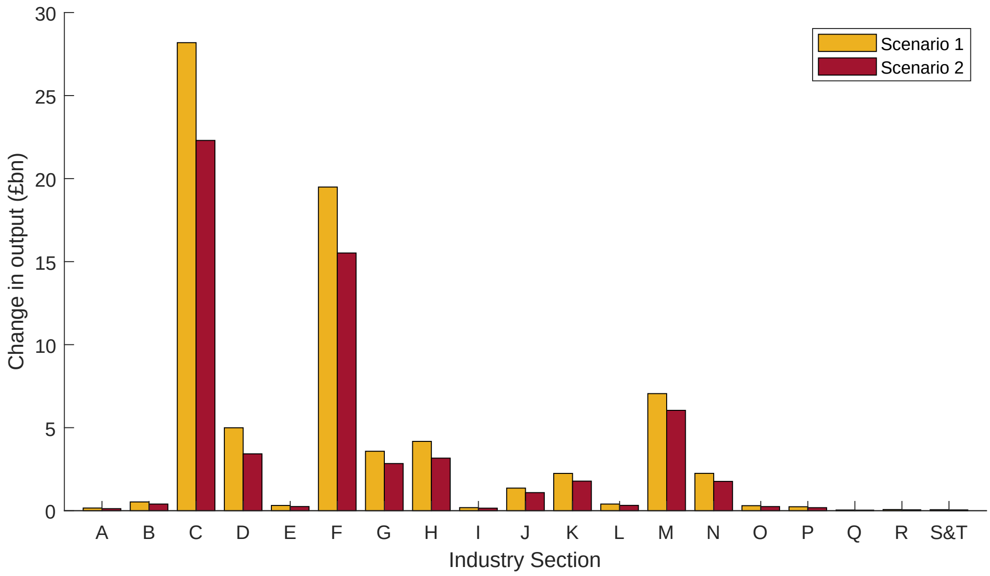

Figure 6.6: Change in output per industry section – Scenario 1 vs Scenario 2

was just below 417,000 jobs[17]. Compared with Scenario 1, these represent a 20.6% and 19.7% reduction respectively. The difference between the two metrics relates to the relative value added and labour intensities of the various sectors of the economy and the level of discounting applied to the relevant sectoral expenditure.

As evidenced in the figures, the largest step-change in both GVA and employment was seen in years *5* and *6* when the change in demand due to the manufacturing spend of the ScotWind projects was introduced into the economy. This type of peak would not be sustainable in reality, and is an artefact of the timeline selected for the case study with all projects developing concurrently, and each project stage consecutively. Whilst the demand-driven IO methodology assumes that all requests for an increase in output can be fulfilled, such a spike would be expected to cause problems for the supply chain were this to occur. Firstly, the two years of manufacturing spend indicate that 240,000 extra jobs will be supported across years *5* and *6*. While spread across all sectors, it would clearly be unrealistic for these jobs to be filled in such a short timeframe and for the work to be carried out within the supply chain to manufacture such a

[17]Discounted jobs. Undiscounted employment impact would be 518,700 as generated in Scenario 1.

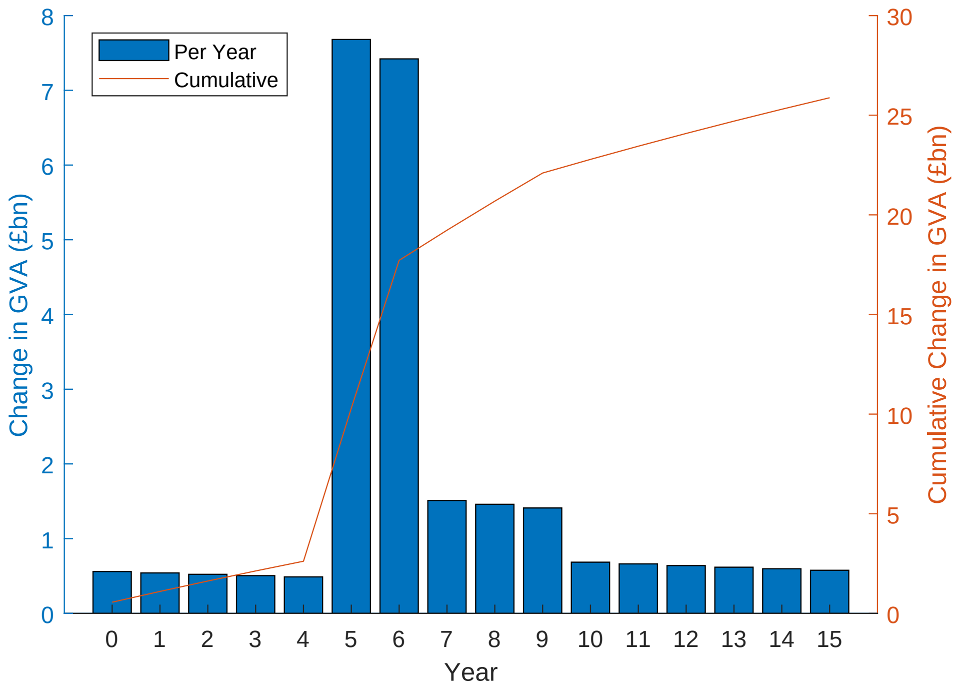

Figure 6.7: Change in GVA per year – Scenario 2

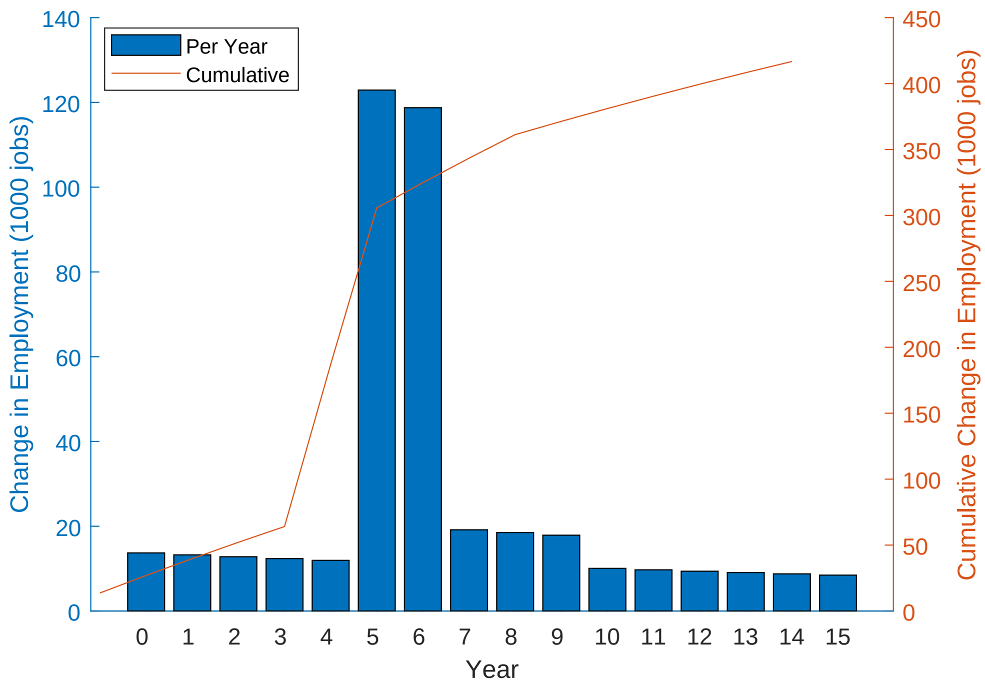

Figure 6.8: Change in employment per year — Scenario 2

sharp increase in output. Additionally, this type of peak would not be sustainable for the supply chain long-term, with jobs created to meet a need and then lost when the demand dries up. This ties in with the discussions in Chapter 5 on the need to create both a UK supply chain but also a reliable pipeline of projects which can be sustained long-term. Nonetheless, by splitting out the stages in the manner carried out here, the relative impact across the stages can be seen — which is instructive for policymakers as it demonstrates the importance of developing manufacturing capability for offshore wind within the UK. The scale of the opportunity available if this investment can be capitalised upon far outweighs the benefit that can be obtained from incremental gains in the supply chain capability that serves other project stages.

The bars representing each stage also illustrate the effect of discounting to present value. Considering the GVA impact shown in Figure 6.7, the same absolute expenditure generated both the year *5* and year *6* impact; but a reduced impact is seen in year *6* due to discounting the spend input into the IO model to the relevant present value for the year. This demonstrates the importance of developing a project sooner rather than delaying, as the value of the impact is reduced the longer into the future it occurs[18]. However, whilst these direct effects were delayed, indirect effects were still occurring in sections which did not receive any increase in demand until later through the project lifecycle; or, indeed, any direct increase from the ScotWind investment at all. The share of impacts throughout the years of the analysis as sectors across the economy made purchases to produce their own output is expanded upon in Section 6.4.3.

6.4.3 Direct and Indirect Impacts

Under the base case scenario discussed in Section 6.4.1, the importance of indirect economic impacts of the ScotWind investment was touched upon. In this section, the split of direct and indirect effects in the GVA and employment impacts of Scenario 2 are analysed, with Figures 6.9 and 6.10 showing the respective breakdown per industry

[18]This is explored further in Section 6.4.4 when the impact of delays to project spend are analysed.

section. Considering first the change in GVA within the UK due to the ScotWind investment, for a total of £25.9bn across the 16 years of expenditure, 54.05% of this increase in GVA was found to be due to direct effects, with the remaining 45.95% due to indirect effects across the rest of the economy. The split for employment was slightly closer, with the 417,000 increase in jobs exhibiting a direct to indirect share of 52.75% to 47.25%. This ratio is broadly aligned with current estimates for employment in offshore wind, where around 54% of the workforce are considered to be direct jobs (RenewableUK 2024).

At a more detailed level, the direct to indirect split varies across industry section and sector. Section C (manufacturing), with the largest change in GVA and employment of any section, saw almost 80% of its impact in both metrics from direct effects. This is not surprising, as this section received the largest investment from ScotWind; however, the indirect effects were also substantial in scale despite being a low percentage of the total for the section, with impacts higher than the GVA totals for 16 other sections and 15 sections for employment. Some of this indirect effect was due to sectors within the manufacturing section purchasing from other manufacturing sectors, though some will also have been generated from other sectors across the economy making purchases from the manufacturing section to produce their own output. Section F (construction) and Section M (activities of head offices etc.) also had their impacts dominated by direct effects (65% and 54% of GVA respectively, and 65% and 64% of employment), but to a lesser extent than for manufacturing.

One notable contribution to the total change in GVA driven mostly by indirect effects was Section N (administrative and support service activities). Sectors in this area received only 0.4% of the initial ScotWind investment, localised in the O&M stage[19], while the Section accounted for 4% of the overall increase in GVA throughout the investment period and 7% of the increase in employment. Indirect effects generated 94% of the GVA in the section, and 98% of the employment, with a substantial contribution

[19]The investment was exclusively into SIC sector N77 (rental and leasing activities), accounting for the hire of vessels and equipment for offshore activities and the leasing of port infrastructure.

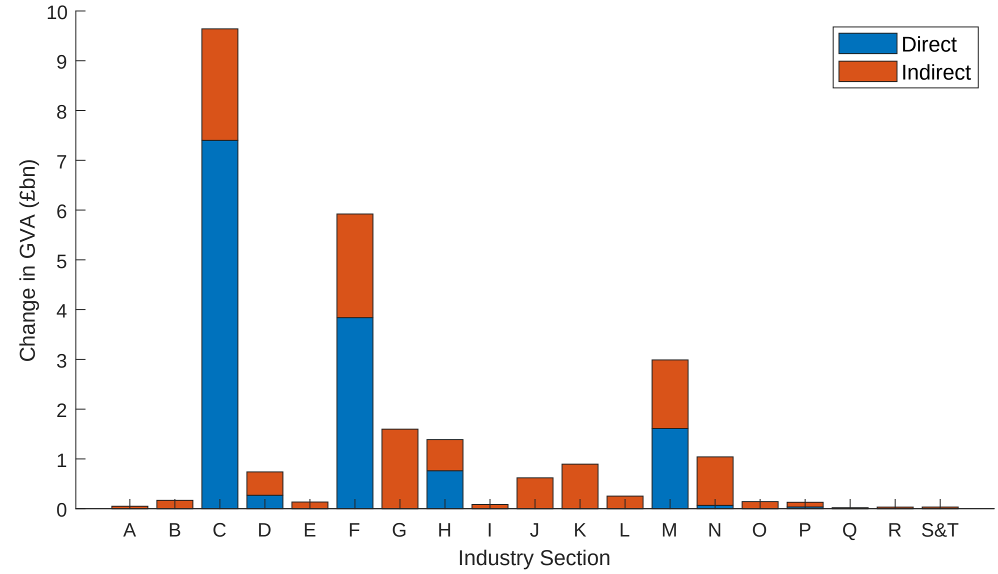

Figure 6.9: Direct & indirect change in GVA per industry section – Scenario 2

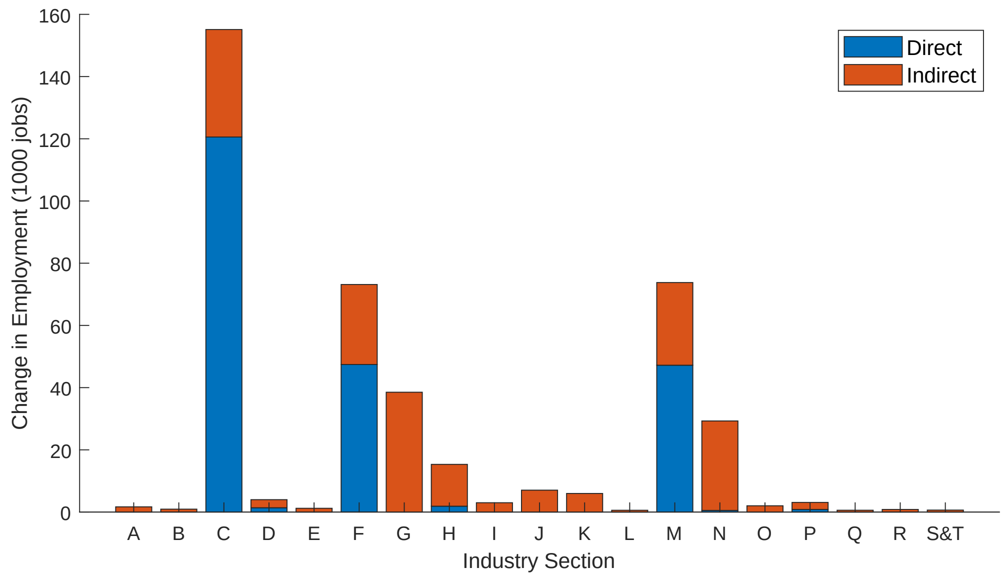

Figure 6.10: Direct & indirect change in employment per industry section – Scenario 2

seen from the sector relating to employment activities in the years of the ScotWind direct manufacturing expenditure. While sectors in Section N did not see a change in final demand during these years, the linkage of these sectors with the rest of the economy means that those sectors which were receiving investment increased their input from Section N to an extent great enough to generate a significant portion of the total increase in GVA and employment. While this value is obviously dwarfed by the contribution from other sectors such as construction and manufacturing, it is a clear demonstration of the importance of these kind of knock-on effects — with similar economic behaviour creating indirect demand across all sectors of the economy and generating almost half of the overall benefit observed.

In each of the industry sections discussed thus far, the direct to indirect share has been broadly similar in both GVA and employment (i.e. within 10%). One section exhibited results contrary to this, with Section H (transportation and storage) receiving 55% of its total GVA impact through direct effects but only 12% of its increase in employment. For GVA, the direct effects were induced mostly by expenditure during the installation and O&M stages into the water transportation sector (SIC sector H50). New employment was also stimulated directly by this expenditure, but this was small compared to the indirect jobs supported in the sectors relating to freight and cargo activities (SIC sectors H49 and H52) during the manufacturing stage. Delving into the original GVA and employment figures for sector H50 in 2018, the GVA contribution compared to the output of the sector is in line with the average across all sectors of the economy. However, for employment, the total number of jobs supported by the sector was fairly small. As a result, calculating the change in employment via the employment-output coefficient (following Equation 6.5 as outlined in Section 6.2.1) resulted in a limited increase in job numbers in this sector to fulfil the change in output expected from the ScotWind demand. In terms of sectoral output, the water transportation sector in 2018 was relatively small. It is unlikely, then, that these employment figures are a true representation of the labour intensity of the sector as would be required for the scale of increased demand from the ScotWind projects. A significant boost in the economic activity would likely require more new jobs than the results here suggest, possibly reducing the disparity in the direct to indirect employment shares.

The direct supply chain of offshore wind rightfully receives a lot of focus in relation to the benefit that the UK can generate from the sector if it focuses its attention and develops capability, but the analysis here demonstrates that it is not solely from these companies where benefit can be obtained. There would be indirect effects across the entire economy, stimulating GVA and employment in sectors where one may not expect to see any change from the growth of the offshore wind industry.

6.4.4 Impact of Project Delays

When discussing the differences seen in the economic impact of the ScotWind investment once discounting to present value was taken into account in Section 6.4.2, it was demonstrated that the level of impact diminished with time for the same absolute investment. The landscape surrounding the offshore wind industry has developed in recent years, with supply chain constraints, consenting delays, and inflationary pressure combining to see many projects delayed. To model the possible effects of a delay of this nature to the economic impact of the ScotWind projects, this section discusses the analysis of Scenario 3, where half of the ScotWind spend was delayed by five years.

The purchases followed the same timeline as previously set out for 50% of the expenditure, while the remaining 50% followed the same schedule but starting in year *5*, for a total GVA impact at the end of year *20* of £23.8bn and a discounted employment impact of 384,000 jobs. The GVA impact in each year of investment is shown in Figure 6.11, along with the cumulative GVA until the end of year *20*. Incorporating the delay in expenditure, the previous spike due to the manufacturing spend in years *5* and *6* was smoothed out slightly, with an additional peak now visible over years *10* and *11* when the delayed manufacturing spend hit the economy. Putting aside the previous discussion on the ability of a genuine supply chain to respond to such a demand shock, and that a smoother investment curve would actually be beneficial in reality, the main

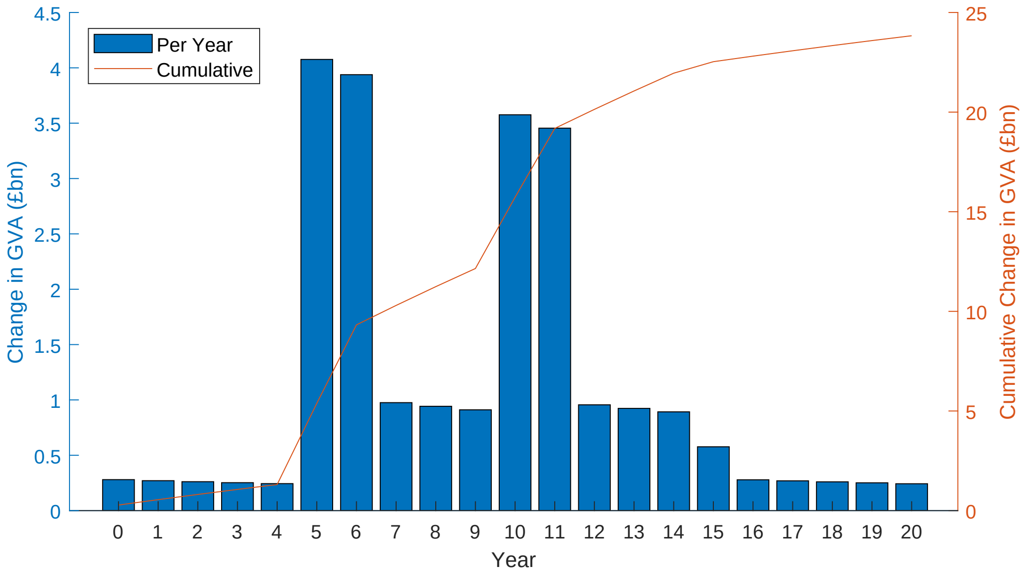

Figure 6.11: Change in GVA per year – Scenario 3

point to notice from Figure 6.11 is the difference in scale between the first manufacturing years and the delayed expenditure. The same outright investment was input into the model in each year, but the effect of discounting to present value is more pronounced here with the gap in between the two peaks, compared to solely the two years of spend shown for Scenario 2 in Figure 6.7.

To better illustrate the difference in GVA impact between the original and delayed cases of Scenario 2 and Scenario 3, Figure 6.12 shows the cumulative total for both over the investment period. The GVA impact of the Scenario 2 investment is extended out to year *20* with a dotted line on the graph, to more clearly demonstrate the offset in the cumulative impact between the two cases. At the end of the initial investment of Scenario 2 in year *15*, the total GVA impact was £25.9bn — 7.9% higher than at the end of investment under Scenario 3.

For employment, the same scaling results, with around 33,000 less jobs supported in the delayed case. Even if undiscounted jobs are considered, i.e. the 518,700 figure demonstrated under Scenario 1, a reduction in overall economic benefit can still be

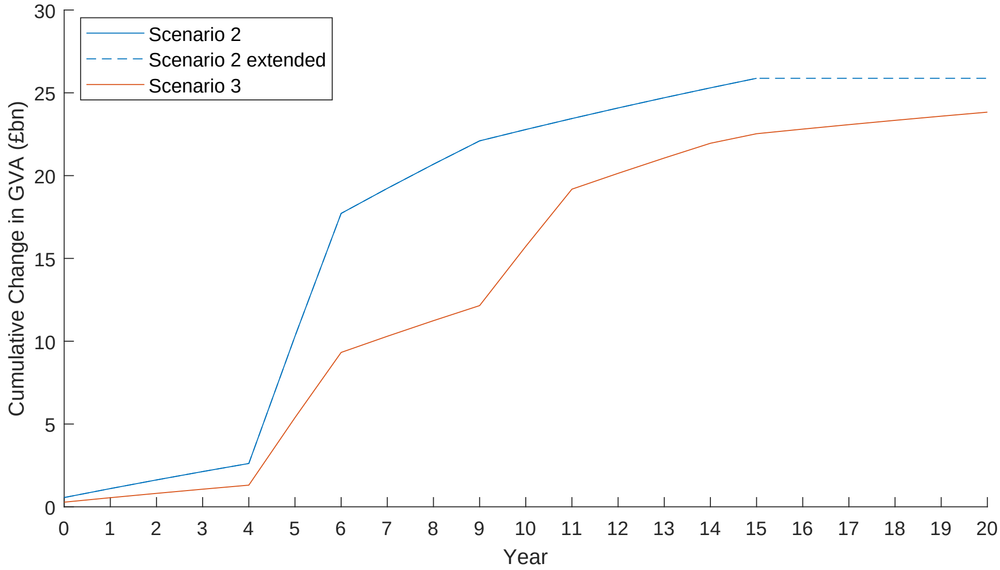

Figure 6.12: Comparison of change in GVA generated in Scenario 2 and Scenario 3

seen between Scenarios 2 and 3 by assessing the ratio of change in GVA to change in employment. In Scenario 2, the ratio is calculated as £49.9m GVA per 1000 jobs; while Scenario 3 returns a value of £45.9m GVA per 1000 jobs as the present value of the change in GVA is lower but the employment change remains the same — thus indicating a lower impact when investment is delayed.

The analysis here took a straightforward approach to the application of a delay that would not, in actuality, result in such a distribution of project spend. However, what it demonstrates in a clear-cut way is how the economic benefit of an investment is diluted whenever a delay occurs. The larger the delay in getting the investment into the economy, the greater the reduction in the value of its impacts. If the UK is to successfully capitalise upon the economic gains that could be available through the development not only of ScotWind but of the growth of the offshore wind sector more widely, effort should be made at a nationwide, governmental level to minimise delays as effectively as possible to facilitate the deployment of new projects at pace. The roll-out is already a focus with regards to meeting the renewable energy goals and climate change targets of the UK, but these results further emphasise that the sooner this development happens the better for the benefit that can be gained economically. The discussion in Chapter 5 proposed four key areas where policy action could be focused to ensure a project pipeline for offshore wind and encourage development in the supply chain. These aspects — namely; targeted investment, speeding up project consent and approvals, reforming the grid connection process, and improving port infrastructure — will all need to combine in order to reduce the likelihood of significant delays. There are global, contributory factors which may be outwith direct control of the sector or the UK, such as widespread price inflation or geopolitical impacts to supply chain availability, so concerted effort should be made in the areas where the UK Government has power in order to ensure that targets for the sector can be met.

6.4.5 Impact of Committed versus Ambition Expenditure

The results in the previous sections considered the possible economic impact to the UK of the committed expenditure proposed by the ScotWind projects. However, the SCDS provided by the ScotWind developers also set out the possible spend under an 'ambition' case, which aligned with a more developed local supply chain and increased sourcing from the UK. Under this case, the ScotWind investment into the UK economy rose from £42bn to £57bn. The remainder of this section assesses the possible impact in GVA and employment terms of this increased level of demand and investment, Scenario 4 as set out in Section 6.3.4, compared to the impact calculated from the committed investment in Scenario 2.

Utilising the ambition expenditure from ScotWind as the input to the model, the potential GVA impact in the UK at the end of year *15* of investment totalled £35.3bn, a 36% increase on the £25.9bn generated in Scenario 2. For employment, the ambition spend generated 562,000 jobs — a 35% increase on the 417,000 under Scenario 2[20]. The change in GVA per industry section is presented in Figure 6.13, while the equivalent plot for employment is shown in Figure 6.14. The section which saw the

[20]Discounted jobs. Undiscounted employment impact would be 697,500 for Scenario 4 versus 518,700 for Scenario 2 — a 34% increase.

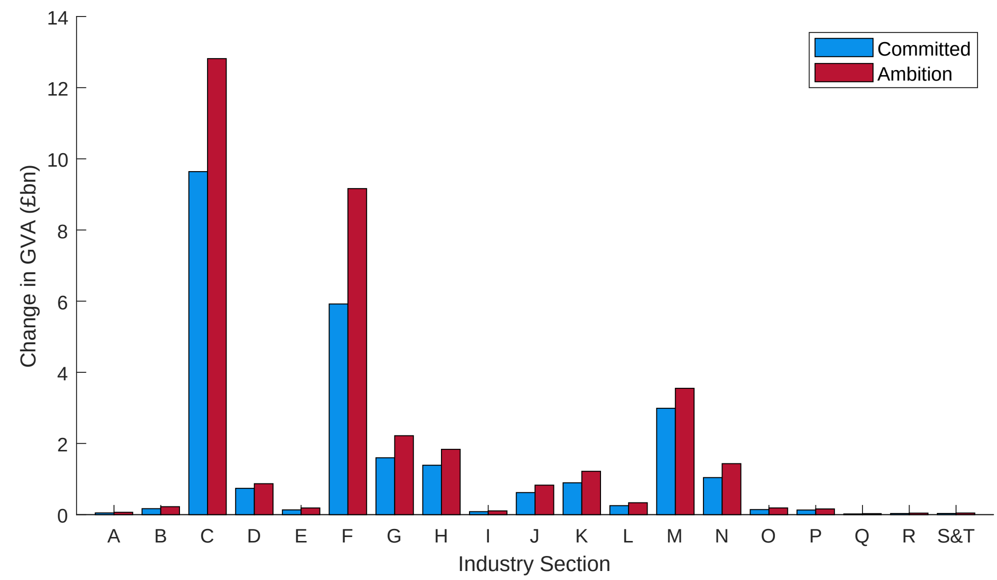

Figure 6.13: Change in GVA from committed and ambition ScotWind expenditure – Scenario 2 and Scenario 4

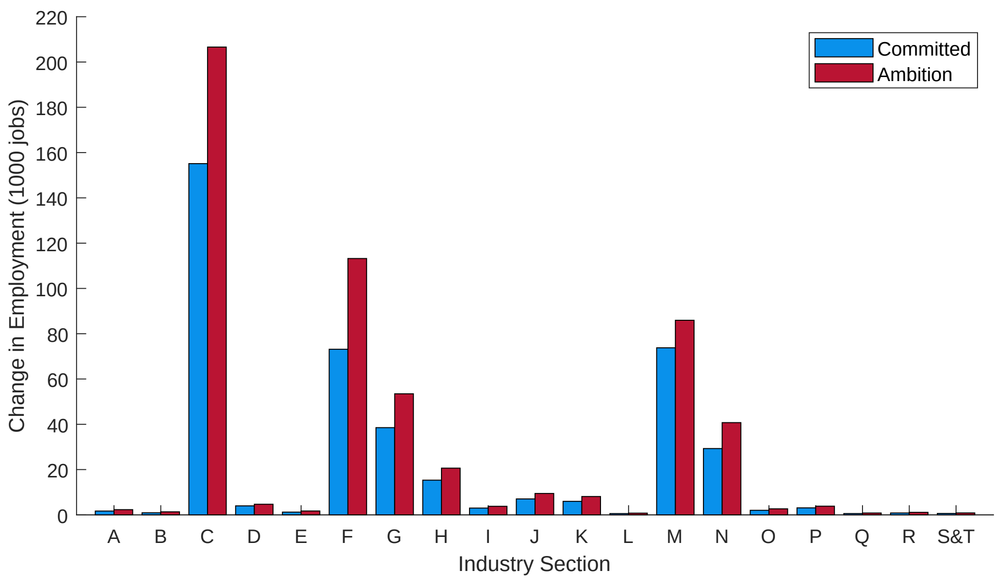

Figure 6.14: Change in employment from committed and ambition ScotWind expenditure – Scenario 2 and Scenario 4

largest change in GVA and employment between the two scenarios was construction (Section F), which follows from the sectoral allocation discussed in Section 6.3.2, where the biggest increased share was within the construction sector to reflect increased UK purchases of turbine foundations. The manufacturing sectors (Section C) also saw a significant rise — reflective of the ScotWind projects aiming to increase their UK spend in the manufacturing stage under their ambitious case.

Improvement of more than a third in the change in GVA and employment that could be generated if the offshore wind supply chain in the UK developed sufficiently to capture the ScotWind investment would be a significant boost to the economy, beyond the benefit that has been demonstrated as possible from just the committed expenditure. Of course, there are limitations with the IO methodology applied here, so the GVA and employment results should not be taken as absolute. As mentioned previously, IO assumes no economies of scale, and that all requested demand can be catered for with no supply constraints. In reality, a significant scale up, as indicated by the ambition spend in ScotWind, may stretch the capability of existing businesses. Additionally, IO does not allow for substitution of inputs like other methods such as CGE. While the existing setup of a specific industrial sector may make a lot of purchases from another given sector, a new business (for instance, manufacturing floating wind foundations) may generate a different pattern of purchases while fitting into the description of an existing sector. They may also purchase more from imports than the existing businesses within the sector. Clearly, the full impact of these type of changes and how they may change the results of the case study cannot be fully assessed, the analysis must operate within the assumptions of the underlying IO model. However, it should be noted that this works both ways — the benefit generated in these type of cases could even be greater than under the existing pattern.

To fully capitalise on the increase in GVA and employment possible under the ambition expenditure, the offshore wind supply chain in the UK will need to scale up from its current capabilities. As discussed in Chapter 5, currently many components of an offshore wind farm have minimal manufacturing capacity within the UK — though local content is better represented in the development and O&M stages. The increased ambition expenditure of the ScotWind projects is reflective of what the investment could be if the supply chain was there to be called upon. Components such as floating wind foundations have been particularly highlighted as an area where UK businesses could thrive, utilising an extensive knowledge base learned from the longstanding oil and gas sector, and gaining advantage in the global supply chain as an early adopter of the technology. In order to achieve this, focus should be placed on the growth of the sector — ensuring that not only a healthy supply chain is developed, but also to achieve the best results in terms of economic benefit to the UK.

6.5 Conclusion

Throughout this chapter, the potential economic impact of the UK investment from the ScotWind offshore wind projects has been analysed. With the offshore wind sector positioned as a key technology in transitioning the UK electricity sector away from fossil fuels, and ambitious deployment targets set for the coming years, the growth of the industry is an area of focus domestically and it is crucial for policymakers to understand the possible impacts to the economy from its development. Utilising IO modelling, the work presented in this chapter has demonstrated how the GVA and employment generated by the ScotWind investment varies across the sectors of the economy and through time, with a further contribution indicating the scale of reduction in the economic benefit that could be gained by the UK if project spending was delayed.

The results of the study demonstrated that significant impacts are seen beyond the sectors receiving direct purchases from the ScotWind projects — with 28% of the total change in GVA, and 31% of the total change in employment, generated in sectors which received no investment. The impacts in these sectors were generated solely through intersectoral purchases. Beyond this, indirect effects were also generated in sectors which did receive initial investment — for example, the construction sector (Section F) saw 35% of its total change in both GVA and employment come from indirect effects.

This is due to the construction sector operating as an input to other sectors, which draw on its output to produce their own. Across the economy as a whole, 54% of GVA was generated from direct effects, with 46% indirect; while for employment, 53% was direct and 47% was indirect. The comparison of direct to indirect impacts through this study demonstrates that while it is important for the UK to develop the supply chain of offshore wind to capitalise on the available investment as the industry grows, the spill-over effects into other sectors is non-trivial and the economic benefit could be widespread.

The analysis in this chapter went beyond the outright level of investment to assess the impact to the UK economy in present value terms. By discounting the expenditure to year *0*, under the assumption that money spent now is worth more in terms of its impact than the same amount spent a number of years into the future, the relative scale of impact throughout the lifetime of the ScotWind investment was analysed. Utilising the present value of the investment also allowed for the potential impact of any project delays to be understood. To demonstrate how the scale of economic gain could differ, Scenario 3 saw 50% of the project investment delayed by five years as compared to Scenario 2. For the same outright expenditure, Scenario 3 would generate around 8% less GVA and employment over the time of investment than Scenario 2. Given the scale of expenditure and economic impacts generated, this potential loss in benefit is not insignificant. In recent years the offshore wind industry has weathered multiple concurrent issues that have combined to cause project delays and cancellations, from inflationary and supply chain concerns to lengthy waits for consent approvals or grid connections. For policymakers looking to understand the benefits that could be captured over the next half-decade to 2030, and onwards to 2050 for net zero, this work demonstrates how, regardless of the cause, delaying investment into future years minimises the scale of its impact in present value terms. To maximise the benefit to the UK in scaling up the domestic offshore wind industry, effort should be placed to minimise delays and to lessen pressures on the supply chain wherever possible.

While IO modelling is informative for understanding the possible impacts that can be gained under an investment into the economy, the method does have limitations. The assumptions inherent under IO mean that no supply constraints are considered, and the pattern of inputs to a sector are fixed — with constant returns to scale assumed, and no substitution of inputs possible. In reality, a significant scale up of demand for UK outputs may mean that bottlenecks in supply are seen in the offshore wind supply chain, or that the relative GVA or labour intensity of a sector will change compared to the current ratios. Nonetheless, the modelling presented here remains instructive to policymakers as, while the outright size of the impacts may change under different assumptions, there are elements in the results which are unchanging. Notably, the high percentage of indirect impacts demonstrates how there is a much bigger benefit to be gained than just in the direct industries. Focusing on development and investment into this direct supply chain will pay dividends across the wider economy. In order to maximise the benefit achieved, action is needed on consenting and grid approvals to reduce the scale of delay felt by new offshore wind developments — reinforcing the policy findings discussed in Chapter 5.

Chapter 7

Conclusion

Throughout this thesis, the desire to transition the energy sector in the UK away from fossil fuels to cleaner, renewable energy sources has been highlighted — with the transformation of the electricity sector of particular importance globally for the reduction of greenhouse gas emissions. The preceding chapters have demonstrated how offshore wind power has been positioned as one of the key technologies for clean growth in the UK over the coming years, with ambitious targets in place for its deployment. The scale-up of the sector from its first installation in the year 2000 to almost 15GW of operational projects in 2024 has been instrumental in helping to reduce UK emissions to date, with wind increasingly displacing fossil fuels from the generation mix. However, with a target of 50GW installed capacity by 2030, a significant expansion of the sector is required in an increasingly short timeframe.

Beyond solely helping to reach decarbonisation goals, there has been growing recognition in recent years that there is scope to improve the economic benefit achievable from the offshore wind industry by increasing levels of local content in new developments. Local content manifests itself through the supply chain, representing the share of project expenditure that is invested into businesses within the UK. Consequently, the development of the domestic supply chain has become an area of intensifying focus in more recent national strategies. The aim of this thesis was to improve the understanding of the offshore wind supply chain in the UK, bridging the gap between potential economic impact and policy actions taken by government. Through both ex-post and ex-ante economic analysis, and a comprehensive review of climate change, renewable energy, and supply chain policies, this work should be of interest to both industry stakeholders and those formulating policy for the future development of the sector having demonstrated how progress has been achieved to date, and highlighting where emphasis should be placed looking forward.

The objectives set out in the introduction of Chapter 1 have been met by the work presented throughout the body of this thesis. Overall, the contribution contained in these preceding chapters serves as the first attempt in the academic literature at presenting a holistic view of key considerations for the offshore wind supply chain — highlighting its progress, current state, and challenges — alongside an examination of the economic impacts from its development, showing the opportunity available if the UK can only capitalise on it.

The remainder of this chapter is presented as follows: Section 7.1 features a summary of each of the preceding chapters of this thesis, highlighting their main results and key contributions; while Section 7.2 makes some recommendations for future extensions to the work.

7.1 Chapter Summary and Key Contributions

This section provides a summary of each of the constituent chapters of this thesis, highlighting the importance of the work presented therein and their key contributions.

Following the introductory first chapter where the objectives of this thesis were outlined, an appraisal of the history of policies relating to UK renewable energy in Chapter 2 set the context for the thesis, demonstrating the changing priorities of government through the start of the 21st century. The overarching background to much of the development in the field of energy over recent decades was the growing awareness of the global impacts of GHG emissions, and the desire of many regions worldwide to take action against climate change. In this chapter, policy interventions related to emissions and renewable energy development in the UK from 2000 to 2021 were discussed, with a focus throughout on how the offshore wind sector was being advanced over the period, providing a detailed overview of the changing landscape. The key funding mechanisms employed for offshore wind in the UK and some of the challenges facing the sector were introduced, with these topics carried through to the analysis in subsequent chapters.

Against the backdrop of critical legislation to target global warming, such as the UK Climate Change Act 2008, the UN Paris Agreement, and the subsequent setting of net zero goals, the review in Chapter 2 demonstrated the significant progress of the UK offshore wind sector as it scaled from its first installation to the third largest generating technology by 2020. Despite the progress in the sector as capacity grew to around 10GW by 2020, comparing with targets for the year set for Scotland and the UK in earlier policies and strategies revealed how growth in delivery had fallen short of previous aims. For example, a 2010 strategy for Scotland aimed for over 10GW of Scottish capacity by 2020, while in reality less than 1GW had been installed in Scottish waters by that time. The lack of capacity installation also had a knock-on effect in the level of jobs and GVA delivered. While UK-wide capacity did not miss targets by such an extent, estimates for the number of jobs that could be supported were not met. From this landscape, the Offshore Wind Sector Deal in 2019 focused attention for the sector, targeting an improvement in capacity, jobs, and economic benefit through increasing local content — and spotlighting offshore wind as a key technology for the future UK energy system. With the importance of developing the sector to meet net zero goals clear, and the desire to maximise UK benefit from doing so, this chapter highlighted the lessons that need to be learned from past progress to inform the response to the challenges facing offshore wind today.

Chapter 3 presented a review of existing literature surrounding the economics of renewable energy, and offshore wind in particular. Studies employing Input-Output

(IO) and Computable General Equilibrium (CGE) analyses were found to be prevalent in the extant research, with the literature in broad agreement that the energy transition will bring increased economic benefits in terms of employment and GVA. Chapter 3 also featured a review of costs of offshore wind. Considering both measures of levelised cost of energy (LCOE) and strike prices achieved through the Contracts for Difference (CfD) subsidy auctions, offshore wind costs in the UK have fallen drastically as the sector has scaled. As the new generation of projects start to be developed, increasingly utilising nascent floating wind technology and extending to more challenging offshore locations, costs may rise in the short term. However, experience gained in the growth of offshore wind to date and sustained policy support through mechanisms such as CfD should ensure that future cost reductions occur at an even faster rate than exhibited previously.

The final area of review in Chapter 3 explored the literature surrounding local content within the supply chain. Studies on the efficacy of local content requirements have generally found that while outright levels may increase when requirements are imposed, the content is more likely to be focused in stages such as project development or in the manufacture of low value components. The most crucial way that greater local content and increased economic benefit has been identified is through early adoption of a technology. This demonstrates the opportunity available for the UK if the pipeline of projects from ScotWind, the INTOG leasing round, and the upcoming Celtic Sea leasing can be capitalised upon and a supply chain for floating wind can be developed early in the evolution of the sector.

Following the chronological review of energy policy and climate change, and the identification of relevant modelling techniques, Chapter 4 presented the results of a Structural Decomposition Analysis (SDA) assessing the drivers of changes in UK GHG emissions from fuel use across all sectors of the economy. National IO tables for the years 2010 and 2018 were environmentally-extended with fuel use data to analyse the difference in resultant production emissions of the UK. The novel contribution of the separation of the electricity sector allowed for the impact of changes in the energy system to be quantified, demonstrating the scale of emissions changes within electricity generation versus the rest of the economy. In addition, with the fuel use data available by type, the SDA was extended to understand the specific contribution of changes in coal and natural gas usage — reflective of the transition of the power sector from fossil fuels to renewable energy sources.

Indeed, the most significant driving factor of the drop in GHG emissions from fuel use between the two years was revealed through the SDA as the improvement in emissions intensity of the electricity sector. Across all fuels and all sectors, there was a 30% drop in emissions between 2010 and 2018. Considering coal and natural gas use in particular, their respective emissions fell by 76% and 19%. Without the improvements in emissions intensity, both in the electricity sector and through the remaining economic sectors, overall GHG emissions would have risen in the UK. The analysis of the difference due to changes in production technology or final demand showed that, with emissions intensity held constant, changes to purchases between sectors and increased demand from exogenous sources would have driven increased GHG emissions. This chapter demonstrated how crucial the transition to the power sector is to the climate change goals of the UK, illustrating the main driving force behind the change seen thus far. However, it also showed where emphasis should be placed in the future. Firstly, through the demonstration of the continuing level of emissions from natural gas use in the power sector. Secondly, the results showing an increase in production emissions throughout the economy indicate the importance of considering beyond the power sector, with efforts required to decarbonise the broader supply chain.

The concept of the supply chain was carried through into Chapter 5, which detailed the first comprehensive review of the development of supply chain planning and related policy actions for offshore wind in the UK. The first part of the chapter covered the history of policy development related to the sector, demonstrating how the focus changed through time from the expansion of installed capacity to a desire to grow local content levels by expanding the domestic supply chain; ultimately to capitalise on the economic boost available from the growth of UK industry. An overview was provided of the current supply chain planning requirements of offshore wind — namely the SCP within the CfD auctions and the SCDS provision within the ScotWind leasing round — with a comparison between the two accenting differences in their structure. The main point of difference proposed in the discussion was the relative transparency of the two mechanisms, with the ScotWind SCDS found to offer much more visibility to industry on the possible pipeline of investment. The challenges facing the supply chain were reviewed in detail, from specific challenges in scaling up production domestically and capturing the targeted level of local content, to supply chain bottlenecks and global financial pressure, and the issues of project delays due to consenting, grid approvals, and lack of sufficient port infrastructure creating a riskier investment picture. Having indicated clearly to policymakers both the scope and scale of the challenges facing the offshore wind sector, the contribution from the first part of this chapter was in demonstrating where policy focus ought to be targeted. This will ensure that not only are projects given the best opportunity to be built and contribute to the installed capacity and climate change goals of the UK, but that pressures on the supply chain can be eased and allow the sector to operate to its full potential, ultimately producing the greatest benefit to the UK economy.

Chapter 5 was concluded by a novel examination of the data provided in the ScotWind SCDS, which detailed the planned expenditure of the successful projects in four project stages (development, manufacturing, installation, and O&M) per geographical region (Scotland, rUK, rest of Europe, rest of world). The proposed combined UK content of the projects was analysed — considering any trends or themes throughout the proposals that dictated differing levels of expected local content. Aggregating the projects, 55% of the total investment was committed to the UK (dropping to 49% when excluding four projects which withheld their non-UK spend). Clearly this is lower than the 60% local content target set by the Offshore Wind Sector Deal, indicating that on the whole the ScotWind developers did not yet view the UK supply chain capability as sufficient to meet this goal. The projects also outlined an 'Ambition' spend, reflecting the investment that could be expected if the supply chain in the UK were to develop in the coming years. Under this expenditure, local content rose to 63%. Across the projects, there was some correlation that those with a higher local content had a higher spend per unit capacity — indicating a possible disconnect between the desire to keep costs low and the ability to source within the UK. Otherwise, no association was found to link varying local content levels with any other criteria — indicating that the strongest driver is likely just developer preference. This is an area where focus is likely to be required in order to understand the attitudes held by companies, and to understand what barriers could be broken down to encourage them to select more UK content.

With the analysis of supply chain planning in the UK highlighting the ScotWind SCDS as one of the two key mechanisms currently employed, Chapter 6 extended the high-level consideration of the SCDS previously discussed to an analysis of the potential economic impact that could be gained in the UK via the project investment. By implementing IO modelling, the GVA and employment impacts of introducing the ScotWind expenditure as a shock to the economy were assessed. The macroeconomic impact of the significant £42bn investment was calculated for the whole economy, with sectoral impacts also investigated alongside the split between direct and indirect effects. Representing the first detailed economic study of the ScotWind investment in the economic literature, the capacity of the ScotWind projects allows for a representative analysis of the investment required to reach the UK target of 50GW installed capacity by 2030. Using the real, planned expenditure of such a large scale of projects is not typical within the literature, with the implementation of the data from the SCDS particularly novel.

Through the modelling in Chapter 6, it was demonstrated that having spread the investment from a representative year *0* to year *15*, the present value of the committed ScotWind investment could contribute a £25.9bn change in GVA and support 417,000 additional jobs across the economy. The spread of investment through time and through industrial sectors was decided based on the potential delivery date of the ScotWind projects and and a survey of the sectors that companies active in the offshore wind supply chain self-reported as being part of. The results showed that there would be significant indirect effects across the economy, outwith the direct offshore wind supply chain, with GVA showing a 54% to 46% direct to indirect split and employment showing 53% to 47%. This illustrates that the benefit that the UK could hope to gain from the development of the offshore wind sector goes far beyond the direct supply chain, so encouraging its progress would deliver significant knock-on impacts to many other sectors. The final novel extension to this chapter was the consideration of project delays, and how this would affect the value of the resultant economic impacts. The results here showed that, for the case of 50% of the spend being delayed for 5 years, the impact delivered would be around 8% lower. Given the considerable scale of the potential change in GVA and employment, this is not a trivial level of loss. This finding is of key interest to both policymakers and the wider industry, signalling the importance of minimising the project delays and challenges that were outlined earlier in this thesis to ensure that the greatest level of economic benefit to the UK can be generated from the development of the offshore wind sector.

7.2 Future Work

The work contained within this thesis has presented novel contributions to the literature around the original aim of deepening the understanding of the offshore wind supply chain in the UK, and answered the questions set out in its initial objectives. However, across the three quantitative contributions to the literature in Chapter 4, Chapter 5, and Chapter 6, there are possible extensions to the work in each case which could advance the findings from this thesis, given the ever-changing landscape of the offshore wind sector. The remainder of this section makes some suggestions on possible avenues for future work.

Considering the SDA of changes in GHG emissions in the UK presented in Chapter 4, possible future extensions to this work could lie in three directions. First, a more detailed analysis of the final demand driver could be considered. While the current analysis utilised only final demand volume (in line with the study by Brizga et al. (2014)), some research has separated this into looking at both the level and shares of final demand (e.g. Su et al. (2017)). This would further indicate how emissions have been impacted by changes in domestic and international demand for UK production.

Second, one limitation of the analysis is that the electricity sector was not disaggregated into different generation types, as the UK IO tables only have one aggregated sector for electricity, comprising generation as well as other transmission, distribution, supply and trading activities. As such, the exact impact of (for instance) the increasing share of wind energy, and its different input technology from other electricity generation technologies, cannot be determined at present. Employing a disaggregation method to the IO tables could elucidate further detail in the decomposition.

Finally, while the analysis in Chapter 4 focused on the UK, some studies have employed multi-regional IO (MRIO) analysis with SDA to look at changes in environmental factors on a global level or due to international trade. Some examples include Dietzenbacher et al. (2020), who incorporated energy transition as a driving factor in global energy use; and Jiang et al. (2021) where the change in global carbon emissions was decomposed into drivers such as domestic and international input structure, and carbon intensity. Additionally, SDA on MRIO data was employed by Q. Wang and Yang (2020) to consider imports and exports on the oil intensity of Germany. Kulionis and R. Wood (2020) utilised MRIO tables covering the period 1970 to 2009 to perform an SDA on the energy footprint of each of Denmark, the UK, France, and the USA — showing the decoupling of energy footprint and economic growth for each country, and considering drivers including energy efficiency, population, and production technology. Extending the analysis presented in Chapter 4 by employing a MRIO approach would allow for embedded emissions in UK imports to be assessed. At present, the analysis has included only those emissions created from domestic fuel use by production sectors. By incorporating multi-regional data, the GHG emissions created by the UK supply chain but in non-UK areas could also be included, which would be of relevance to policy makers in ensuring that the reduction of UK emissions does not come at the expense of increasing those in other regions.

Chapter 5 presented a comprehensive overview of supply chain and local content policies in the UK, up to mid-2024, and their respective impact on the offshore wind industry. The policy landscape is ever developing, so a straightforward expansion of the work would be to consider changes in strategy or legislation in the intervening time. As noted in Chapter 5, the sixth allocation round (AR6) of the Contracts for Difference scheme was run over 2024. Ten offshore wind farms with a combined capacity of almost 5GW capacity were awarded CfD in AR6 — however, almost 1.6GW of this came from projects previously awarded a CfD who were reapplying for a change in strike price for part of their capacity (DESNZ 2024a). Nonetheless, improvements were still seen from the previous round when no offshore wind projects bid. One avenue of study could involve an assessment of the strike prices awarded to the successful AR6 offshore wind projects, with a view to understanding how feasible the construction and operation of these wind farms are at these prices — given the ongoing inflationary and supply chain issues that saw the Norfolk Boreas project shelved in 2023.

In a significant change from the ARs run to date, from AR7 (expected in 2025) offshore wind farms will no longer produce a Supply Chain Plan in the form discussed in detail throughout Chapter 5 (DESNZ 2025a). Instead, under the Clean Industry Bonus (CIB) framework[1], developers will submit a CIB proposal and could be awarded extra CfD funding if they elect to make sustainable investments above a minimum criteria decided by DESNZ. A useful extension to the work in Chapter 5 would be a thorough assessment of the possible impacts to supply chain planning and local content for offshore wind developments in the UK with the replacement of SCP submissions with CIB proposals; and how the bonus funding could incentivise developers to make more sustainable choices within their supply chain.

One final avenue for future work relating to Chapter 5 could be undertaking stakeholder engagement to assess the industry views on SCDS, SCP, and the new CIB. It

[1]Previously called Sustainable Industry Reward, as outlined in Chapter 5.

was outlined in the chapter that a knowledge gap exists as to the attitudes of offshore wind developers towards these requirements and the inherent local content emphasis within them. While industry worked with the UK Government to produce the 60% local content target for 2030 set in the Offshore Wind Sector Deal in 2019, it is not apparent how developers intend to meet the targets that they previously agreed. The views of industry on the supply chain planning process and pathways to growing local content in the UK would, as such, represent a meaningful contribution to the literature.

For the economic analysis of the ScotWind investment in Chapter 6, variations on the existing methodology could be pursued to perform a sensitivity analysis on the results presented. For instance, the spread of investment could be reconsidered — investment from the projects could be allowed to start at different times, or with overlap in the spend of each project stage. This type of change could represent a more realistic investment profile than the simple case employed in the study, though the method selected allowed for each stage of the projects to be analysed in isolation and demonstrate the relative scale of impacts. The same reasoning on the investment profile could also be applied to the consideration of project delays. While a representative case of 50% of the spend, delayed by five years, was utilised in the case study, as time progresses more information relating to the real projects within ScotWind may become available. Incorporating this type of data into an economic impact analysis would be a novel contribution. One example of differing the delay could involve a separation of the fixed and floating offshore wind projects. Floating wind is still a relatively nascent technology, so it is not unreasonable to expect that these projects may be built with a delay when compared to those employing the more standard fixed-bottom foundations. Splitting the two project types, and considering the possible differences in spend allocation per industry sector in each case, would provide an interesting extension to the case study.

The final area which could be pursued, representing a fuller model of the UK economy, could be the extension to include Type II effects. By endogenising household spend and income, induced effects of the ScotWind investment could also be analysed.

An income-output coefficient would also then be of interest, to demonstrate how household income may be impacted by the growth of the offshore wind sector in the UK. Emissions could also be investigated, by incorporating emissions-output coefficients per sector in a similar way to that demonstrated in Chapter 4. Displacing fossil fuels in the electricity mix has been shown to reduce GHG emissions, but the inclusion of emissions-output coefficients would allow for the overall change in emissions across the economy to be estimated by assessing how the emissions of each sector may be impacted by the investment from the ScotWind projects.

Appendix A

Review of Economic Models

This appendix presents a review of the two main economic modelling techniques that are found in the literature surrounding offshore wind, as discussed in Chapter 3. Given that the aim of this thesis is to better understand how the supply chain of offshore wind contributes to its economic impacts, both Input-Output (IO) and Computable General Equilibrium (CGE) analysis offer a useful methodology as they allow for sectoral impacts to be assessed. Both models have been employed extensively in the literature, and each offers pros and cons depending on the aims of the study.

To that end, this section presents an appraisal of both techniques in turn, touching upon their methodologies, data requirements, and limitations. IO is considered first, in Section A.1, where the concepts of linkages and multipliers are detailed in Sections A.1.1 and A.1.2 respectively, with the assumptions inherent in the use of IO discussed in Section A.1.3. The CGE method is outlined in Section A.2, where its assumptions are also summarised. The discussion is finalised by Section A.3 which considers a comparison of the two methods — with the aim of selecting the most appropriate for the economic analysis carried out within this thesis.

A.1 Input-Output Modelling

The input-output framework is widely employed in economic analysis, as demonstrated within the literature review in Chapter 3. The data within an IO table allows the flow of products between industrial sectors to be analysed, to assess the interdependence of industries. Typically, the data is expressed in monetary terms, for instance millions of pounds. A basic example of an industry-by-industry IO table for a two sector economy is given in Table A.1. Essentially, an IO table captures both where the outputs of a sector are used, and where the inputs to a sector are sourced. Within the table, *interindustry* transactions illustrate how each sector acts as both a producer and a consumer, and how the output of one sector is used as an input in another — termed the *intermediate sales* between industries (Miller and Blair 2022b). Additionally, the table captures elements of *final demand* — where outputs may be purchased by, for example, households, government or other regions as exports.

Each row of the IO table details how the output of a given sector is sold throughout the economy. From the example in Table A.1, it can be seen that for sector 1, 150 units of output are sold within the same sector, while 450 are sold as inputs to sector 2. Additionally, the output is distributed to households (HHs) within the region (80 units) and government (170 units), while 115 units are exported. Reading down the columns of the IO table illustrates the inputs that a given sector requires in order to produce its own output. As well as the interindustry purchases, *value added* inputs such as labour and capital are also detailed. Again looking at the example in Table A.1, it can be seen that sector 1 requires an input of 150 units from businesses within its own sector, as well as purchasing 180 units from sector 2. To complete its output sector 1 also purchases 90 units as imports, 210 units of labour (in the form of wages paid to workers), pays 40 units in tax, and has to account for 295 units of capital. From the table it can be seen that, reading along the row, sector 1 produces 965 units of gross output. Reading down the column, it is also shown that it consumes 965 units of gross input. This will always be the case, in that gross output of a sector has to

Table A.1: Example input-output table for two industrial sectors (Source: Author's own)

		Sector		Final Demand			
		Sector 1	Sector 2	HHs	Gov.	Exports	Gross output
	Sector 1	150	450	80	170	115	965
	Sector 2	180	340	220	135	455	1330
Primary Inputs	Imports	90	75	40	5	10	220
	Taxes	40	35	55	10	30	170
	Labour	210	320	-	-	-	530
	Capital	295	110	-	-	-	405
	Gross inputs	965	1330	395	320	610	3620

equal the gross input to the sector (Erickson and Kane 2017).

The fundamental equations that form the basis of IO modelling are discussed in detail in Chapter 4, but essentially the IO system consists of a series of simultaneous equations, which can be easily represented by linear algebra in the simplest cases, and matrix algebra more generally (Miller and Blair 2022b). The key equation which governs IO modelling, as derived in Section 4.2.1, is:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f} \tag{A.1}$$

Where $\mathbf{x}$ is the vector of gross output, $\mathbf{I}$ is an identity matrix, $\mathbf{A}$ is the matrix of technical coefficients, $\mathbf{f}$ is the vector of final demand, and $\mathbf{L}$ is known as the *Leontief inverse matrix*, with elements l_{ij} (Miller and Blair 2009a). Each element l_{ij} captures the amount of output needed from sector i to produce one unit of final demand for sector j — with the Leontief inverse accounting for both the direct and indirect input requirements to allow for a change in the level of final demand (Erickson and Kane 2017). Reading down column j in $\mathbf{L}$ will hence show the direct and indirect input requirements on all sectors i to generate one additional unit of output in sector j. The summation of these elements in column j then produce the *output multiplier* for sector j, which details the total amount of output stimulated in the overall economy per unit increase in sector j (Scottish Government 2020a).

Through the application of shocks to the model of the economy described by the IO table, equation A.1 and the Leontief inverse matrix can be used to analyse the overall impact as it ripples through the economy. Additionally, analysis may be performed through the use of *linkages* or *multipliers*. Brief discussions on these two measures are provided in Sections A.1.1 and A.1.2 respectively.

A.1.1 Linkages

A key benefit of IO modelling is that it provides a framework to analyse the interconnectedness of sectors within the economy (Miller and Blair 2009b). As explained in Section A.1, any given sector j can be assumed to be both a producer of outputs, and a consumer of inputs from other sectors in order to produce its own output. As such, it is clear that each sector is connected to other sectors both 'upstream' and 'downstream' of itself (Miller and Blair 2009d). If, for instance, sector j needs to increase its output, it will increase its demand for inputs from all sectors upstream that it makes purchases from. How interconnected a given sector is with those sectors from which it makes purchases is termed *backward linkage*.

Considering only direct effects, i.e. how connected a sector is only with those sectors from which it makes purchases, the strength of backward linkage is characterised by the ratio of these intermediate inputs to the overall output of the sector. This is summarised as (Miller and Blair 2009d):

$$BL(d)_j = \sum_{i=1}^{n} a_{ij} \tag{A.2}$$

Where $BL(d)_j$ is the direct backward linkage of column j, calculated as the sum of column j of the technical coefficient matrix $\mathbf{A}$. To measure the true level of interconnection between sectors in the economy, there may be a desire to look beyond solely direct relationships between sectors. To this end, the *total* backward linkage may be a more appropriate measure (Miller and Blair 2009d):

$$BL(t)_j = \sum_{i=1}^{n} l_{ij} \tag{A.3}$$

In this case, the Leontief inverse matrix, **L**, is used as it captures both direct and indirect relations between sectors. As mentioned in Section A.1, the column sum of the Leontief inverse matrix is also the output multiplier. This measure indicates how interconnected sector j is with those sectors from which it makes direct purchases, and the sectors from which its suppliers make purchases.

As mentioned, sector j is also connected with those sectors downstream of it which use its output as an input to their own processes. The interconnection of sector j with these sectors is termed *forward linkage*. If sector j increases its output, it is assumed that there will then be an increased supply of its product to be used in production within downstream sectors. In this supply-side interpretation, an alternative model is typically employed termed the *Ghosh* model. In the Ghosh interpretation of the IO system, instead of considering a unit of final demand altering the economy like the Leontief model, the impact of one unit of production entering the economy is assessed (Miller and Blair 2009d). In the simplest terms, this essentially means that instead of considering the columns j of the IO table, it utilises rows i instead — analysing the impact being driven by sectors as producers rather than consumers.

To this end, an alternative matrix representation of the IO table is required for analysis of the supply driven model and forward linkages. Firstly, the technical coefficients of matrix **A** are not suitable for this representation. Instead, a *direct-output coefficients* matrix **B** is defined, with elements b_{ij} which illustrate how the output of sector i is distributed as interindustry inputs throughout sectors j (Miller and Blair 2009d):

$$b_{ij} = \frac{z_{ij}}{x_i} \tag{A.4}$$

Where each element b_{ij} denotes the share of output from sector i that is used by each sector j. Though it will not be derived here, through matrix algebra it is possible to define the Ghosh, or *output*, inverse similarly to the Leontief inverse (Miller and Blair 2009d):

$$\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1} \tag{A.5}$$

Where $\mathbf{B}$ is the direct-output coefficients matrix, $\mathbf{I}$ is again an $n \times n$ identity matrix, and $\mathbf{G}$ is the Ghosh inverse matrix with elements g_{ij}. Each g_{ij} represents the amount of production (direct and indirect) that is stimulated by one unit of primary input in sector i (Miller and Blair 2009d). Utilising equations A.4 and A.5, expressions for direct and total forward linkage can be produced, similarly to the backward linkage case from equations 4.3 and 4.8. As such, the direct forward linkage is formulated as:

$$FL(d)_i = \sum_{j=1}^{n} b_{ij} \tag{A.6}$$

While the total forward linkage, capturing both direct and indirect impacts, is given by:

$$FL(t)_i = \sum_{j=1}^{n} g_{ij} \tag{A.7}$$

The similarities between these two equations and those for backward linkage (A.2 and A.3) are clear, with both derived in the same way but for different views of the economy. Through the calculation of these linkage measures, how embedded within the economy a particular sector is can be determined. Theoretically speaking, the higher the forward and backward linkages of a sector, the greater its relative importance within the economy (Miller and Blair 2009d).

A.1.2 Multipliers

The concept of a multiplier within IO modelling is used to quantify the total impact of a change within the economy, covering direct, indirect and induced effects (Miller and Blair 2009c). Multipliers capture not only the change due to the initial shock, but also the knock-on effect throughout all sectors of the economy. Assuming an exogenous change to final demand for sector j, the *output* multiplier for sector j will capture the total amount of production required from all sectors to produce this one unit increase. This measure is calculated by the column summation of the Leontief inverse matrix (Scottish Government 2020a):

$$(O_{mult})_j = \sum_i l_{ij} \tag{A.8}$$

Though there may be circumstances where total output is the measure of interest, typically measuring the impact of an exogenous change on elements such as employment or GVA would be of greater importance. To this end, multipliers to estimate these effects can be defined. Considering employment, the information contained within the IO table is still required, but combined with this is a 1 × n column matrix of *employment-output coefficients*, e_i. These are defined as:

$$e_i = \frac{E_i}{x_i} \tag{A.9}$$

Where E_i is the FTE employment in sector i, and x_i is the gross output of that sector. Following this, the *employment effect*, or *employment-output multiplier*, for a unit increase in final demand of sector j is calculated as (Scottish Government 2020a):

$$(E_{eff})_j = \sum_i e_i l_{ij} \tag{A.10}$$

Where l_{ij} are elements of the Leontief inverse matrix. This measure indicates the total amount of employment generated within the economy per unit change in sector j output. Alternately, it may be preferable to investigate the amount of FTE employment created throughout the economy not for a unit change in sector j, but for a change large enough to bring about one additional FTE job within that sector (Scottish Government 2020a). This is termed the *employment multiplier*, and is given by:

$$(E_{mult})_j = \sum_i \frac{e_i l_{ij}}{e_j} \tag{A.11}$$

Where e_j is the employment-output coefficient for sector j, the sector which is receiving the change in final demand. Similar calculations can be performed to produce multipliers for GVA, with the resulting equations (Scottish Government 2020a):

$$(GVA_{eff})_j = \sum_i (gva)_i l_{ij} \quad \text{and} \quad (GVA_{mult})_j = \sum_i \frac{(gva)_i l_{ij}}{(gva)_j} \tag{A.12}$$

Where $(gva)_i$ is the ratio of GVA for sector i to the total output for sector i, in the same way as the employment-output coefficients are calculated in equation A.9. The measures covered here are not an exhaustive list, and multipliers for other markers such as household income can be calculated in a similar way. However, it is instructive to know that there are ways of calculating the impact on different socioeconomic markers through the information held in the Leontief inverse matrix.

The measures discussed until now can be classed as *Type I* multipliers, capturing the direct and indirect impacts of a change in final demand of a sector. To extend the analysis to induced effects requires the introduction of *Type II* multipliers. In the Type II model, household expenditure is no longer considered exogenous as part of final demand, and is instead endogenised — often termed "clos[ing the model] with respect to households" — with households essentially treated as an additional industry in the interindustry inputs section of the IO table (Miller and Blair 2009c, p244). This action allows for induced effects to be assessed within the economy, as households receive payment for labour in the form of wages, and then spend this income across various sectors of the economy.

If a change in final demand is again considered, this triggers the same increase in output as before, but now it is also included that the change will induce an increase in wages paid to households working in that sector (Miller and Blair 2009c). This in turn means they will spend this extra wage on increased household expenditure, distributing it out across multiple sectors of the economy, thus stimulating an increased demand for these sectors which may not be captured in the direct or indirect case. Thus it is expected that Type I multipliers underestimate the true impact on the economy of an increase in final demand of sector j (Miller and Blair 2009d). As such, it is important when carrying out any IO modelling that consideration is taken to ensure that the most appropriate multipliers are being analysed.

A.1.3 Assumptions of Input-Output Modelling

Though touched on at the start of Section A.1, it is important to outline any assumptions made to allow for IO analysis to be carried out. These are often viewed as drawbacks of the model, so it is imperative to understand these when making a choice on the most appropriate modelling technique for a given investigation.

1. The technical coefficients, a_{ij} are assumed to be fixed (Miller and Blair 2009a). For example, if the output of sector j was to double, the inputs it uses from sector i also have to double. This removes any economies of scale in production from being accounted for in the IO model, and the framework is said to operate under 'constant returns to scale'. Over a short period of time, this assumption can be justified as the technologies within a given sector should not be expected to change (Tan et al. 2018).

2. In addition to fixed technical coefficients, the ratio of inputs from different sectors

into sector j is assumed to be fixed — i.e. inputs are used in 'fixed proportions' (Erickson and Kane 2017). For instance, if sector j uses 2 units from sector 1 and 4 units from sector 2, the ratio of inputs between sectors 1 and 2 is 0.5. If sector j wants to double its output, it now has to use 4 units from sector 1 and 8 from sector 2. Thus the ratio between the two sectors remains at 0.5. Additionally, this implies that there can be no substitution between inputs. If sector 2 is not able to double its output, then the output of sector j cannot increase (Erickson and Kane 2017).

3. Within an IO model, there are assumed to be no supply constraints (Tan et al. 2018). For an increase in final demand of a given sector, it is assumed that all upstream sectors can immediately react to the change in demand.

4. In the demand-driven model, it is assumed that all interindustry trade is dependent on the output of the sector acting as the purchaser (Miller and Blair 2009a). In other words, the flow of inputs depends only on the output of sector j. This is the assumption which underpins the technical coefficients, and allows for analysis after a change in the level of final demand for sector j.

5. Finally, the last major assumption which impacts upon the suitability of IO modelling for some purposes is the aggregation of 'households' into only one sector (Erickson and Kane 2017). In this formulation, distribution of household incomes cannot be analysed, nor can transfers between households and government. This issue is remedied under CGE analysis, which utilises a Social Accounting Matrix (SAM) instead of a simple IO table. In the SAM, which is still an extension of the IO accounts, there is additional data in the table which illustrates the flows between value added inputs and final demand (Erickson and Kane 2017). For instance, households as providers of labour are linked to households or government as consumers of final demand. The details of how the SAM is used in CGE analysis are discussed in Section A.2.

A.2 Computable General Equilibrium Modelling

Computable General Equilibrium (CGE) is a commonly applied economic modelling method which, similarly to IO, can be used to account for interdependencies between different economic sectors (Scottish Government 2016). One key area of difference from IO however, is that both supply and demand sides of the economy can be modelled. This allows for variations in prices to be accommodated within the model, unlike in the IO case. Additionally, CGE modelling allows constraints within resource and capacity to be applied and accounted for.

The input data used for CGE modelling is the Social Accounting Matrix, which was mentioned in Section A.1.3 as an extension of an IO table. The SAM is a square matrix which takes IO data as one of its inputs, but also requires data for a range of other transactions such as household and government expenditure (Scottish Government 2016). In the CGE case these are treated as both producers and consumers (Hosoe et al. 2010). For instance, households provide labour as an output, but their expenditure includes taxes paid to the government alongside their consumption of intermediate inputs as included in the IO formulation. This additional data may come from sources such as national accounts (Scottish Government 2016), or may be inferred based on the rule that row and column sums must be equal (Hosoe et al. 2010).

In the context of economic modelling, equilibrium describes the situation when agents within the economy from both the supply and demand side reach a trade agreement on the best price for a given commodity (Cardenete et al. 2017a). Essentially this is the case when supply and demand for the commodity are the same. Under a partial equilibrium model, the focus is only on one sector which is in equilibrium, whilst changes in the rest of the economy do not impact upon it. On the other hand, a general equilibrium model covers the case where “the economy [is] a closed and interdependent system of markets where equilibrium prices and quantities are the result of [...] economy-wide interactions” (Cardenete et al. 2017a, p7). In other words, all sectors within the economy are in equilibrium, and changes in one can have knock-on effects in others (Scottish Government 2016).

The theory of general equilibrium was first proposed by Léon Walras in 1874 (Cardenete et al. 2017b). However, this was a purely theoretical formulation, and modelling based on this theory using real economic data was not developed until much later. Models which apply a numerical framework to the general equilibrium theory are hence termed *computable* equilibrium models, as they can be solved numerically (Hosoe et al. 2010). The use of these models allows for computational analysis of shocks to the economy, or the impact of changes in policy (Scottish Government 2016). As discussed by Hosoe et al. (2010), the popularity of CGE modelling has increased as it offers a way to assess issues relating to lack of resources across the economy, and the application of policy developed to target the problem.

The structure of CGE modelling applies real economic data to a series of equations which are formulated to represent the structure of the economy and inter-relationships between sectors (Scottish Government 2016). The original, baseline, data is assumed to represent an economy in equilibrium. A shock is then applied to the model, and through the system of equations a new equilibrium for the economy is computed — finding the new level of prices and shares of commodities across all sectors of the economy to allow for equilibrium with the shock present. The difference between this new equilibrium and the baseline state then represents the impact of the shock (Scottish Government 2016).

Thus, though the basic data which informs the CGE model is essentially a reframing of the IO table with some additions, the process of analysis is fundamentally different. CGE requires more detailed numerical analysis than in the basic IO case, with a system of n equations representing the relationships of all sectors of the economy having to be defined. However, there are a number of aspects of CGE modelling which overcome the assumptions that have to be made for IO modelling. These include:

1. Under the IO framework, no supply constraints are modelled. The CGE case

allows for constraints to be applied to the system (Scottish Government 2016).

2. Within IO, fixed technical coefficients and input ratios are assumed. From this, it is implicit that there can be no substitution of inputs. The CGE modelling framework does not prohibit substitutions within production (Hosoe et al. 2010).

3. The CGE model incorporates both the supply and demand sides of the economy (Cardenete et al. 2017a).

As such, there will be cases where the argument will be for using CGE over IO in economic analysis, depending on the metrics or shocks that are to be assessed within the research.

A.3 IO versus CGE

Having performed a brief overview of both IO and CGE modelling, it is then pertinent to compare the framework of both and determine which is most applicable to the analysis which is presented within this thesis. In both cases the base data is essentially the same, with the core SAM being formulated from IO tables and the sectoral interdependency of the IO accounts (Scottish Government 2016; Rose 1995). Thus the question can solely be framed as a modelling preference, rather than being subject to differing data requirements — though there is the added onus on disaggregating the value added and final demand categories (Hosoe et al. 2010).

Considering first some of the underlying assumptions within IO modelling (as discussed in Section A.1.3), these are often proposed as limitations to the technique and justification that other methods such as CGE are inherently more accurate. However, the CGE framework is not without its own drawbacks. Primarily, the key assumption within the model is that the economy is in equilibrium (Cardenete et al. 2017a). This in and of itself is a restrictive assumption which relies upon the economy having optimised itself (Rose 1995).

Additionally, a further often cited criticism of IO is that households are not properly accounted for under the IO framework (Erickson and Kane 2017). While it is true that the SAM has the possibility for the household sector to be assessed at a greater level of disaggregation, and accounts for households as a producer of commodity as well as a consumer, utilising Type II IO analysis does endogenise household behaviour into the model (Hosoe et al. 2010; Miller and Blair 2009c). The primary impacts would be the influence upon induced effects caused by any change in levels of household income. The aims of this thesis are to assess the supply chain impacts of offshore wind and, as such, household behaviour is not assumed to directly influence the metrics regarding the offshore wind sector which will be analysed. If household effects are deemed to be relevant to particular aspects, then the use of Type II multipliers can be introduced into the IO framework.

With regards to the aim of the economic analysis of this thesis, one of the key themes throughout the research is the embeddedness of the offshore wind industry within the economy. As stated by Rose (1995), Leontief's IO technique is a "general interdependence" model, rather than general equilibrium (Rose 1995, p295). It does not require that the economy is equilibrated, and the emphasis is instead on interactions between sectors. Finally, input-output tables comprise real, observable data from the nation or region they cover Miller and Blair (2009b). This means that the information contained within is quantifiable and easily understood by non-economists, represented as it is in a relatively simple table format and analysed primarily through matrix algebra Rose (1995). Much of the the work in this thesis relates to the policy and engineering aspects of offshore wind, and how supply chain considerations should be recognised as an important part of gaining local content and ultimately improving economic benefit. As such, the work is of interest and relevance to stakeholders across industry and government. The relatively lower complexity of IO analysis as compared to CGE is of benefit for the wider understanding and accessibility of the outputs of this thesis, to ensure that the results of the analysis performed is as communicable as possible to stakeholders from a variety of backgrounds. With this in mind, it is then justifiable to make the argument to utilise the IO framework for the analysis within this thesis, as there is a clear alignment between these points and the thesis aims.

Appendix B

IO Table Sectors

Table B.1: Aggregated SIC sectors of 2010 and 2018 UK IO tables

SIC		
Section	**Sector**	**Industry**
A	1	Crop and animal production, hunting and related service activities
	2	Forestry and logging
	3	Fishing and aquaculture
B	5	Mining of coal and lignite
	6 & 7	Extraction of crude petroleum and natural gas & mining of metal ores
	8	Other mining and quarrying
	9	Mining support service activities
C	10.1	Processing and preserving of meat and production of meat products
	10.2 – 3	Processing and preserving of fish, crustaceans, molluscs, fruit and vegetables
	10.4	Manufacture of vegetable and animal oils and fats
	10.5	Manufacture of dairy products
	10.6	Manufacture of grain mill products, starches and starch products
	10.7	Manufacture of bakery and farinaceous products

Continued on next page

Table B.1 — continued from previous page

Section	**Sector**	**Industry**
C	10.8	Manufacture of other food products
	10.9	Manufacture of prepared animal feeds
	11.01 - 06 & 12	Manufacture of alcoholic beverages & tobacco products
	11.07	Manufacture of soft drinks; production of mineral waters and other bottled waters
	13	Manufacture of textiles
	14	Manufacture of wearing apparel
	15	Manufacture of leather and related products
	16	Man. of wood & products of wood & cork, except furniture; man. of articles of straw and plaiting materials
	17	Manufacture of paper and paper products
	18	Printing and reproduction of recorded media
	19	Manufacture of coke and refined petroleum products
	20.3	Manufacture of paints, varnishes and similar coatings, printing ink and mastics
	20.4	Manufacture of soap & detergents, cleaning & polishing, perfumes & toilet preparations
	20.5	Manufacture of other chemical products
	20A	Manufacture of industrial gases, inorganics & fertilisers (inorganic chemicals) - 20.11/20/13/15
	20B	Manufacture of petrochemicals - 20.14/16/17/60
	20C	Manufacture of dyestuffs, agro-chemicals - 20.12/20
	21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
	22	Manufacture of rubber and plastic products
	23.5 – 6	Manufacture of cement, lime, plaster and articles of concrete, cement and plaster
	23OTHER	Manufacture of glass, refractory, clay, porcelain, ceramic, stone products - 23.1-4/7-9
	24.1 – 3	Manufacture of basic iron and steel
	24.4 – 5	Manufacture of other basic metals and casting
	25.4	Manufacture of weapons and ammunition

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Section	Sector	Industry
C	25OTHER	Manufacture of fabricated metal products, exc. weapons and ammunition - 25.1-3/5/9
	26	Manufacture of computer, electronic and optical products
	27	Manufacture of electrical equipment
	28	Manufacture of machinery and equipment n.e.c.
	29	Manufacture of motor vehicles, trailers and semi-trailers
	30.1	Building of ships and boats
	30.3	Manufacture of air and spacecraft and related machinery
	30OTHER	Manufacture of other transport equipment - 30.2/4/9
	31	Manufacture of furniture
	32	Other manufacturing
	33.15	Repair and maintenance of ships and boats
	33.16	Repair and maintenance of aircraft and spacecraft
	33OTHER	Rest of repair; Installation - 33.11-14/17/19/20
D	35.1	Electric power generation, transmission and distribution
	35.2 – 3	Manufacture of gas; distribution of gaseous fuels through mains; steam and aircon supply
E	36	Water collection, treatment and supply
	37	Sewerage
	38	Remediation activities and other waste management services
F	41 – 43	Construction
G	45 – 47	Wholesale and retail trade
H	49.1 – 2	Rail transport
	49.3 – 5	Land transport services and transport services via pipeline, exc. rail transport
	50	Water transport
	51	Air transport
	52	Warehousing and support activities for transportation
	53	Postal and courier activities
I	55	Accommodation

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Section	Sector	Industry
I	56	Food and beverage service activities
J	58	Publishing activities
	59 – 60	Motion picture, video and TV programme production, sound recording and music publishing activities & programming and broadcasting activities
	61	Telecommunications
	62	Computer programming, consultancy and related activities
	63	Information service activities
K	64	Financial service activities, except insurance and pension funding
	65.1 – 3	Insurance, reinsurance and pension funding, except compulsory social security
	66	Activities auxiliary to financial services and insurance activities
L	68	Real estate activities
M	69.1	Legal activities
	69.2	Accounting, bookkeeping and auditing activities; tax consultancy
	70	Activities of head offices; management consultancy activities
	71	Architectural and engineering activities; technical testing and analysis
	72	Scientific research and development
	73	Advertising and market research
	74	Other professional, scientific and technical activities
	75	Veterinary activities
N	77	Rental and leasing activities
	78	Employment activities
	79	Travel agency, tour operator and other reservation service and related activities
	80	Security and investigation activities
	81	Services to buildings and landscape activities

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Table B.1 — continued from previous page

Section	Sector	Industry
N	82	Office administrative, office support and other business support activities
O	84	Public administration and defence; compulsory social security
P	85	Education
Q	86	Human health activities
	87 – 88	Residential care and social work activities
R	90	Creative, arts and entertainment activities
	91	Libraries, archives, museums and other cultural activities
	92	Gambling and betting activities
	93	Sports activities and amusement and recreation activities
S	94	Activities of membership organisations
	95	Repair of computers and personal and household goods
	96 & T97	Other personal service activities

Appendix C

Case Study Results

Table C.1: Case study results per SIC sector

SIC Sector	**Δx** (£m)				**ΔGVA** (£m)				**ΔE** (jobs)			
	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
A1	86	68	63	94	33	27	24	37	1463	1160	1069	1610
A2	69	51	47	69	28	21	19	28	670	496	457	663
A3	5	4	4	6	1	1	1	2	28	23	21	32
B5	9	6	6	8	4	3	3	4	30	22	20	29
B6 – 7	196	137	126	165	124	87	80	105	82	57	53	69
B8	265	213	196	316	84	67	62	100	861	690	636	1026
B9	57	44	40	60	14	11	10	15	213	164	151	225
C10.1	75	60	56	85	18	15	14	21	344	277	255	389
C10.2 – 3	48	39	36	54	13	10	10	15	239	192	177	269
C10.4	3	2	2	3	0	0	0	0	8	6	6	9
C10.5	22	17	16	24	5	4	4	6	54	43	39	59
C10.6	14	11	11	16	3	3	2	4	24	19	18	27
C10.7	48	39	36	54	19	16	14	22	490	394	363	554
C10.8	58	47	43	65	21	17	15	23	279	224	206	313
C10.9	17	14	13	19	3	2	2	3	38	31	28	43
C11.01-06&12	22	18	16	24	8	6	6	9	62	50	46	68
C11.07	9	7	7	10	4	3	3	4	21	17	16	23
C13	41	33	30	46	22	18	17	25	310	251	231	349
C14	4	3	3	4	2	2	2	3	22	17	16	24
C15	3	2	2	3	1	1	1	1	30	24	22	34
C16	368	295	272	443	136	109	100	164	2969	2376	2188	3570

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Table C.1 — continued from previous page

SIC Sector	Δ**x** (£m)				Δ**GVA** (£m)				Δ**E** (jobs)			
	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
C17	115	91	84	124	39	31	28	42	556	440	405	599
C18	63	50	46	68	28	22	21	30	571	452	416	615
C19	438	335	308	459	47	36	33	49	131	101	93	138
C20.3	71	55	51	81	24	19	17	28	338	263	243	383
C20.4	13	10	9	14	6	5	5	7	46	37	34	51
C20.5	34	28	25	40	11	9	8	13	134	107	98	154
C20A	45	34	32	47	9	7	6	9	112	85	78	115
C20B	161	130	120	185	31	25	23	36	262	212	195	302
C20C	8	6	5	8	3	3	2	4	24	19	18	27
C21	38	31	28	41	19	15	14	20	60	48	44	64
C22	449	357	328	520	145	115	106	168	3043	2416	2225	3526
C23.5 – 6	435	347	319	531	180	143	132	220	1639	1308	1204	2003
C23OTHER	213	171	157	266	75	60	56	94	1759	1414	1302	2203
C24.1 – 3	268	209	192	314	60	47	43	70	1069	833	767	1253
C24.4 – 5	240	189	174	243	82	65	59	83	1259	989	911	1272
C25.4	39	29	27	37	11	9	8	11	131	97	90	123
C25OTHER	5918	4866	4482	6188	2887	2374	2186	3018	60602	49833	45895	63366
C26	291	223	205	296	168	129	119	171	1508	1152	1061	1531
C27	3865	3188	2936	5548	1411	1163	1071	2025	22560	18605	17135	32381
C28	4470	3652	3363	4449	1875	1532	1411	1867	19743	16130	14856	19653
C29	175	134	123	181	46	35	32	48	457	350	322	475

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Table C.1 — continued from previous page

SIC Sector	Δ**x** (£m)				Δ**GVA** (£m)				Δ**E** (jobs)			
	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
C30.1	2841	2347	2162	3773	1305	1078	993	1733	20736	17128	15775	27532
C30.3	63	50	46	68	21	16	15	22	200	160	147	216
C30OTHER	39	27	25	33	12	9	8	10	197	139	128	170
C31	42	34	31	51	20	16	15	24	432	347	320	521
C32	2468	2038	1877	2115	1245	1028	947	1067	18492	15268	14061	15843
C33.15	109	88	81	138	75	61	56	95	646	523	482	819
C33.16	26	20	19	27	9	7	7	10	94	74	68	96
C33OTHER	4518	2975	2740	3339	2090	1376	1267	1544	34420	22666	20875	25441
D35.1	4341	2963	2729	3469	952	650	599	761	4875	3328	3065	3896
D35.2 – 3	653	461	424	560	127	90	82	109	927	654	603	796
E36	83	66	61	89	58	46	42	62	286	228	210	309
E37	70	56	51	80	56	44	41	64	167	133	123	192
E38	159	126	116	179	53	42	39	60	1038	825	759	1174
E39	4	3	3	4	2	1	1	2	30	24	22	34
F41 – 43	19493	15520	14294	24023	7436	5920	5453	9164	91876	73150	67370	113222
G45 – 47	3580	2840	2615	3942	2015	1598	1472	2218	48567	38523	35479	53471
H49.1 – 2	21	16	15	23	7	6	5	8	87	69	63	96
H49.3 – 5	713	569	524	779	338	270	248	369	7380	5885	5420	8061
H50	2469	1810	1667	2351	1060	777	716	1009	2614	1917	1766	2489
H51	201	160	147	201	39	31	29	39	611	486	447	611
H52	505	400	369	540	232	184	169	248	5646	4476	4122	6041

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Table C.1 — continued from previous page

SIC Sector	Δ**x** (£m)				Δ**GVA** (£m)				Δ**E** (jobs)			
	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
H53	265	211	194	282	152	121	111	162	3140	2496	2299	3339
I55	112	93	85	114	63	52	48	64	1815	1505	1386	1852
I56	73	59	55	77	39	32	29	41	1837	1493	1375	1934
J58	61	48	44	64	33	26	24	35	335	262	242	352
J59 – J60	101	81	75	108	45	36	33	48	351	282	260	374
J61	390	312	287	412	246	196	181	259	1455	1163	1071	1538
J62	710	569	524	770	393	315	290	426	6119	4901	4514	6633
J63	98	79	73	102	57	47	43	60	530	430	396	555
K64	1360	1081	995	1475	684	544	501	742	3927	3121	2875	4260
K65.1 – 3	276	218	201	306	102	80	74	113	361	285	262	400
K66	609	482	444	646	343	271	250	364	3247	2569	2366	3444
L68	400	321	296	425	315	253	233	335	716	574	529	760
M69.1	441	357	329	476	340	275	253	366	4056	3283	3024	4374
M69.2	360	291	268	368	291	235	216	297	5266	4251	3915	5376
M70	2299	2039	1878	2290	1093	969	893	1088	38167	33857	31182	38018
M71	1963	1665	1533	1998	870	737	679	885	20326	17236	15874	20689
M72	169	138	127	180	77	63	58	82	737	603	555	785
M73	333	269	248	354	196	158	146	209	1718	1388	1278	1829
M74	1483	1282	1181	1448	636	550	506	621	15187	13129	12092	14824
M75	3	3	2	4	2	2	2	3	41	33	30	46
N77	600	455	419	618	407	308	284	419	3178	2409	2219	3276

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Table C.1 — continued from previous page

SIC Sector	**Δx** (£m)				**ΔGVA** (£m)				**ΔE** (jobs)			
	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
N78	832	665	613	939	527	421	388	595	18358	14678	13519	20725
N79	233	174	161	225	95	71	66	92	902	675	621	872
N80	102	81	75	122	61	49	45	74	3762	2996	2760	4529
N81	239	192	177	257	115	92	85	124	7704	6192	5703	8283
N82	243	198	182	259	122	99	91	130	2869	2337	2152	3057
O84	303	249	229	329	174	142	131	188	2462	2019	1859	2671
P85	239	182	168	226	170	130	119	160	4058	3097	2852	3834
Q86	27	22	20	31	17	13	12	19	398	320	295	448
Q87 – 88	14	11	11	16	9	7	6	10	330	263	243	369
R90	14	11	11	15	7	6	6	8	98	81	74	104
R91	2	2	2	3	1	1	1	2	63	51	47	69
R92	17	14	13	19	11	8	8	12	120	96	88	131
R93	34	28	25	37	20	16	15	21	757	608	560	812
S94	20	16	15	21	12	10	9	12	369	297	273	385
S95	13	10	10	14	8	7	6	9	154	123	114	170
S96 & T97	27	21	19	30	21	17	16	24	269	213	196	298
TOT. (1,000)	**75.6**	**59.7**	**55.0**	**82.1**	**32.6**	**25.9**	**23.8**	**35.3**	**518.7**	**416.7**	**383.8**	**562.1**

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