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Energy Systems Transition towards Carbon Neutrality:

**Insights from the United Kingdom and Assessments
of the United Arab Emirates**

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Declaration

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Declaration of Originality

I hereby declare, unless explicitly indicated otherwise, that the work presented in this dissertation is my own.

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Abstract

This thesis investigates the complex landscape of decarbonisation with a specific focus on energy net-importers and net-exporters. Drawing on case studies of the United Kingdom (UK) and the United Arab Emirates (UAE), this thesis highlights their distinct paths and challenges. The UK, as a net-importing nation, grapples with energy security concerns amid external economic influences, while the UAE, a major net-exporter of fossil fuels, faces the challenge of reconciling transition efforts with its economy. In the UK, it was found that biomass-based generating capacities persisted despite fuel price fluctuations, emphasising the necessity of maintaining a diversified portfolio of biomass supply. From a net-exporters perspective, carbon capture and storage (CCS) emerges as pivotal in decarbonisation with direct air capture removing hard-to-abate emissions. Tailored strategies critically will need to emerge for both nations, with the UK emphasising the role of existing infrastructure and biomass-based technologies, while the UAE prioritising clean energy initiatives. By understanding their differences and leveraging tailored approaches, these nations can navigate the transition through strategies focused on biomass in the UK and natural gas in the UAE, ensuring a sustainable and resilient future while safeguarding economic prosperity and energy security.

Dedication

I dedicate this work to the esteemed Rulers of the United Arab Emirates. May Allah grant them a long, healthy and prosperous life.

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

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‘Every individual has to perform his duty. Man is mortal, but his work is not. Therefore, work is greater than wealth.’

Shaikh Zayed bin Sultan Al Nahyan

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List of Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
bio	Biomass-Based
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Dioxide Removal
CO₂	Carbon Dioxide
DAC	Direct Air Capture
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ESO	Energy Systems Optimization
EU	European Union
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added

GW	Gigawatt
H.H.	His Highness
HEFA	Hydroprocessed Esters and Fatty Acids
HFO	Heavy Fuel Oil
Hz	Hertz (Frequency)
IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organisation
ICE	Internal Combustion Engine
IRENA	International Renewable Energy Agency
JEDI	Job and Economic Development Impact
KSA	Kingdom of Saudi Arabia
LNG	Liquified Natural Gas
MENA	Middle East and North Africa
MILP	Mixed-Integer Linear Programming
MSW	Municipal Solid Waste
mt	million ton(s)
mt/yr	million ton(s) per annum
NDC	Nationally Determined Contributions
NETs	Negative Emissions Technologies
OPEX	Operating Expenditure
OPEXFix	Fixed Operating Expenditure
OPEXNL	Non-Linear Operating Expenditure
OPEXSU	Operating Expenditure for Start-Up

PHSto	Power-to-Hydrogen Storage
PtL	Power to Liquid
SAF	Sustainable Aviation Fuel
TJ	Terajoule
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

Chapter 1

Introduction

1.1 Background

The process of carbonisation within economies spanned over a century, culminating in the challenge of climate change [1, 2]. The repercussions of this phenomenon manifest as abysmal environmental shifts, ranging from widespread droughts, floods and wildfires [3, 4, 5]. Recognition of the issue gained traction as early as 1968 within the United Nations (UN) [6], eventually leading to the historic 2015 Paris Agreement. This landmark accord saw the commitment of 175 nations to curbing the global temperature increase to below 2°C [7, 8]. In response to the imperative outlined in the Agreement, the Intergovernmental Panel on Climate Change (IPCC) issued its fifth report, emphasising the necessity of mitigating greenhouse gas (GHG) emissions to counteract the global temperature impact [9]. The collective pursuit of this objective found expression in the following Conference of Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC), where collaborative efforts were fostered [10]. Notably, the most recent iteration (COP-28) marked the initiation of a comprehensive global financing framework aimed at further incentivising actions to reduce GHG emissions [11].

In the pursuit of decarbonisation, the availability of monetary incentives plays a pivotal role in reducing associated costs required by stakeholders [12, 13]. Stakeholders encompass a spectrum from public sectors to private entities, each with distinct priorities, where the goal remains consistent – decarbonisation [14]. Given diverse regional contexts, with some countries nationalising resources and others adopting privatisation strategies, there is no universal pathway for decarbonisation. In considering the economic impacts, it becomes imperative to explore this multifaceted landscape of different economic structures to optimise the cost of decarbonisation [15]. Crafting a thorough strategy that alleviates the impact of escalating energy prices is crucial. This strategy ensures that decarbonisation efforts do not negatively affect the job market and the broader economy. By undertaking this whole system approach, stakeholders not only contribute to maintaining a stable economy, but also safeguard sectoral employment levels. This, in turn, fosters increased economic value, establishing a positive feedback loop that reinforces the sustainability of decarbonisation efforts [16].

In the context of global decarbonisation commitments, a rigorous examination of the current position of nations is imperative. As an illustration, countries within the European Union (EU) have pledged to attain a 2050 target, yet their current trajectories exhibit variances as shown in Figure 1.1 within the power sector. The observed shifts are noteworthy; certain nations have undergone a lateral adjustment to the left attributed to nuclear power decommissioning, while others have undergone a vertical descent attributable to fossil fuel decommissioning. This multifaceted panorama emphasises the urgency of adopting a comprehensive decarbonisation approach in each nation for the anticipation and comprehension of future developments. An additional illustrative commitment implemented by the EU is the enforcement of the Carbon Border Adjustment Mechanism (CBAM), designed to forestall emissions offshoring [17]. This regulatory measure stands as an exemplar, constituting a constructive stride towards the goal of global decarbonisation for both importing and exporting countries. Remarkably, this mechanism requires net-exporting countries to either neutralise the emissions linked to the products exported to the EU or pay a carbon tax [18], thereby exerting additional pressure on

non-EU nations to actively participate in the transition towards carbon neutrality.

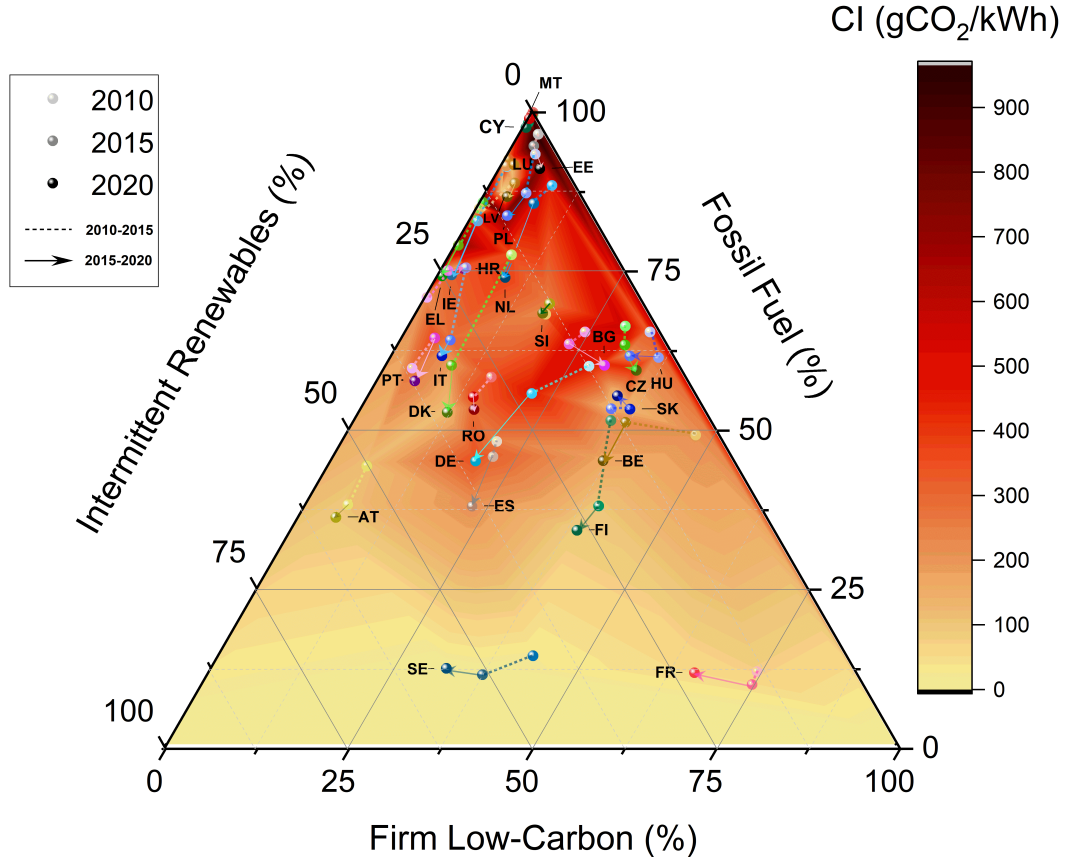


Figure 1.1: This figure illustrates the power generation mix of European Union countries for the years 2010, 2015, and 2020. The color intensity of the symbols corresponds to the timeline, with darker shades indicating more recent years. The arrowhead points to the year 2020. All data presented in this figure are sourced from the European Commission database [19].

The central challenge lies in determining the optimal starting points to initiate the decarbonisation process within an economy. This inquiry gains complexity when considering the intricate interconnections among diverse economic sectors [20]. A notable illustration of this complexity lies in the endeavour of electrifying the transport sector. This pursuit requires substantial expansion of the power grid [21] that is constrained by the geographically available resources [22, 23]. To effectively address the intricate web of sectoral interactions it is necessary to adopt an integrated modelling approach that considers multiple economic sectors. Such modelling are indispensable for identifying effective decarbonisation pathways which can provide policymakers with a strategic foundation for

formulating incentives aimed at fostering carbon mitigation measures [24, 25]. This brings paramount significance given the diversity of available mitigation methods, ranging from energy efficiency, demand reduction [9, 26], decreasing fugitive emissions [27], fuel switching [9] to carbon dioxide removal (CDR) [28, 29]. Recognising the geographic nuances in the application of these methods is crucial for crafting tailored strategies capable of adapting to unforeseen events.

1.2 Motivation

Nations worldwide from different continents have made a collective commitment to attain carbon neutrality, marking a global shift towards net-zero emissions. This movement is inclusive of countries with diverse economic structures, prompting a critical examination of how these nations will translate their ambitious pledges into tangible actions. The European continent has emerged as a trailblazer, pledging to achieve decarbonisation by establishing its 2019 Green Deal [30]. Notably, Asian nations, such as Japan and Singapore, joined the 2050 carbon neutrality commitment in 2020 and 2022, respectively [31, 32]. Subsequently, these countries have taken substantial measures to actualise their goals, with Japan mandating the installation of solar panels in new built homes from 2025 and Singapore adopting a carbon tax strategy aiming for \$50 per ton of carbon dioxide (CO₂) by 2030 [33, 34]. However, despite the earnest efforts towards decarbonisation, unexpected global events can disrupt these trajectories. For instance, the Russian-Ukrainian war that led to a surge in natural gas prices, compelling countries like Germany to re-evaluate its coal-phaseout strategies [35]. A similar scenario unfolded during the COVID-19 pandemic when natural gas prices dropped, impacting foreign investments in the energy sector [36]. These setbacks show the vulnerability of the decarbonisation path when energy security is compromised, directly affecting a nation's economic growth [37, 38].

Energy security plays a central role in a nation's pursuit of economic growth, serving as a critical component of the energy trilemma alongside environmental sustainability and energy equity. Achieving energy security is not only an independent objective, but also a linchpin for realising the broader goals of the energy trilemma [39]. The successful realisation of energy security hinges upon balancing factors encompassing energy dependence, supply security, self-sufficiency, resilience and the diversification of energy sources. This intricate and multifaceted definition is imperative for effectively safeguarding a country's energy security [40]. Net-importing nations are particularly vulnerable to energy security challenges due to their dependence on energy net-exporters and the economic dynamics associated with these exporting countries [41, 35, 37]. A robust energy security framework not only shields a nation from potential disruptions, but also facilitates a seamless transition to carbon neutrality without adverse effects on the economy. Therefore, the careful consideration and enhancement of energy security are crucial for maintaining the delicate balance between economic prosperity and sustainable energy practices [42].

While existing decarbonisation studies predominantly focus on energy net-importing nations, there is a critical gap in understanding how energy net-exporters can achieve national net-zero goals while ensuring the stability of their economies and meeting the needs of net-importers. This thesis aims to address this gap by investigating an energy system that serves as an energy supplier to multiple economies, working towards achieving net-zero emissions. The study utilises a national Integrated Assessment Model (IAM) to navigate the complex interplay of factors, with a central focus on maintaining a secure and resilient economy throughout the decarbonisation process. Furthermore, this thesis will shed light on the complex interdependence between net-importing and net-exporting economies, illustrating how economic conditions in exporting nations critically impact the energy security and decarbonisation efforts of importers

1.3 Climate Change and Net-Exporters

In the pursuit of leadership in a carbon-free world, numerous nations, both exporters and importers, have initiated programs focused on carbon-free fuels [43]. These fuels are developed through carbon-free technologies and are anticipated to counteract the projected growth of CO₂ in the atmosphere. Moreover, they are expected to usher in new industries, introducing technologies for both production and consumption. The looming challenge revolves around determining the costs associated with producing these future fuels and the requisite technologies for their consumption [44, 45, 46]. Currently, ammonia, hydrogen [47] and biofuels [48, 49] are among the prominently discussed alternatives with ongoing exploration. Consequently, fossil fuel-producing nations face the challenge of transitioning their economies towards these fuels while aligning with the Paris Agreement, meeting national commitments to carbon neutrality and economic strength.

Acknowledging the economic imperatives of net-exporters during the transition, this work aims to explore the challenges and strategies for achieving carbon neutrality without compromising economic stability. Notably, countries like the United Arab Emirates (UAE), Kingdom of Saudi Arabia (KSA) and Norway exemplify major net-exporters with ambitious decarbonisation goals. The UAE envisions carbon neutrality by 2050 [50], aligning with the economic milestone of 3 trillion Gross Domestic Product (GDP) by 2031 [51]. Similarly, KSA targets decarbonisation by 2060 [52] while achieving 50% share of non-oil exports by 2030 from a current 18.7% [53]. Norway, responsible for 117 billion cubic meters of natural gas needs in the EU [54], aspires to cut 55% of its emissions by 2030 from 1990 levels [55]. These nations highlight the intricate balance required by net-exporters to transition smoothly towards carbon neutrality without detrimental impacts on their economic and social fabric.

In light of time limitations, this thesis concentrates on a particular net-exporting country in its early stages of carbon mitigation. Historical perspectives are gleaned from a

net-importing country that is extensively examined in the literature and have initiated environmental sustainability measures long ago. Furthermore, the examination extends to evaluating the influence of external economies on the net-importing economy. This methodological approach facilitates an exploration of challenges and insights relevant to the distinctive contexts of both net-exporting and net-importing nations.

1.3.1 Case Studies

This thesis employs the United Kingdom (UK) and the UAE as case studies. The UK serves as the focal point for a net-importer assessment, examining the country's susceptibility to external economies. Given the multifaceted nature of these influences, fuel prices are selected as the primary measure for studying the impact on the transition in the UK. On the other hand, the UAE is chosen as the case study for net-exporting considerations, as the country is actively pursuing robust initiatives to decarbonise its economy.

The UK has been at the forefront of addressing climate change, setting a pioneering example for other nations by legally committing to achieving net-zero emissions by 2050 [56]. Recognising the imperative to curtail global warming, numerous studies assert that electricity will play a pivotal role as a primary energy carrier in the UK [57]. The UK has been a trailblazer in various clean technologies, particularly in offshore wind, where numerous projects are in progress [58, 59]. Moreover, the country has instituted a CDR initiative to counterbalance hard-to-abate sectors, primarily focusing on leveraging negative emissions technologies (NETs) within the power sector [60, 61]. This thesis conducts a rigorous examination of the power sector in the UK, stressing its resilience and adaptability to external economies in the context of carbon transition. While numerous external factors can influence this transition, this study places particular emphasis on fuel prices. Recent global events such as the COVID-19 pandemic and the Russian-Ukrainian war have shown the vulnerability of the UK's reliance on imported fuels [37], making fuel prices a pertinent factor for analysis.

The UAE stands as one of the world's foremost exporters of fossil fuels, contributing significantly to the energy needs of numerous major economies globally. In 2021 alone, the UAE exported 135 million tons per annum (mt/yr), equivalent to 2.7 million barrels of oil per day [62], accounting for 3.2% of the world's consumption [63]. Despite historically relying on fossil fuels within its economic framework, the UAE has demonstrated remarkable commitment to environmental conservation and decarbonisation in that frame. A noteworthy recent initiative to transitioning away from fossil was unveiled during COP-28, bolstering the UAE's dedication to advancing sustainability within its borders [64]. Furthermore, the nation has actively engaged in initiatives exploring alternative fuels, including ammonia [65], hydrogen [66] and sustainable aviation fuel (SAF) [67]. With an ambitious target of achieving net-zero emissions by 2050 [50] and simultaneously increasing oil exports to 250 mt/yr by 2027 [68], the UAE faces a pivotal challenge in orchestrating a seamless transition towards a sustainable and decarbonised future. This thesis seeks to comprehensively analyse and understand the strategies and mechanisms employed by the UAE in navigating this critical transition.

The remainder of this chapter will elaborate on the research questions that this thesis seeks to address and outline the structure of the subsequent chapters.

1.4 Objectives

This thesis acknowledges the imperative of achieving a seamless transition to a carbon-free economy without causing disruptive effects on the societal fabric, particularly to fluctuations in energy prices. The research presented in this thesis focuses on investigating the role and value of various low-carbon technologies. Specifically, the study explores the intricate interplay between sector characteristics, policy and techno-economic parameters of technologies in the context of the UK and the UAE. Through an examination of these two distinct countries, the thesis aims to:

- Evaluate and quantify the impact of fuel prices on the transition of the power sector towards carbon neutrality in the UK, with a specific focus on illustrating how external economies can influence net-importers.
- Assess and identify national priorities in the UAE to provide insights into the country's transition to a carbon-free economy.
- Measure the role and value of low-carbon dispatchable technology within the power sector in the UAE, focusing on the sector's contribution to the overall transition efforts.
- Quantify the available options for decarbonising existing industrial activities in the UAE, explore strategies to deliver decarbonised products to customers, and investigate technologies suitable for producing alternative fuels. Analyse the potential impact of these technologies on various sectors in terms of expansion and sustainability.
- Showcase how the transport sector in the UAE can transition to carbon neutrality by considering both passenger and freight transport, identifying key strategies and technologies for achieving sustainable practices in this sector.

- Quantify the social-economic impact of transition to a carbon-free economy in the UAE, examining its implications on various aspects of the society and economy.

1.5 Structure

The remainder of this thesis is organised as follows:

Chapter 2: This section outlines the IAM framework utilised throughout the thesis. It presents the system parameters and associated technology costs applied to the UK and the UAE.

Chapter 3: The initial part of this chapter delves into the history of environmental sustainability in the UK to extract valuable lessons. Subsequently, the chapter investigates the impact of fuel prices; specifically natural gas and biomass, on the transition, aiming to demonstrate a flexible strategy for ensuring a smooth transition.

Chapter 4: This chapter commences with an exploration of the political structure in the UAE, shaping the environmental practices. It then discusses the decarbonisation targets the UAE aspires to achieve and provides an in-depth analysis of the results within the power, industrial and transport sectors. The chapter also outlines various pathways to offset carbon in the UAE, along with the associated costs of each pathway. A sensitivity analysis for the relevant sectors is presented.

Chapter 5: To examine the social impact of transition in the UAE, this chapter showcases the positive impact of decarbonisation on the economy in terms of value added and employment levels. These are discussed for each sector.

Chapter 6: This concluding chapter summarises the key findings of the thesis regarding priorities for delivering a decarbonised energy system. It offers recommendations on how

the results can be utilised in response to fluctuations and suggests the needed actions. Additionally, this chapter provides insights for future research.

Chapter 2

Framework

2.1 Literature Overview

Numerous mathematical frameworks documented in the literature offer diverse approaches to model energy transition pathways for achieving specific goals. Various entities have developed distinct energy models, as evidenced in the literature. Comprehensive reviews conducted by Gargiulo et al. [69], Prokopczuk [70], Hall et al. [71], Ringkjøb et al. [72] and Lopion et al. [73] present recent lists, comparisons and categories of these models. A recurring theme among these models is their categorisation into top-down, bottom-up and hybrid models [74]. The top-down model primarily emphasises the economic aspects of transition, often neglecting the technical side. On the other hand, the bottom-up model examines the technical feasibility of transition, often overlooking the economic dimensions [75]. Nevertheless, hybrid models reconcile these categories by incorporating both economic and technical parameters in modelling energy transition. While the hybrid models appear to address the dual aspects of top-down and bottom-up, it typically relies on a soft link between the two models. In this arrangement, each model operates independently and the data output is transferred manually or through automation. Herbst

et al. highlights the scarcity of a hard link, where both models coexist in a single layout and run simultaneously [74]. The identified scarcity draws attention on a significant need that was addressed through the application of the Energy Systems Optimization (ESO) model. The ESO model systematically addresses transition problems by integrating both economic and technical aspects of the transition process. Therefore, this framework is employed in the present study to address the research objectives.

2.2 Energy Systems Optimisation (ESO) Framework

As discussed in Chapter 1, this thesis aims to explore the impact of fuel prices on the transition of an energy net-importer and investigate the decarbonisation of an energy net-exporter's entire economy. To accomplish this, the ESO tool developed by Heuberger et al. is employed in this study. This tool exists in several versions, each designed for specific purposes. Mainly, the ESO version is employed when detailed technical operation is required [76], where the ESO-X version focuses on capacity expansion. ESO-XEL examines the effect of a technology learning system [77] and ESONE is utilised when a focus on the spatio-temporal distribution of energy transition is necessary [78]. As the focus of this thesis is to achieve cost-optimal transition through capacity expansion, perfect foresight is assumed to be the most suitable approach. Accordingly, the ESO-X version is selected to model the energy systems of both the UK and the UAE. This model is a Mixed-Integer Linear Programming (MILP) model designed to minimise the total system cost. It operates on a multiscale framework, incorporating capacity expansion with unit commitment and utilising a 5-year planning period. Furthermore, this model utilises the S curve approach, which facilitates the growth of emerging technologies beyond historical build rates. The adaptation of the model to each country is elaborated upon in the subsequent sections of this chapter.

2.2.1 Framework Definition

In recent research focusing on the ESO-X model, Ganzer [79] brought attention to a significant gap in numerous energy models, particularly the lack of consideration for the industrial sector. Responding to this gap, an extension of the ESO-X model was developed to incorporate the industrial sector and its social economic impact. Building upon this foundation, the present study explores the representation of the transport sector within energy models and the value of alternative fuels for decarbonisation.

A thorough literature review indicates that the majority of energy models treat the transport sector merely as a component of overall power demand, often neglecting the existing infrastructure of fossil-dependent transport systems. Furthermore, emerging technologies and fuels in maritime and air transportation are frequently overlooked. Research by Detner et al. [80], Zencir et al. [81] and Oguntona et al. [82] did examine the decarbonisation of sea/air transport; however, these models were run in isolation. The predominant focus tends to be on road transport, with maritime and air transport always falling outside the model's scope. This tendency is evident in the reviews conducted by Nasrin et al. [83], Huma [84] and Huang et al. [85], where the discussed models exclusively consider the transport sector without other sectors and specifically road transport. While some publications, such as the work by Li et al. [86], do consider other sectors along transport, they often fall short of addressing the industrial sector or other facets of the transport sector. A similar pattern is observed in recent publications by Fu et al. [87] and Cleg et al. [88], where the focus is on meeting transport demand and the power sector relies solely on current generating technologies with a focus on hydrogen, neglecting NETs for carbon removal.

A recurring theme in the models available in the literature is the absence of an industrial representation, overlooking both the demand and fuel production aspects for transport. Furthermore, the consideration of NETs to address residual emissions from both the

industrial and transport sectors is frequently neglected. This literature gap emphasises the need for an integrated modelling approach that addresses the demand for power generation and industrial products, while considering the existing transport infrastructure and allowing NETs to remove residual emissions from all the sectors of the economy. To address this, the thesis adopts an innovative approach wherein the power, industrial and transport sectors are modelled simultaneously. This novel approach considers emerging technologies for delivering various products, particularly alternative fuels that can add value in terms of future industries and in decarbonising the transport sector.

The Power Sector Module

In detailing the power sector within the ESO-X model, comprehensive formulations are provided in section 2.2.2. Here, an overview will be presented, focusing on key aspects of the model pertaining to the power sector. The most relevant segment of the model to this work is addressing system requirements. This segment encompasses the electricity supplied by the grid and storage technologies to meet the energy requirement of hourly system demand and transmission losses while considering unmet demand. This component of the model has undergone further modifications to incorporate the electrical demand of the industrial and transport sectors. The final adjustment to this formula is presented later in this section and is captured in Equation 2.7. Moreover, the model integrates constraints related to the grid such as system inertia and reserve margin. For these constraints, a constant value is assumed irrespective of the system design.

To effectively represent the power sector, the model accounts for the retrofitting of existing unabated fossil capacity with carbon capture and storage (CCS). This strategic inclusion is designed to prevent premature decommissioning of new plants in alignment with the planned net-zero targets. Beyond this, the model incorporates the option of early decommissioning for technologies when retrofitting or maintaining the existing technology is not economically viable. This choice is particularly relevant due to the model's consid-

eration of no-load Operational Expenditure (OPEXNL) for operation in any mode. The model reflects this by considering existing coal, Combined Cycle Gas Turbine (CCGT) and biomass power plants as candidates for retrofitting with CCS.

It is important to highlight that a time clustering approach was employed to profile the hourly data input for electricity demand along solar, onshore and offshore wind availability profiles. This approach facilitates the computational efficiency of the model using the k-means clustering algorithm approach. The k-means algorithm is an iterative method that partitions datasets into subgroups, ensuring each data point belongs exclusively to one group. These data points are then assigned to a cluster in a manner that minimises the sum of squared distances between the data point and the cluster's centroid. To maintain consistency, all data are normalised by the maximum value present in each dataset. The outcome of this pre-processing step is the formation of 11-day clusters from the full-year hourly profiles, with each day encompassing 24 hours. This method enhances the model's ability to handle temporal variations in electricity demand and intermittent renewable energy availability efficiently. Table 2.1 describes the available technologies in this segment of the model.

Table 2.1: List of technologies used in the power sector segment of the ESO model [77].

Technology	Description
Nuclear	A facility that generates electricity through controlled nuclear reactions.
Coal	A steam turbine facility that produces electricity by burning coal, which heats water in a boiler to produce steam that drives a turbine connected to a generator.
Bio	A steam turbine facility that generates electricity using biomass, such as wood chips or agricultural waste.
CCGT	A combined cycle gas turbine facility that produces electricity by burning natural gas in a gas turbine, with the waste heat used to generate additional power in a steam turbine.

Continued on next page

Table 2.1 – continued from previous page

Technology	Description
OCGT	A facility that generates electricity using an open cycle gas turbine, which burns natural gas to drive a generator directly.
Coal-PostCCS	A new coal-fired power plant equipped with CCS technology.
Coal-PostCCSr	An existing coal-fired power plant retrofitted with CCS technology.
CCGT-PostCCS	A new natural gas-fired power plant equipped with CCS technology.
CCGT-PostCCSr	An existing natural gas-fired power plant retrofitted with CCS technology.
BECCS	A facility that generates electricity using biomass and incorporates CCS technology to achieve negative emissions by capturing and storing CO ₂ .
BECCSr	An existing facility that generates electricity using biomass that is retrofitted with CCS technology to achieve negative emissions.
Wind-Onshore	A wind farm located on land that generates electricity using wind turbines.
Wind-Offshore	A wind farm situated offshore that generates electricity using wind turbines.
Solar	A facility that generates electricity using solar energy through photovoltaic panels.
InterImp	A cross-border high voltage direct/alternative current electricity interconnector that facilitates the import of electricity from neighboring countries.
PHSto	Pumped hydro storage technology, involving two reservoirs at different elevations, where water is pumped to the upper reservoir during periods of low electricity demand and released to the lower reservoir during high demand to generate electricity.
Oil	A facility that generates electricity using a diesel generator fueled by diesel oil.

Continued on next page

Table 2.1 – continued from previous page

Technology	Description
H ₂ -CCGT	A facility that generates electricity using a combined cycle gas turbine fueled by hydrogen .

The Industrial Sector Module

In this section of the model, the production of industrial products is addressed following the mathematical formulation outlined in the work of Ganzer [79] and section 2.2.2. This segment considers the emissions associated with the production process to meet domestic demand while accounting for both import and export. A noteworthy novel extension to this model segment involves the inclusion of various products, each associated with its distinct production technologies. The added products are liquefied natural gas (LNG), aluminium, ammonia, hydrogen and SAF. The corresponding technologies for each product are detailed in Table 2.2 and Appendix B. This addition enhances the model’s capability to comprehensively capture the emissions and technological intricacies with the power sector for industrial production.

Table 2.2: List of technologies used in the industrial sector segment of the ESO model [65, 79, 89, 90, 91, 92, 93, 94].

Technology	Description
Cement	A facility specialising in cement production utilising kiln technology.
Cement-PCCS-r	An existing cement production facility retrofitted with CCS technology.
Cement-PCC-n	A newly constructed cement production facility equipped with CCS.
Cement-Oxy-r	A cement production plant retrofitted with oxy-combustion and post-combustion CCS technologies.
Cement-Oxy-n	A newly established cement production plant incorporating oxy-combustion and post-combustion CCS technologies.

Continued on next page

Table 2.2 – continued from previous page

Technology	Description
Steel-DRI	A plant employing direct reduction of iron (DRI) technique using syngas derived from natural gas to produce steel.
SteelDRI-CCS-n	A newly established plant utilising DRI technique with natural gas and equipped with CCS technology.
SteelDRI-CCS-r	An existing plant employing direct DRI technique with natural gas retrofitted with CCS technology.
SteelDRI-30H-n	A newly established plant employing DRI technique with a fuel blend of natural gas and 30% hydrogen.
SteelDRI-30H	An existing plant employing DRI technique that switched to a fuel blend of natural gas and 30% hydrogen.
SteelDRI-CCS-30H-n	A newly established plant utilising DRI technique that uses natural gas blended with 30% hydrogen and equipped with CCS technology.
SteelDRI-CCS-30H	An existing plant employing DRI technique and CCS that switched to a fuel blend of natural gas and 30% hydrogen.
SteelDRI-CCS-30H-r	An existing plant employing DRI technique fueled by natural gas blended with 30% hydrogen that is retrofitted with CCS technology.
Steel-BioGasif.-DR-n	A newly established steel production plant employing DRI technique and utilising a gasifier with biomass as feedstock for syngas production.
Steel-BioGasif.-DR-highCCS-n	A newly established steel production plant employing DRI technique and utilising a gasifier with biomass as feedstock for syngas production. The plant is equipped with CCS that contributes as a NET.
Steel-BioGasif.-DR-highCCS-r	An existing steel production plant employing DRI technique and utilising a gasifier with biomass as feedstock for syngas production. The plant is retrofitted with CCS technology that contributes as a NET.
Steel-BioGasif.-DR-highCCS-rg	An existing steel production plant utilising the DRI technique with CCS and retrofitted with a biomass gasifier to replace natural gas.

Continued on next page

Table 2.2 – continued from previous page

Technology	Description
Steel-MOE	A facility utilising molten oxide electrolysis (MOE) approach for steel production, relying solely on electricity for the process.
Steel-EAF-scrap	A facility utilising electric arc furnace (EAF) technology for steel production, utilising steel scrap as feedstock and operating solely on electricity.
Steel-EW	A facility utilising electrowinning (EW) technology for steel production, relying solely on electricity for the process.
Refinery	A facility for crude oil refining.
Refinery-PCCS-r	An existing crude oil refinery retrofitted with CCS technology.
Refinery-PCCS-n	A newly constructed crude oil refinery equipped with CCS technology.
LNG Process	A facility specialising in natural gas liquefaction to produce LNG.
LNG Process - CCS - n	A newly established LNG production facility incorporating CCS technology.
LNG Process - CCS - r	An existing LNG production facility retrofitted with CCS technology.
E-LNG	A facility specialising in natural gas liquefaction to produce LNG, with electrified refrigeration process.
Al-Smelter	A facility producing aluminum utilising an electrolyser connected to a CCGT plant.
Al-Smelter-CCS	A newly established aluminum production facility utilising an electrolyser connected to a CCGT plant equipped with CCS technology.
Al-Smelter-CCS-r	An existing aluminum production facility utilising an electrolyser connected to a CCGT plant that is retrofitted with CCS technology.
Al-Smelter-Grid-c	An existing aluminum production facility utilising an electrolyser disconnected from a CCGT plant and connected to the grid for power supply.
Al-Smelter-Grid	An existing aluminum production facility utilising an electrolyser connected directly to the grid for power supply.
Ammonia-HB	A facility producing ammonia using the Haber Bosch process.

Continued on next page

Table 2.2 – continued from previous page

Technology	Description
AmmoniaBlue-r	An existing ammonia production facility utilising the Haber Bosch process retrofitted with CCS technology.
AmmoniaBlue-n	A newly established ammonia production facility utilising the Haber Bosch process equipped with CCS technology.
AmmoniaGreen	A facility producing ammonia using green hydrogen as feedstock.
HydrogenGrey	A facility producing hydrogen using conventional Steam Methane Reforming (SMR) process.
HydrogenBlue - n	A facility producing hydrogen using conventional SMR process equipped with CCS technology.
HydrogenBlue - r	An existing facility producing hydrogen using conventional SMR process retrofitted with CCS technology.
HydrogenGreen	A facility producing hydrogen using water electrolysis process.
SAF-HEFA-SPK	A facility utilising hydrogenation process with cooking oil/vegetable oil as feedstock to produce SAF.
SAF-PtL-Green	A process utilising green hydrogen and captured CO ₂ in the Fischer Tropsch (FT) process for the production of SAF.

The Transport Sector Module

To incorporate the transport sector into the model, the formulation shown in equations 2.1 - 2.4 were integrated in the ESO-X model. The used nomenclature is detailed in Table 2.4. Equation 2.1 leverages various technologies to fulfill the demand for different modes of transport. The considered transport modes encompass road vehicles (cars, buses and trucks) as well as maritime vessels for sea transport and airplanes for air transport. It is important to note the inclusion of a slack variable in equation 2.1 that is limited by equation 2.2. This addition is to relax equation 2.1 and is constrained by a very small fraction (0.0005%) of the transport demand for each mode. The slack variable was introduced because the demand constraint was not met due to the high granularity of

the transport demand, which rendered the model infeasible. By incorporating the slack variable, the model can achieve a feasible solution through this slight relaxation. Equation 2.3 addresses transport emissions, which is subsequently incorporated into equation 2.6. Similarly, the power requirements for transport are handled in the same manner, with the associated power needs being reflected in equation 2.4. This comprehensive representation of the transport sector in the model ensures a detailed consideration of various modes, technologies and associated emissions. The technologies used to meet the demand for each mode of transportation are outlined in Table 2.3 and Appendix C.

$$\sum_{itransp} (Ttype_{mo,itransp} \times trans_{itransp,a} \times tDes_{itransp}) = TDem_{mo,a} - slakT_{mo,a} \quad (2.1)$$

$$slakT_{mo,a} \leq 0.000005 \times TDem_{vehicles,a} \quad (2.2)$$

$$eTrans_{itransp,a} = tDes_{itransp} \times trans_{itransp,a} \times TTech_{itransp,ems} \quad (2.3)$$

$$pTrans_{itransp,a} = trans_{itransp,a} \times TTech_{itransp,power} \quad (2.4)$$

Refer to Table 2.4 for a description of the nomenclature

Table 2.3: List of technologies used in the transport sector segment of the ESO model [95, 96, 97, 98, 99].

Technology	Description
Car-Gasoline	An internal combustion engine (ICE) vehicle designed for passenger transportation, powered by gasoline.
Car-Hybrid	An ICE vehicle designed for passenger transportation utilising gasoline and complimented with an electric motor.

Continued on next page

Table 2.3 – continued from previous page

Technology	Description
Car-Electric	A passenger vehicle powered solely by an electric motor and rechargeable battery.
Car-Hydrogen	An ICE vehicle designed for passenger transportation, fueled by hydrogen gas.
Bus-Diesel	A mini bus equipped with an ICE running on diesel fuel.
Bus-Hybrid	A mini bus equipped with an ICE running on diesel fuel, complemented by an electric motor.
Bus-Electric	A mini bus powered by an electric motor and rechargeable battery.
Bus-Hydrogen	A mini bus equipped with an ICE running on hydrogen fuel.
Truck-Diesel	A heavy-duty truck powered by an ICE running on diesel fuel for freight transportation.
Truck-Electric	A heavy-duty truck propelled solely by an electric motor and rechargeable battery.
Truck-Hydrogen	A heavy-duty truck equipped with an ICE running on hydrogen fuel.
Train-Diesel	A locomotive-powered train utilising an ICE running on diesel fuel for rail transportation.
Train-Electric	A train powered by electricity.
Train-Electric-r	A train formerly powered by a diesel locomotive, now operates using electricity.
Train-Hydrogen	A locomotive-powered train fueled by hydrogen gas.
Ship-HFO	A maritime vessel fueled by heavy fuel oil (HFO).
Ship-Ammonia-r	An existing maritime vessel retrofitted with an ammonia engine for propulsion, transitioning from conventional fuel to ammonia.
Ship-Ammonia	A maritime vessel powered by an ammonia engine.
Plane-JetFuel	A conventional aircraft powered by jet fuel for air transportation.
Plane-50SAF-fs	An existing aircraft transitioning from 100% jet fuel to a blend of 50% SAF and 50% jet fuel.
Plane-50SAF	A new aircraft fueled by a blend of 50% SAF and 50% jet fuel.

Carbon Dioxide Removal Technologies Module

In the ESO-X version utilised, only biomass-based power plant with CCS (BECCS) is employed for carbon emissions removal. A novel extension to the model includes the incorporation of direct air capture (DAC) and is introduced as an independent service linked to the grid. To meet the power requirements for operating DAC, equation 2.5 is employed to calculate the power demand based on the required levels of carbon removal. The extent of carbon removal is determined using equation 2.6. This enhancement broadens the model's capability to explore and optimise carbon removal strategies by integrating DAC alongside BECCS.

$$pDAC_{DAC,a} = eDAC_{DAC,a} \times DTech_{PowerDAC} \quad (2.5)$$

Refer to Table 2.4 for a description of the nomenclature

System Emissions Module

In this section of the model, modifications were made to incorporate the emissions of the transport sector and the emissions removed by DAC. The emissions removal by DAC is introduced as a free variable and is determined by the need for adjusting the system's emissions to meet the wanted target of carbon reduction. As presented in equation 2.6, the emissions removal ($eDAC_{DAC,a}$) compensates for any emissions from any sector. This adjustment enables a comprehensive consideration of both the transport sector emissions and the flexible emissions removal capability provided by DAC for the overall sectors in the model framework.

$$\begin{aligned}
\sum_{ipc,c,t} e_{ipc,a,c,t} WF_{c,a} + \sum_{ii} eInd_{ii,a} + \sum_{i_{transp}} eTrans_{i_{transp},a} + \\
\sum_{i_{DAC}} eDAC_{DAC,a} \leq SE_a
\end{aligned} \tag{2.6}$$

Refer to Table 2.4 for a description of the nomenclature

Power Requirement Module

To incorporate all the shown modifications above into the power demand, the constraint in the model was revised to include the demands from each sector individually (power, industry and transport) along with DAC as shown in equation 2.5. The assumption is that the power demand for transport is evenly distributed throughout the year and the same distribution applies to DAC. This refinement ensures a more accurate representation of power demand across various sectors and facilitates a more detailed understanding of sectoral power requirement.

$$\begin{aligned}
\sum_{ipg} p2d_{ipg,a,c,t} + \sum_{ips} s2d_{ips,a,c,t} = SD_{c,t,a}(1 + TL) - slak_{a,c,t} + \\
\sum_{DAC} \frac{pDAC_{DAC,a}}{8760} + \sum_{i_{transp}} \frac{pTrans_{i_{transp},a}}{1000 \times 8760} + \sum_{ii,comm} \frac{pInd_{a,ii,comm}}{8760}
\end{aligned} \tag{2.7}$$

Refer to Table 2.4 for a description of the nomenclature

2.2.2 ESO Formulation

This section presents the mathematical formulation of the ESO model, providing a detailed overview of the framework governing equations and constraints. The formulation here extends and integrates the foundational equations previously introduced in the framework definition (section 2.2.1). By incorporating these established equations below, along with newly developed components, the model offers a comprehensive and robust representation of the energy system. This enhanced formulation allows for a comprehensive analysis of the interactions between the power, industrial and transport sectors.

Building upon this foundation, the objective function of the model aims to minimise the total system cost (tsc), which consists of the capital expenditure ($CAPEX_i$) and the annual operating expenditure ($AnOPEX_i$) of the technologies, as detailed in Equations 2.8 and 2.9. To account for the end-of-horizon effect, the model incorporates a Weighted Fractional Adjustment ($WFA_{i,a}$), which represents the ratio of the technology's useful lifetime within the time horizon to its physical lifetime. This adjustment assumes a linear depreciation of assets over time.

$$\text{Min. tsc} = \sum_{i,a>1} b_{i,a} CAPEX_i Des_i WFA_{i,a} / Disc_a + \sum_i AnOPEX_i / Disc_a \quad (2.8)$$

$$\begin{aligned}
AnOPEX_i = & \sum_{ipg,c,t} u_{ipg,a,c,t} OPEXSU_{ipg} WF_{c,a} \\
& + \sum_{ipg,c,t} (p_{ipg,a,c,t} OPEX_{ipg,a} + n_{ipg,a,c,t} OPEXNL_{ipg}) WF_{c,a} \\
& + \sum_{ips,c,t} (s2d_{ips,a,c,t} OPEX_{ips,a} + o_{ips,a,c,t} OPEXNL_{ips}) WF_{c,a} \\
& + \sum_{c,t} ImpElecPr_{c,t,a} p(InterImp)_{a,c,t} WF_{c,a} \\
& + \sum_{c,t} Slak_{a,c,t} VoLL WF_{c,a} + \sum_i d_{i,a} OPEXFix_i Des_i \\
& + biofuelcost_a \\
& + \sum_{ii} Des_{ii} q_{ii,a} OPEX_{ii} \\
& + \sum_{iDAC} eDAC_{iDAC,a} OPEX_{iDAC,a} \\
& + \sum_{itransp} trans_{itransp,a} OPEX_{itransp,a} \\
& + \sum_{ipg,c,t} TEems_{ipg,'ems'} e_{ipg,a,c,t} WF_{c,a} CP_a \\
& + \sum_{ii} eInd_{ii,a} CP_a \\
& + \sum_{itransp} eTrans_{itransp,a} CP_a \quad \forall a, TEems > 0, ITech_{ii,'ems'} > 0 \quad (2.9)
\end{aligned}$$

Refer to Table 2.4 for a description of the nomenclature

The system requirements within the model are governed by a series of equations, specifically equations 2.10 through 2.14. Equation 2.10 establishes the energy balance by accounting for the hourly system demand, transmission losses, unmet demand and the electricity supplied by both power generation (ipg) and storage technologies (ips). Equation 2.11 ensures that there is sufficient installed capacity to meet peak demand, while equation 2.12 guarantees that the grid's reserve requirements are satisfied. To maintain grid stability, equation 2.13 secures the minimum inertia necessary. Additionally, equa-

tion 2.14 imposes a constraint on unmet demand, limiting it to no more than 0.5% of the annual electricity demand to ensure system reliability.

$$\sum_{ipg} p2d_{ipg,a,c,t} + \sum_{ips} s2d_{ips,a,c,t} = SD_{a,c,t} (1 + TL) - Slack_{a,c,t} \quad \forall a, c, t \quad (2.10)$$

$$\sum_i d_{i,a} Des_i Cmax_i \geq PL_a (1 + RM) \quad \forall a \quad (2.11)$$

$$\begin{aligned} \sum_{ipg} r_{ipg,a,c,t} Rp_{ipg} + \sum_{ips} s2r_{ips,a,c,t} Rp_{ips} &\geq PL_a RM \\ &+ \sum_{ir} p2d_{ir,a,c,t} WR \quad \forall a, c, t \end{aligned} \quad (2.12)$$

$$\sum_{ipg} n_{ipg,a,c,t} Des_{ipg} Ip_{ipg} + \sum_{ips} o_{ips,a,c,t} Des_{ips} Ip_{ips} \geq SI \quad \forall a, c, t \quad (2.13)$$

$$\sum_{c,t} Slack_{a,c,t} WF_d \leq 0.005 \sum_{c,t} SD_{a,c,t} WF_{c,a} \quad \forall a \quad (2.14)$$

Refer to Table 2.4 for a description of the nomenclature

The capacity expansion in the model is managed using equations 2.15 to 2.17. The number of units installed ($d_{i,a}$) in the first period is fixed based on the initial installed capacity data, as specified in equation 2.15. In subsequent periods, equation 2.16 is used to calculate the installed capacity by accounting for both the new capacity ($b_{i,a}$) and the retired capacity ($d_{i,a}^{out}$). This approach allows the model to dynamically adjust the installed capacity over time while adhering to maximum capacity limits ($DMax_i$) for each technology using equation 2.17.

$$d_{i,a} = DIni_i \quad \forall i, a = 1 \quad (2.15)$$

$$d_{i,a} = d_{i,a-1} + b_{i,a} - d_{i,a}^{out} \quad \forall i, a > 1 \quad (2.16)$$

$$d_{i,a} \leq DMax_i \quad \forall i, a \quad (2.17)$$

Refer to Table 2.4 for a description of the nomenclature

Equation 2.18 defines the number of new units built ($b_{i,a}$) as the sum of two components, $BR1_{i,a}$ and $BR2_{i,a}$. $BR1_{i,a}$ is constrained by the S-curve, as outlined in equation 2.19, while $BR2_{i,a}$ is limited by the maximum historical build rate, as shown in equation 2.20. This structure allows emerging technologies to exceed their historical build rates by applying a build rate multiplier (BRM_i), which is derived from the maximum deployment rates observed in any country that has implemented these technologies. To ensure that only one build rate component is utilised at any given time, equations 2.21 through 2.23 enforce a binary choice between $BR1_{i,a}$ and $BR2_{i,a}$, with M representing a sufficiently large number. The binary variables $bBR1_{i,a}$ and $bBR2_{i,a}$ control this selection, with $bBR_{i,0}$ set to the number of units built during the first planning period (2015 to 2020).

$$b_{i,a} \leq BR1_{i,a} + BR2_{i,a} \quad \forall i, a > 1 \quad (2.18)$$

$$BR1_{i,a} \leq b_{i,a-1} BRM_i M A_{i,a} \quad \forall i, a > 1 \quad (2.19)$$

$$BR2_{i,a} \leq BR_i \Delta_a M A_{i,a} \quad \forall i, a > 1 \quad (2.20)$$

$$BR1_{i,a} \leq bBR1_{i,a} M \quad \forall i, a > 1 \quad (2.21)$$

$$BR2_{i,a} \leq bBR2_{i,a} M \quad \forall i, a > 1 \quad (2.22)$$

$$bBR1_{i,a} + bBR2_{i,a} = 1 \quad \forall i, a > 1 \quad (2.23)$$

$$bBR1_{i,a} \in \{0, 1\} \quad \forall i, a > 1 \quad (2.24)$$

$$bBR2_{i,a} \in \{0, 1\} \quad \forall i, a > 1 \quad (2.25)$$

Refer to Table 2.4 for a description of the nomenclature

Equation 2.26 summarises all potential paths for decommissioning a technology, considering units that are either decommissioned, retrofitted immediately ($d_{i,a}^{ret,now}$) or scheduled for retrofit later ($d_{i,a}^{ret,later}$). The relationship between the original and retrofit units is established in equation 2.27, where the parameter $\rho_{i,i'}$ links these units to the original capacity. The capacity available for retrofitting or decommissioning is constrained by equation 2.28, ensuring that the units removed do not exceed the existing capacity. Equation 2.29 mandates that the number of repurposed units to at least meet those that are retired according to a predefined schedule ($d_{i,a}^{eol}$) and those newly built units that reach the end of their operational life. The formulation also allows for capacity to be retrofitted or retired before the end of its lifecycle. Finally, Equations 2.30 to 2.32 impose limits on the number of active units, ensuring that they do not exceed the available capacity.

$$d_{i,a}^{out} = d_{i,a}^{dec} + d_{i,a}^{ret,now} + d_{i,a}^{ret,later} \quad \forall i, a > 1 \quad (2.26)$$

$$d_{i,a}^{ret,now} + d_{i,a,a-1}^{ret,later} = \sum_{i'} \rho_{i,i'} b_{i',a} \quad \forall i, a > 1 \quad (2.27)$$

$$d_{ia}^{out} \leq d_{i,a-1} \quad \forall i, a > 1 \quad (2.28)$$

$$\sum_{a'}^{1 \leq a' \leq a} d_{ia'}^{out} \geq \sum_{a'}^{1 \leq a' \leq a} d_{i,a'}^{eol} + b_{i,a'-LT_i/5} \quad \forall i, a > 1 \quad (2.29)$$

$$q_{ii,a} \leq d_{ii,a} \quad \forall i, a \quad (2.30)$$

$$trans_{i,trans,a} \leq d_{i,trans,a} \quad \forall i, trans, a \quad (2.31)$$

$$eDAC_{DAC,a} \leq d_{DAC,a} \quad \forall DAC, a \quad (2.32)$$

$$d_{i,1}^{out} = 0 \quad \forall i \quad (2.33)$$

$$d_{i,1}^{ret, later} = 0 \quad \forall i \quad (2.34)$$

$$d_{i,7}^{ret, later} = 0 \quad \forall i \quad (2.35)$$

Refer to Table 2.4 for a description of the nomenclature

For unit commitments, the model utilises equations 2.36 to 2.41. Equations 2.36 and 2.37 constrain the number of online units by the number of installed power generation and storage units, respectively. The online and offline status of conventional technologies is governed by equations 2.38 and 2.39, which track the transitions of units between these states. The flexibility of each technology is further defined by its start-up (UT) and shutdown (DT) durations, specified by equations 2.40 and 2.41.

$$n_{ipg,a,c,t} \leq d_{ipg,a} \quad \forall ipg, a, c, t \quad (2.36)$$

$$o_{ips,a,c,t} \leq d_{ips,a} \quad \forall ips, a, c, t \quad (2.37)$$

$$u_{ic,a,c,t} \geq n_{ic,a,c,t} - n_{ic,a,c,t-1} \quad \forall ic, a, c, t > 1 \quad (2.38)$$

$$w_{ic,a,c,t} \geq n_{ic,a,c,t-1} - n_{ic,a,c,t} \quad \forall ic, a, c, t > 1 \quad (2.39)$$

$$w_{ic,a,c,t} \leq n_{ic,a,c,t+(t'-1)} \quad \forall ic, a, c, t > 1, t' \leq UT_{ic} \quad (2.40)$$

$$w_{ic,a,c,t} \leq d_{ic,a} - n_{ic,a,c,t+(t'-1)} \quad \forall ic, a, c, t > 1, t' \leq DT_{ic} \quad (2.41)$$

Refer to Table 2.4 for a description of the nomenclature

The minimum stable generation (P_{min}) and maximum power output (P_{max}), along with the reserve capacity for each technology, are defined by equations 2.42 and 2.43. The power output of generated electricity, including contributions from both power generation and storage technologies, is calculated using equation 2.44. To determine the emissions produced from power generation, equation 2.45 is applied. In the model, hydropower plants are assumed to regulate their power output, with the output constrained by the daily capacity as shown in equation 2.46. This differs from wind and solar power, whose generation depends on hourly clustered profiles, as captured by equations 2.47 and 2.48.

$$p_{ic,a,c,t} \geq n_{ic,a,c,t} Des_{ic} Pmin_{ic} \quad \forall ic, a, c, t \quad (2.42)$$

$$p_{ipg,a,c,t} + r_{ipg,a,c,t} \leq n_{ipg,a,c,t} Des_{ipg} Pmax_{ipg} \quad \forall ipg, a, c, t \quad (2.43)$$

$$p2d_{ipg,a,c,t} + p2s_{ipg,a,c,t} = p_{ipg,a,c,t} \quad \forall ipg, a, c, t \quad (2.44)$$

$$ems_{ipg,a,c,t} = e_{ipg,a,c,t} TEms_{ipg,ems'} \quad \forall ipg, a, c, t \quad (2.45)$$

$$\sum_t p_{Hydro,a,c,t} \leq \sum_t AV_{Hydro,c,t,a} Des_{Hydro} n_{Hydro,a,c,t} \quad \forall a, d \quad (2.46)$$

$$p_{ir,a,c,t} \geq n_{ir,a,c,t} Des_{ir} Pmin_{ir} AV_{ir,c,t} \quad \forall ir \neq \text{"Import"}, a, c, t \quad (2.47)$$

$$p_{ir,a,c,t} + r_{ir,a,c,t} \leq n_{ir,a,c,t} Des_{ir} AV_{ir,c,t,a} \quad \forall ir \neq \text{"Import"}, a, c, t \quad (2.48)$$

Refer to Table 2.4 for a description of the nomenclature

For storage technologies, the model imposes several constraints to manage storage output and capacity effectively. Equations 2.49 and 2.50 limit the storage output by ensuring it aligns with the technology's minimum stable generation and available online capacity. Additionally, the amount of electricity that can be stored is constrained by equation 2.51, which factors in the previous storage level, discharge losses and the efficiency of the storage process. Equation 2.52 ensures that the total electricity stored matches the amount received from power generation. To prevent the storage of imported electricity, equation 2.53 sets this value to zero. Finally, the maximum and minimum levels of electricity stored are limited by the technology's state of charge, as defined by Equations 2.54 and 2.55, ensuring that the storage system operates within its designated capacity limits.

$$s2d_{ips,a,c,t} + s2r_{ips,a,c,t} \geq o_{ips,a,c,t} Des_{ips} Pmin_{ips} \quad \forall ips, a, c, t \quad (2.49)$$

$$p2is_{ips,a,c,t} \leq o_{ips,a,c,t} Des_{ips} \quad \forall ips, a, c, t \quad (2.50)$$

$$\begin{aligned} s_{ips,a,c,t} &= s_{ips,a,c,t-1}(1 - SDis_{ips}) - s2d_{ips,a,c,t} \\ &\quad + p2ips_{ips,a,c,t} SEta_{ips} \quad \forall ips, a, c, t > 1 \end{aligned} \quad (2.51)$$

$$\sum_{ipg} p2s_{ipg,a,c,t} = \sum_{ips} p2is_{ips,a,c,t} \quad \forall a, c, t \quad (2.52)$$

$$p2s_{ir,a,c,t} = 0 \quad \forall ir = \text{"Import"}, a, c, t \quad (2.53)$$

$$s_{ips,a,c,t} \leq o_{ips,a,c,t} Des_{ips} SOCMa_{ips} SDur_{ips} \quad \forall ips, a, c, t \quad (2.54)$$

$$s_{ips,a,c,t} \geq o_{ips,a,c,t} Des_{ips} SOCMin_{ips} SDur_{ips} \quad \forall ips, a, c, t \quad (2.55)$$

Refer to Table 2.4 for a description of the nomenclature

To quantify the emissions produced by the industrial sector, equation 2.56 is employed. This equation calculates the emissions based on the activity level of each industry and the associated emission factors. Equations 2.57 and 2.58 ensure that the balance between domestic production, exports and demand is maintained. Specifically, equation 2.57 sets the industrial demand ($IDem_{a,comm}$) as less than or equal to the available supply ($f_{a,comm}$), while equation 2.58 ensures that the total production, including exports, does not exceed the sum of all industrial outputs. Lastly, equation 2.59 limits industrial production to the operational units, taking into account the operational capacity and limits of the technologies employed in the production process.

$$e_{ii,a}^{ind} = \sum_m g_{a,ii,comm} IFeat_{ii}^{ems} \quad \forall ii, a \quad (2.56)$$

$$IDem_{a,comm} \leq f_{a,comm} \quad \forall a, comm \quad (2.57)$$

$$f_{a,comm} + exp_{a,comm} \leq \sum_{ii} g_{a,ii,comm} \quad \forall a, comm \quad (2.58)$$

$$g_{a,ii,comm} \leq IProd_{ii,comm} Des_{ii} q_{ii,a} IFeat_{ii}^{opfac} \quad \forall a, comm, ii \quad (2.59)$$

Refer to Table 2.4 for a description of the nomenclature

The Jobs and Economic Development Impacts (JEDI) model is integrated into the ESO-X framework to assess the socio-economic impacts of the energy transition following the model's execution. Detailed explanations of the multipliers and economic indicators used in the JEDI model are provided in Chapter 5.

In the ESO-X model, the JEDI section is defined through Equations 2.60 to 2.79. Specifically, the investment Gross Value Added (GVA) for the power, industry and transport sectors is calculated using equations 2.60, 2.61, and 2.62, respectively. These equations determine the GVA as a function of the technology CAPEX and corresponding GVA multipliers.

$$GVASectInv_{sect,a}^p = \sum_{ipg} CAPEX_{ipg} b_{ipg,a} Des_{ipg} WFA_{ipg,a} GVA K_{ipg,sect}^{Inv} / Disc_a \quad (2.60)$$

$$GVASectInv_{sect,a}^{ii} = \sum_{ii} CAPEX_{ii} b_{ii,a} Des_{ii} WFA_{ii,a} GVA K_{ii,sect}^{Inv} / Disc_a \quad (2.61)$$

$$GVASectInv_{sect,a}^{transp} = \sum_{itransp} CAPEX_{itransp} b_{itransp,a} Des_{itransp} WFA_{itransp,a} GVAK_{itransp,sect}^{Inv} / Disc_a \quad (2.62)$$

Refer to Table 2.4 for a description of the nomenclature

Equations 2.63, 2.64 and 2.65 define the GVA obtained from operation and maintenance (O&M) activities in the power, industrial and transport sectors.

$$\begin{aligned} GVASectOM_{sect,a}^p &= \sum_{ipg,c,t} (OPEXSU_{ipg} u_{ipg,a,c,t} + OPEX_{ipg,a} p_{ipg,a,c,t}) \\ &+ OPEXNL_{ipg} n_{ipg,a,c,t} WFA_{ca} GVAK_{ipg,sect}^{OMV} / Disc_a \\ &+ \sum_{ips,c,t} (OPEX_{ips,a} s2d_{ips,a,c,t} + OPEXNL_{ips} o_{ips,a,c,t}) WFA_{ca} GVAK_{ips,sect}^{OMV} / Disc_a \\ &+ \sum_{dip,a} Des_{ipg} CAPEX_{ipg} OPEXFix_{ipg} GVAK_{ipg,sect}^{OMF} / Disc_a \end{aligned} \quad (2.63)$$

$$\begin{aligned} GVASectOM_{sect,a}^{ii} &= \sum_{ii,comm} OPEX_{ii,a} PInd_{a,ii,comm} GVAK_{ii,sect}^{OMV} / Disc_a \\ &+ \sum_{ii} Des_{ii} q_{ii,a} IOPEXFix_{ii} GVAK_{ii,sect}^{OMF} / Disc_a \end{aligned} \quad (2.64)$$

$$\begin{aligned}
GVASectOM_{sect,a}^{transp} = & \sum_{itransp,mode} OPEX_{itransp,a} TUtilised_{a,itransp,mode} GVAK_{itransp,sect}^{OMV} / Disc_a \\
& + \sum_{itransp} Des_{itransp} trans_{trans,a} TOPEXFix_{itransp} GVAK_{itransp,sect}^{OMF} / Disc_a
\end{aligned} \tag{2.65}$$

Refer to Table 2.4 for a description of the nomenclature

The GVA from each economic activity is calculated by aggregating the contributions from the power, industrial and transport sectors. This is performed separately as shown in equation 2.66 for GVA generated from investments and equation 2.67 for GVA from O&M activities.

$$GVASectInv_{sect,a} = GVASectInv_{sect,a}^p + GVASectInv_{sect,a}^{ii} + GVASectInv_{sect,a}^{transp} \tag{2.66}$$

$$GVASectOM_{sect,a} = GVASectOM_{sect,a}^p + GVASectOM_{sect,a}^{ii} + GVASectOM_{sect,a}^{transp} \tag{2.67}$$

Refer to Table 2.4 for a description of the nomenclature

Equation 2.68 aggregates the GVA from both investment and O&M activities, with different weights applied to each planning period based on duration.

$$\begin{aligned}
GVASect_{sect} = \sum_a GVASectInv_{sect,a} + 2.5 \cdot \sum_{a \in \{1,7\}} GVASectOM_{sect,a} \\
+ 5 \cdot \sum_{2 \leq a \leq 6} GVASectOM_{sect,a} \quad (2.68)
\end{aligned}$$

Refer to Table 2.4 for a description of the nomenclature

The total direct GVA generated by the studied sectors is calculated using equation 2.69.

$$GVAdir = \sum_{sect} GVASect_{sect} \quad (2.69)$$

Refer to Table 2.4 for a description of the nomenclature

The equations governing the employment generated from the system follow the same principles as those used for calculating the GVA. Equations 2.70, 2.71 and 2.72 define the number of jobs created from investments in various technologies across the power, industrial and transport sectors.

$$JobsSectInv_{sect,a}^p = \sum_{ipg} CAPEX_{ipg} b_{ipg,a} Des_{ipg} JobsK_{ipg,sect}^{Inv} \quad (2.70)$$

$$JobsSectInv_{sect,a}^{ii} = \sum_{ii} CAPEX_{ii} b_{ii,a} Des_{ii} JobsK_{ii,sect}^{Inv} \quad (2.71)$$

$$JobsSectInv_{sect,a}^{transp} = \sum_{itransp} CAPEX_{itransp} b_{itransp,a} Des_{itransp} JobsK_{itransp,sect}^{Inv} \quad (2.72)$$

Refer to Table 2.4 for a description of the nomenclature

Jobs from O&M activities are calculated using equations 2.73, 2.74 and 2.75.

$$\begin{aligned}
 JobsSectOM_{sect,a}^p = & \sum_{ipg,c,t} (OPEXS U_{ipg} u_{ipg,a,c,t} + OPEX_{ipg,a} p_{ipg,a,c,t}) \\
 & + OPEX N L_{ipg} n_{ipg,a,c,t} W F_{ca} Jobs K_{ipg,sect}^{OMV} \\
 & + \sum_{ips,c,t} (OPEX_{ips,a} s 2 d_{ips,a,c,t} + OPEX N L_{ips} o_{ips,a,c,t}) W F_{c,a} Jobs K_{ips,sect}^{OMV} \\
 & + \sum_{dip,a} Des_{ipg} CAPEX_{ipg} OPEX Fix_{ipg} Jobs K_{ipg,sect}^{OMF}
 \end{aligned} \tag{2.73}$$

$$\begin{aligned}
 JobsSectOM_{sect,a}^{ii} = & \sum_{ii,comm} OPEX_{ii,a} p Ind_{a,ii,comm} Jobs K_{ii,sect}^{OMV} \\
 & + \sum_{ii} Des_{ii} q_{ii,a} IOPEX Fix_{ii} Jobs K_{ii,sect}^{OMF}
 \end{aligned} \tag{2.74}$$

$$\begin{aligned}
 JobsSectOM_{sect,a}^{transp} = & \sum_{itransp,mo} OPEX_{itransp,a} T Utilised_{a,itransp,mo} Jobs K_{itransp,sect}^{OMV} \\
 & + \sum_{itransp} Des_{itransp} trans_{itransp,a} IOPEX Fix_{itransp} Jobs K_{itransp,sect}^{OMF}
 \end{aligned} \tag{2.75}$$

Refer to Table 2.4 for a description of the nomenclature

Using equations 2.76 and 2.77, the number of jobs generated from both investment and O&M activities is calculated. Equation 2.78 then aggregates these values over time to determine the total employment level. Finally, the overall number of jobs created by the

system is obtained using equation 2.79.

$$JobsSectInv_{sect,a} = JobsSectInv_{sect,a}^p + JobsSectInv_{sect,a}^{ii} + JobsSectInv_{sect,a}^{itransp} \quad (2.76)$$

$$JobsSectOM_{sect,a} = JobsSectOM_{sect,a}^p + JobsSectOM_{sect,a}^{ii} + JobsSectOM_{sect,a}^{itransp} \quad (2.77)$$

$$\begin{aligned} JobsSect_{sect} = & \sum_a JobsSectInv_{sect,a} \\ & + 2.5 \cdot \sum_{a \in \{1,7\}} JobsSectOM_{sect,a} \\ & + 5 \cdot \sum_{2 \leq a \leq 6} JobsSectOM_{sect,a} \end{aligned} \quad (2.78)$$

$$Jobs = \sum_{sect} JobsSect_{sect} \quad (2.79)$$

Refer to Table 2.4 for a description of the nomenclature

Table 2.4: Nomenclature used in the mathematical formulation of ESO-X model.

Type	Symbol	Description	Units
Sets	a	Planning periods	years
	c	Clusters	days
	$comm$	Commodities (cement, steel, refinery, LNG, aluminum, ammonia, hydrogen or SAF)	-
	ii	Industrial technologies	-
	ipc	Thermal technologies	-
	ipg	Power generating technologies	-
	ips	Electricity storage technologies	-
	ir	Intermittent renewable technologies	-
	$itransp$	Transport technologies	-
	mo	Modes of transport (cars, bus, truck, train, ship, plane)	-
	t	Time periods	hours
Parameters	$AV_{i,c,t,a}$	Availability factor of intermittent renewable technologies	%
	$bBR1_{i,a}$	Binary indicator for S curve build rate limit	-
	$bBR2_{i,a}$	Binary indicator for maximum historical build rate limit	-
	BRM_i	S curve build rate multiplier	-
	$CAPEX_i$	Capital expenditure per unit	£/unit
	$Cmax_i$	Maximum capacity credit	hour
	CP_a	Carbon price	£/t-CO ₂
	Des_i	Unit size of technology	MW for power and mt-X for industry
	$Disc_a$	Discount factor for planning period	-
	$DIni_i$	Initial number of installed units	Units
	$DMax_i$	Maximum allowable number of units	Units
	$DTech_{PowerDAC}$	Power required for CO ₂ removal by DAC	t-CO ₂ /MWh
	$d_{i,a}^{eol}$	Number of units reaching end-of-life in a planning period	Units
	$exp_{a,comm}$	Export of commodity	mt-X/yr
	$f_{a,m}$	Domestic demand	mt-X/yr
	$GVAK_{i,sect}^{cat}$	GVA multiplier	-
	$IDem_{a,comm}$	Commodity demand	mt-X/yr
	$IFeat_{ii}^{ems}$	Emissions features of industrial technologies	mt-CO ₂ /mt-X
	$IFeat_{ii}^{opfac}$	Load factor of industrial technologies	%
	$ImpElecPr_{c,t,a}$	Imported electricity price	£/MWh
	$Ipipg$	Inertial potential provided by technology	seconds
	$IProd_{ii,comm}$	Production of commodity	mt-X
	$JobsK_{i,sect}^{cat}$	Jobs multiplier	Jobs/m£
	$OPEXFix_{ipg}$	Fixed OPEX for technology in planning period	£/unit
	$OPEXNL_i$	Fixed OPEX per unit produced	£/unit
	$OPEXSU_{ipg}$	Startup OPEX	£/hour
	$OPEX_{i,a}$	Operating and maintenance expenditure in year	£/unit produced

Type	Symbol	Description	Units
	$OPEX_{iDAC,a}$	OPEX for DAC in planning period	£/t-CO ₂
	$OPEX_{ii}$	OPEX for industrial technology	£/mt-X
	$OPEX_{itransp,a}$	OPEX for transport technology in planning period	£/unit of transport mode
	PL_a	Peak load	MWh
	$Pmax_i$	Maximum stable power generation	%
	$Pmin_i$	Minimum stable power generation	%
	Rp_{ipg}	Reserve potential provided by technology	%
	$SD_{c,t,a}$	System demand for electricity	MWh
	$SDis_{is}$	Hourly self discharge	%
	$SDur_{ips}$	Storage duration	hours
	SE_a	System emissions target	t-CO ₂
	SI	Grid inertial requirement	MW.s
	$SOCMax_{ips}$	Maximum state of charge	%
	$SOCMin_{ips}$	Minimum state of charge	%
	$tDes_{itransp}$	Unit size of transport technology	t-CO ₂ /yr
	$TDem_{mo,a}$	Transportation demand	units of transport mode
	$TEems_{ipg,'ems'}$	Emissions feature of power technology	t-CO ₂ /MWh
	TL	Transmission losses	% of MW
	$TTech_{itransp,}$	Features of transport technology (emissions, power)	-
	$Ttype_{mo,itransp}$	Indicator if transport technology can be used for mode of transport	-
	$VoLL$	Value of lost load	£/MWh
	$WFA_{i,a}$	Weighted factor for CAPEX and remaining lifetime	%
	$WF_{c,a}$	Weighted factor for clustered hourly data	-
	WR	System reserve buffer for wind power generation	%-MW wind
	$biofuelcost_a$	Cost of biofuel used in a planning period	£
Variables	$AnOPEX_a$	Annual OPEX	£
	$b_{i,a}$	Number of newly built units	units
	$BR1_{i,a}$	Build rate limited by S curve	units/yr
	$BR2_{i,a}$	Build rate limited by maximum historical rate	units/yr
	$d_{i,a}^{dec}$	Number of decommissioned units	units
	$d_{i,a}^{out}$	Number of repurposed units	units
	$d_{i,a}^{ret, later}$	Number of units to be retrofitted in next period	units
	$d_{i,a}^{ret, now}$	Number of retrofitted units in current period	units
	$eDAC_{DAC,a}$	Emissions removed by DAC	t-CO ₂ /yr
	$eInd_{ii,a}$	Industrial emissions	t-CO ₂ /yr
	$eTrans_{itransp,a}$	Carbon emissions by transport	t-CO ₂
	$e_{i,a,c,t}$	Power emissions	t-CO ₂
	$g_{a,ii,comm}$	Production of commodity	mt-X/yr

Type	Symbol	Description	Units
	$GVAdir$	Total direct GVA generated	m£
	GVA_{sect}	Total GVA	m£
	GVA_{sect}^{ii}	Industrial sector investment GVA	m£
	GVA_{sect}^p	Power sector investment GVA	m£
	GVA_{sect}^{transp}	Transport sector investment GVA	m£
	GVA_{sect}^{inv}	Investment GVA in planning period	m£
	GVA_{sect}^{ii}	Industrial sector maintenance GVA	m£
	GVA_{sect}^p	Power sector maintenance GVA	m£
	GVA_{sect}^{transp}	Transport sector maintenance GVA	m£
	GVA_{sect}^{OM}	Maintenance GVA	m£
	$n_{i,a,c,t}$	Number of operational power technologies	Units
	$Jobs$	Total direct jobs generated	jobs
	$Jobs_{sect}$	Total jobs	jobs
	$Jobs_{sect}^{ii}$	Industrial sector investment jobs	jobs
	$Jobs_{sect}^p$	Power sector investment jobs	jobs
	$Jobs_{sect}^{transp}$	Transport sector investment jobs	jobs
	$Jobs_{sect}^{inv}$	Investment jobs in year and sector	jobs
	$Jobs_{sect}^{ii}$	Industrial sector maintenance jobs	jobs
	$Jobs_{sect}^p$	Power sector maintenance jobs	jobs
	$Jobs_{sect}^{transp}$	Transport sector maintenance jobs	jobs
	$Jobs_{sect}^{OM}$	Maintenance jobs	jobs
	$o_{ips,a,c,t}$	Number of operational storage technologies	Units
	$p2d_{ipg,a,c,t}$	Power to demand	MW
	$pDAC_{DAC,a}$	Power required by DAC	MWh
	$p(InterImp)_{a,c,t}$	Imported electricity price	£/Mwh
	$pInd_{a,ii,comm}$	Power requirement by the industrial sector	MWh
	$pTrans_{itransp,a}$	Power requirement by the transport sector	MW
	$q_{ii,a}$	Number of operational industrial units	units
	$r_{ir,a,c,t}$	Reserve provided	MWh
	$s2d_{ips,a,c,t}$	Storage to demand	MWh
	$slakT_{mo,a}$	Unmet transport demand	units of trans-
	$slak_{a,c,t}$	Unmet electricity demand	port mode MWh
	$trans_{itransp,a}$	Transportation by transport technology	Units
	tsc	Total system cost	£
	$u_{i,a,c,t}$	Number of online power technologies	Units
	$w_{i,a,c,t}$	Number of offline power technologies	Units

¹Except for ships, the value is in dead weight ton (DWT)

2.3 Modelling the UK Electricity Sector

As previously mentioned, there has been extensive research on the decarbonisation of the UK economy. The aim of this thesis is to investigate how external factors influence the decarbonisation process of a nation. This is done to highlight how events in other economies can impact an economy. To this end, fuel price was chosen as a focal point to assess its effect on decarbonising the power sector in the UK. For this purpose, the power segment of the ESO-X model was employed in this case study. Figure 2.1 illustrates the topology of the ESO-UK model.

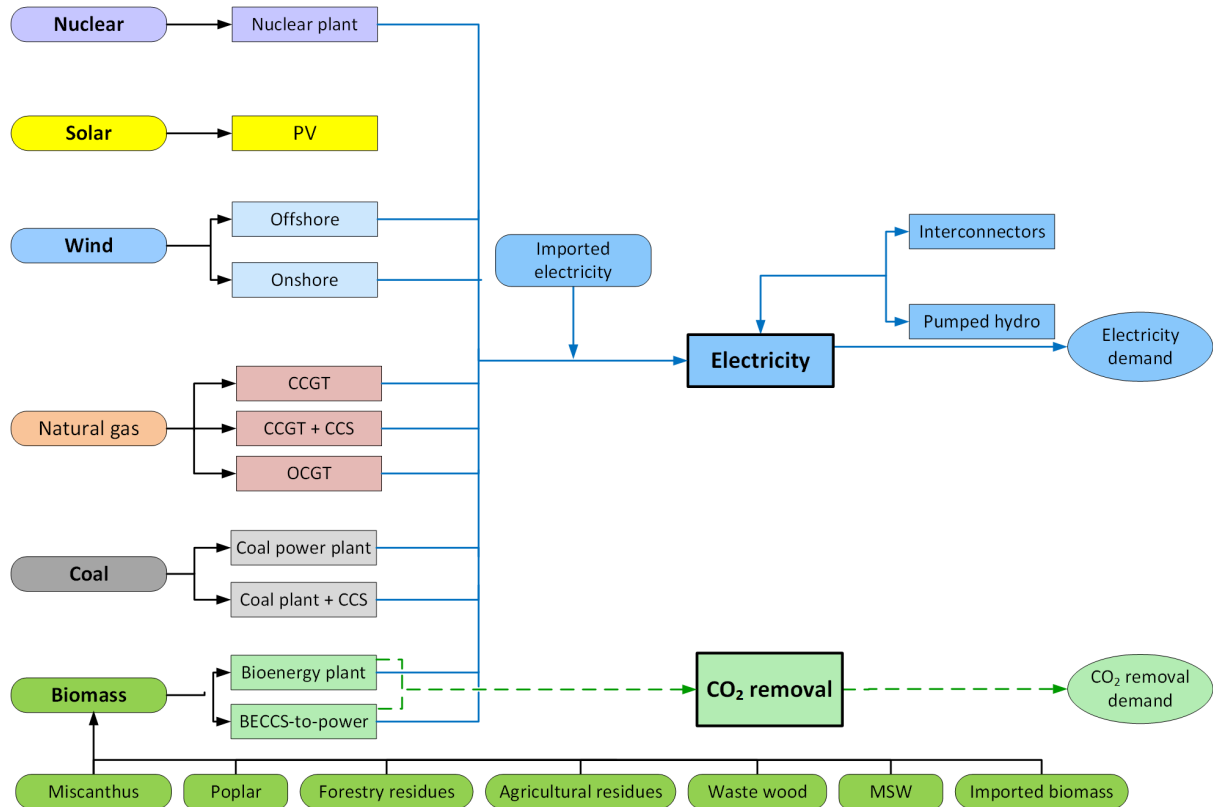


Figure 2.1: ESO topology illustrating the modelled power sector in the UK.

2.3.1 System Parameters

The electricity demand profile used in this study was sourced from the published work by Ganzer et al. [100] where they considered the heating and transport sectors. For this, they proposed three different scenarios, each considering the electrification of the heating and transport sectors. In each scenario, electrification was categorised as either high, central or low. For this segment of the thesis, the central electrification demand profile was chosen to model the power sector in the UK. Additionally, the hourly solar and wind profiles were obtained from Renewables Ninja [101]. The clustered data used in the model is shown in Figure 2.2. The cost of technologies were updated in the model to what is shown in Table 2.5.

Table 2.5: Power generation technology costs used in the ESO-UK model [102, 103, 104, 105, 106].

Technology	CAPEX (£/kW)	OPEXFix (% of CAPEX)	OPEXSU (£/kWh)	OPEXNL (£/h)
Nuclear	4721	2	4000	4
Coal	1540	2	199	3
Bio	2250	2	199	3
CCGT	596	3	80	2
OCGT	444	3	4	0
Coal-PostCCS	3694	3	250	4
Coal-PostCCSr	2506	3	250	4
CCGT-PostCCS	1620	3	84	2
CCGT-PostCCSr	1110	3	84	2
BECCS	3826	4	250	4
BECCSr	1827	4	250	4
Wind-Onshore	981	2	0	0
Wind-Offshore	2047	4	0	0
Solar	616	2	0	0
InterImp	1001	0	0	0
PHSto	1216	1	0	0

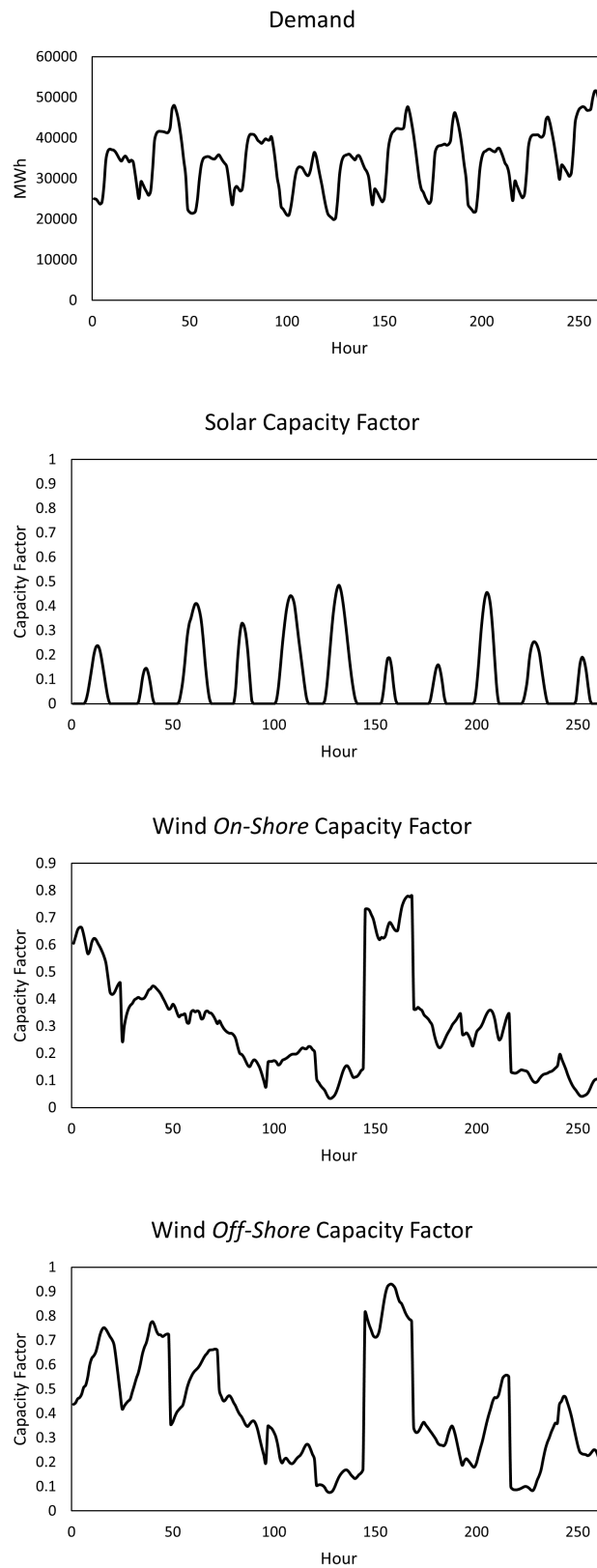


Figure 2.2: Clustered hourly 11 days of power demand along solar and wind capacity factors used in the ESO-UK model.

2.3.2 Fuel Prices and Carbon Price

In this analysis, the primary objective is to investigate the impact of fuel prices. The base fuel prices for the considered technologies are presented in this section. The variation in these prices revolve around future projections, which will be further detailed in Chapter 3. Nonetheless, the base prices for natural gas, coal and uranium are displayed in Table 2.6. Additionally, the price of biomass is derived from a biomass supply chain that is implemented in the model and is as presented in Table 2.7.

Table 2.6: Fuel prices used in the ESO-UK model [107, 108].

Fuel	Price	Units
Natural Gas	22	£/MWh
Coal	8	£/MWh
Uranium	5	£/MWh

Table 2.7: Biomass supply chain used in the ESO-UK model [109].

Biomass Source	Max. Available Supply (TWh/year)	Price (£/MWh)
Waste wood	17	16
Forest residue	7	20
Indigenous miscanthus	98	23
Crop residue	41	25
MSW	35	27
US Import	800	28
EU Import	800	36

2.4 Modelling the UAE Energy System

To simulate the decarbonisation of the UAE economy, the industrial segment of the ESO model by Gazner [79] was extended to incorporate additional technologies that were shown in Table 2.2. Moreover, the transport sector has been integrated into the model, as explained earlier in this chapter. This section provides an overview of the costs and parameters applied in adapting the ESO model to the UAE context. The comprehensive structure of the model is shown in Figure 2.3.

2.4.1 System Parameters

Power Sector

To model the power sector in the UAE using ESO-X, an hourly demand profile was needed for the country. Since this level of granularity was not available, the profile shape was derived from a publication focused on the State of Qatar [110]. The choice of Qatar as a reference was motivated by its geographical proximity to the UAE and its monthly demand profile that aligns closely with that of the UAE [110, 111]. Additionally, both regions share comparable weather temperature variations [112] and like the UAE, Qatar is an energy net-exporter [113]. Given these similarities, the assumption that the UAE's hourly demand profile shape is similar to Qatar's was considered to be a reasonable approximation.

By utilising this assumption, the clustered demand profile for the UAE is illustrated in Figure 2.4, alongside wind and solar availability profiles extracted from Renewables Ninja [101]. It is important to note that for solar availability, data were extracted from locations in Al Dhafra (western) region as vast land is available for solar farms and most

of the existing solar capacity is in that region. Data for onshore wind were collected from regions near Sir Bani Yas, aligning with ongoing onshore wind projects in that area [114]. This region was also observed to have the highest availability of onshore wind. With regards to offshore wind, data were extracted from seawater locations around the Emirate of Fujairah shore, where the highest wind availability was recorded there. In terms of imported electricity price, this price was assumed to be constant as neighbouring countries with existing interconnections (KSA and the Sultanate of Oman) operate based on fixed tariffs that depend on the amount of consumed electricity [115, 116].

The costs, capacity and maximum deployment associated with power generation technologies in ESO-UAE were derived from ongoing investments if the data was available. Tables A.1 and A.2 present the data used in the ESO-UAE model for the power sector. For ancillary services to keep the grid stable at 50 Hz [117], system inertia was kept at 39,000 MW.s, which is based on a blackout incident in the UAE [118, 119]. The reserve capacity was found by trial and error and kept at 20% which was further confirmed by published data [120]. Other relevant assumptions are listed in section 2.4.2.

Industrial Sector

To characterise the industrial sector in the UAE, this study expanded the ESO model to include the production of LNG, aluminum, ammonia, hydrogen and SAF. Details about the future trajectory of each commodity production are provided in Chapter 4. It is important to highlight that fuel switching was integrated into the model using the same formulation as technology retrofitting. Additionally, the DAC archetype technology considered in this model is from Climeworks. This technology utilises waste heat and can operate at low temperatures (100 °C) [121]. Similar to the power sector, investment costs were utilised to represent the implemented technologies in the model when available. Tables B.1 to B.23 present the parameters associated with this segment of the model.

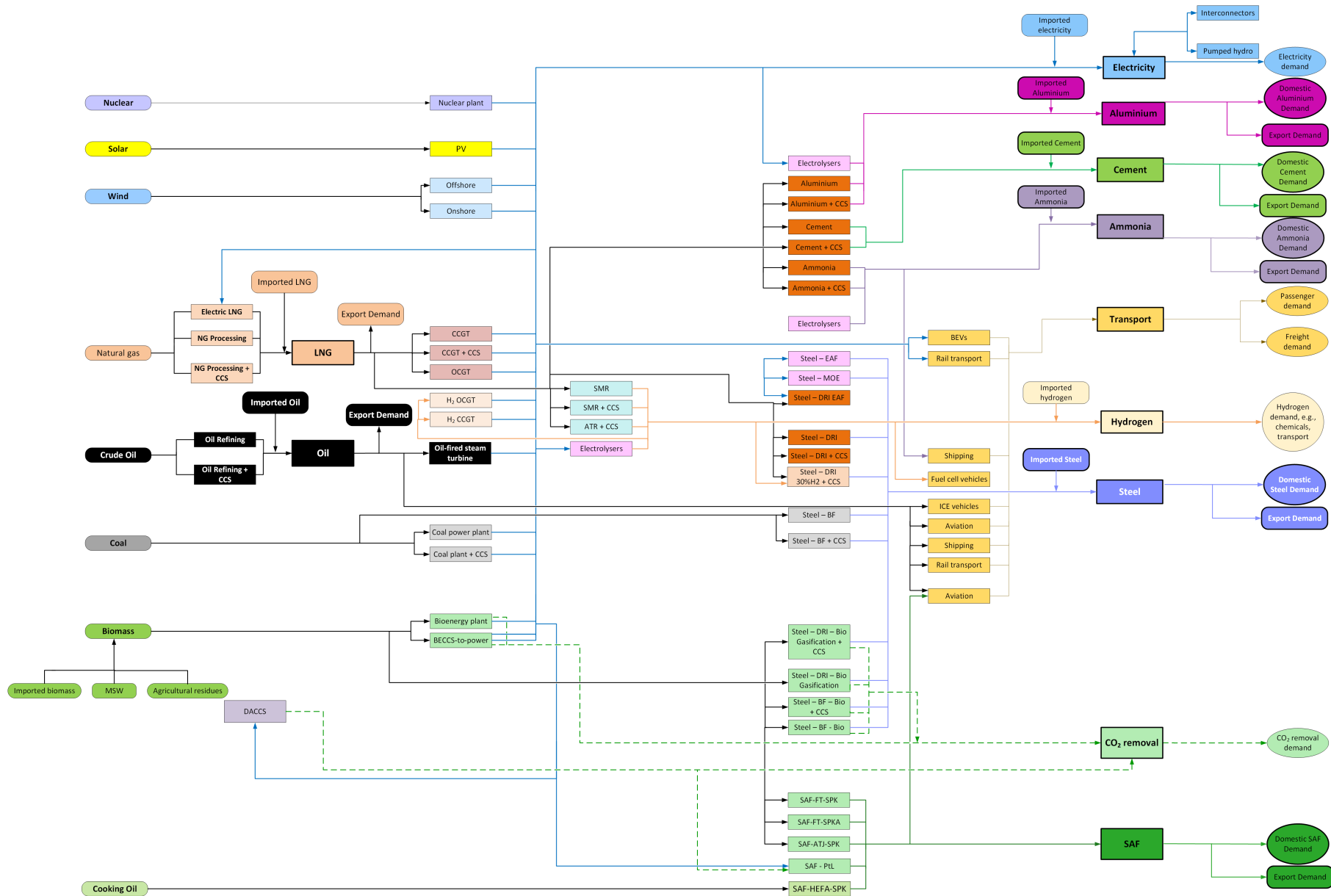


Figure 2.3: ESO topology illustrating the modelled segments for the UAE study.

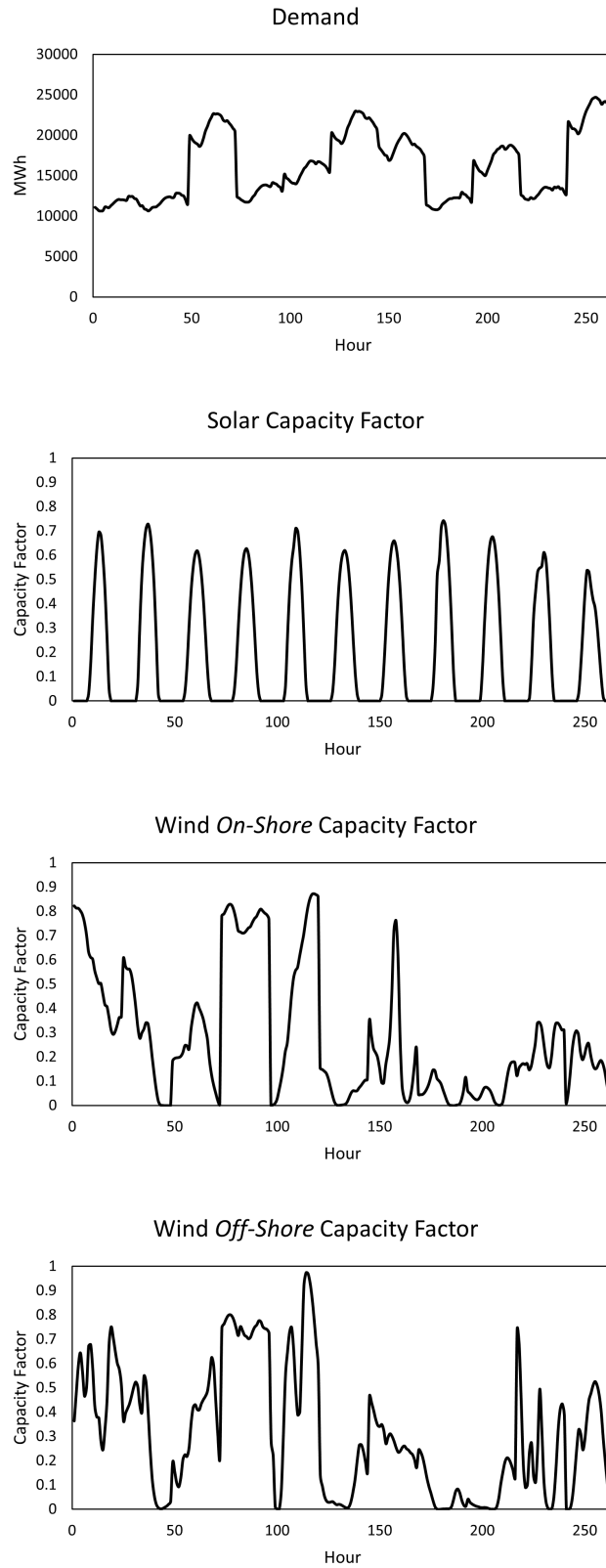


Figure 2.4: Clustered hourly 11 days of power demand along solar and wind capacity factors used in the ESO-UAE model.

Transport Sector

To characterise the transport sector in the UAE, this model considered road, sea and air transport. The existing capacity was derived from available data. Notably, OPEX and emissions for each transportation type were based on the average traveled distance. For shipping, the model employed deadweight tons (DWT) as units for vessels, rather than a single vessel unit. This decision was made considering the diverse sizes of vessels, aiming to identify which vessel types might need transformation.

2.4.2 Key Assumptions

1. **No New Diesel Generators:** It is assumed that no more diesel generators are built. This assumption is based on the existing generators in the Emirate of Sharjah, where new capacity has been utilising natural gas [122].
2. **No Additional Interconnections with KSA and Oman:** It is assumed that no more electrical interconnections are built with KSA due to the frequency mismatch (KSA operates at 60 Hz [123], while the UAE operates at 50 Hz [117]). Similarly, it is assumed that no additional capacity is built with Oman and the existing capacity is sufficient.
3. **H₂-CCGT Build Rate and Operating Magnitude:** It is assumed that the maximum build rate for an H₂-CCGT is the same as that for a CCGT. Additionally, it is assumed that the cost magnitude of operating an H₂-CCGT (excluding fuel) increases at the same magnitude as the CAPEX relative to a conventional CCGT.
4. **Nuclear Power Plant Planning and Construction:** It is assumed that the planning and construction of nuclear power plants occur every 10 years, not during every planning period. This assumption is based on the Barakah nuclear power plant [124].

5. **Biomass-Based Power Plant Size:** It is assumed that the size of biomass power plants (including BECCS-r) is 50 MW when domestically available biomass is used [125, 126].
6. **Plant Lifespan:** It is assumed that all plants are new and will not retire during the modeled time periods.
7. **Demand Profile Shape:** It is assumed that the shape of the demand profile is similar to that of Qatar. This assumption is made because the hourly demand profile for the UAE was not available.
8. **Production Expansion of Steel, Cement and Aluminum:** It is assumed that the production of commodities does not expand. Specifically, in terms of steel, cement and aluminum, this assumption is based on the premise that the existing capacity was utilised for the construction of the Barakah nuclear power plant. Following the completion of this power plant, these commodities can be reallocated for the construction of various technologies during the transition period.
9. **Electrolyser-Produced Products Capacity Factor:** For products produced using electrolyzers, 80% capacity factor is assumed.
10. **Emissions Reduction with 30% H₂ in Steel DRI:** By using 30% hydrogen in steel DRI, it is assumed that emissions are reduced by the amount of hydrogen that replaces natural gas [90].
11. **Road Vehicles Retirement:** It is assumed that the retirement of road vehicles takes place within the first three planning periods. This assumption is based on the UAE regulation that prohibits the renewal of licenses for road vehicles after 15 years of use [127].
12. **Hydrogen Vehicles Operating Expenditure:** It is assumed that the increase in fixed OPEX for hydrogen-fueled vehicles is proportional to the increase of hydrogen vehicles CAPEX relative to ICE vehicles CAPEX.

13. **Diesel Locomotive Capacity:** It is assumed a diesel locomotive has the capacity to carry 8,500 tons.
14. **Air and Sea Transport Emissions:** It is assumed that the UAE takes full responsibility for the emissions associated with their nationally owned fleets, regardless of the travel direction.
15. **Vessel Utilisation:** It is assumed an annual utilisation rate of 65% for all the vessels in the UAE throughout the year [128].
16. **Maritime Fleet Capacity Growth:** It is assumed that every 10 years, the capacity of the maritime fleet increases in alignment with the growth projected for the year 2030 [129].
17. **Truck Fleet Growth:** It is assumed that future freight demand will be predominantly met by the railway fleet and the truck fleet will not experience significant growth.
18. **Public Transport Requirement:** It is assumed that the public transport requirement will be satisfied by the expansion of passenger railway services and the demand for buses will remain constant without substantial growth.
19. **Monetary Performance Assumption:** It is assumed that the monetary performance is similar to that of Qatar. This assumption is employed only in cases where UAE data is not available. The reason for this is that the UAE publishes its data using revision 3 of the International Standard Industrial Classification (ISIC), while Qatar uses revision 4, which is compatible with the JEDI version utilised in this research.

Chapter 3

Insights from the United Kingdom

3.1 Energy Evolution in the UK

3.1.1 Past

Examining the historical trajectory of the UK's energy policy sheds light on the intricate dynamics that have shaped its energy landscape over the decades. The oil shock of the 1970s marked a pivotal moment, compelling the UK to reassess its energy sources. In response, the country gradually transitioned from heavy reliance on oil to diversifying its fuel mix, incorporating coal and nuclear power for electricity generation. Notably, during this era, the UK substantially increased its share of nuclear power in the overall power generation reaching 20% by the early 1990s. Simultaneously, the UK emerged as a global leader in deregulating its electricity market. This decade marked a significant shift, with the UK actively reducing its reliance on coal generation from a staggering 90% to a mere 7% by the early 2000s. The removal of legal barriers to electricity generation using natural gas played a pivotal role in incentivising this transition [130, 131, 132].

However, the subsequent decade, spanning from 2000 to 2010, brought about a notable transformation as the UK transitioned from being a fuel net-exporter to becoming a net-importer [133]. The period culminated in a financial crisis [134], exacerbated in 2009 by gas supply interruptions due to Russian-Ukrainian disputes [135], plunging approximately one quarter of UK households into fuel poverty [136]. In the aftermath of these challenges, the UK government, starting from 2010, embarked on a mission of affordable decarbonisation. Under both Conservative and Liberal Democrat administrations, the Electricity Market Reform (EMR) was instituted. The EMR was to address key pillars in the electricity sector spanning from: decarbonisation, promotion of low-carbon generation through contracts, supply security during peak demand to affordability [137]. The Energy Act of 2013 solidified the implementation of EMR through a legislative framework [138], with the Department for Business, Energy and Industrial Strategy (BEIS) being established in 2016 to oversee these efforts [139].

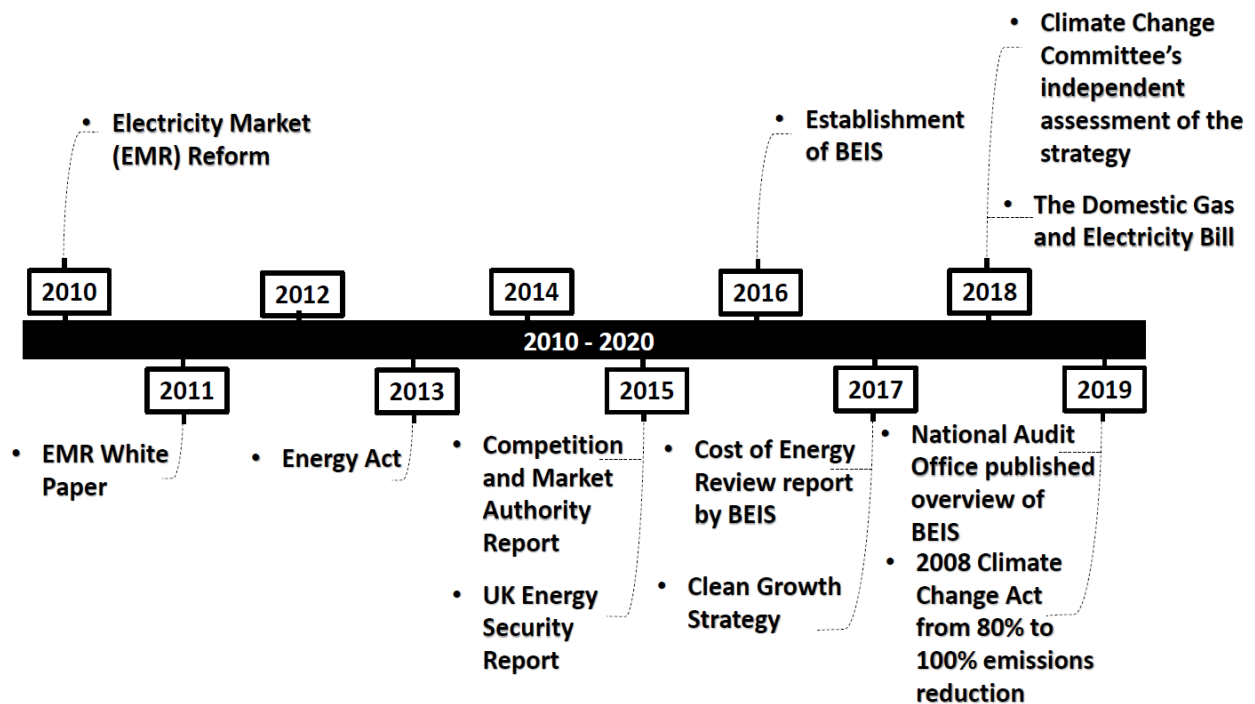


Figure 3.1: A summary of UK's electricity sector evolution during the 2010-2019. Appendix F contains a more detailed timeline for key events that occurred between 1990 and 2019.

With a focus on decarbonisation, the 2010-2019 decade witnessed a momentous change

as the UK elevated its climate targets, shifting from the 80% reduction outlined in the 2008 Climate Act to a more ambitious goal of achieving net-zero emissions by 2050, compared to 1990 levels [140]. The subsequent decade ushered in a transformative vision encapsulated in the Ten Point Plan for Green Industrial Revolution and the Energy White Paper. These initiatives outlined ambitious targets, including 40 GW of offshore wind by 2030, low-carbon hydrogen production, investments in carbon capture, utilisation and storage (CCUS) along nuclear advancements. The commitment to these targets involves a combination of public funds to leverage private investments and stimulate jobs in the market [141].

However, amidst this evolution, recent global events have wielded a profound impact on energy prices, compelling the UK to reassess its goals, including the reconsideration of the decommissioning timeline for coal-fired power plants [142]. This historical overview sets the stage for understanding the complexities and challenges inherent in the contemporary energy landscape and emphasises the imperative for adaptive and resilient energy policies.

3.1.2 Present

The year 2022 marked a significant episode in the UK's energy landscape, triggered by the natural gas price shock that had far-reaching consequences on the economic well-being of its residents [143]. Amidst global geopolitical complexities, the UK, despite importing a mere 4% of its gas from Russia [144], experienced a substantial surge in gas prices, causing financial distress for half of its adult population [143]. This adversity, reminiscent of the 1970s oil shocks [145], unfolded as a consequence of the intricate interplay between global energy dynamics and domestic energy infrastructure.

The dependence on natural gas-powered technologies which is 46% of the UK's electricity supply [146], played a pivotal role in magnifying the repercussions of the natural gas price shock. As Russia supplies 17% of the global natural gas market, the uncertainty in gas

supply due to geopolitical tensions led to a spike in prices within the UK [145]. The intricate web of events in 2022 such as low renewable energy generation, a fire disrupting the national grid England-France interconnector and diminished gas reserves following the closure of Cenrica, all contributed to the crisis that disproportionately affected low-income households [147, 148, 149].

Historically, the UK implemented initiatives to ensure energy affordability, liberalising and privatising the electricity sector as detailed in Appendix F. Despite subsequent measures like fuel switching and technological advancements, assumptions of energy security, particularly price and geopolitical security, were disrupted in 2022. This unforeseen vulnerability prompted a critical examination of the trajectory of energy prices and the implications on the UK's legally binding decarbonisation goals.

Looking forward, uncertainties loom over the direction of natural gas prices, with multiple scenarios contingent on geopolitical factors. Potential shifts in source of supply from European to the international gas market, particularly through increased LNG imports, present both opportunities and risks. The interplay of geopolitical tensions in Europe introduces further complexities, potentially influencing prices to varying extents.

In light of this, the imperative emerges to chart a defined path forward, insulating consumers from the kind of impact witnessed in 2022. Acknowledging the government's commitment to affordable energy and carbon neutrality by 2050, the discussion here explores the necessity of forecasting the impact of future fuel prices on the energy transition. As a policy anchor, the 2050 target necessitates an avoidance of economic recessions to sustain the decarbonisation trajectory. Therefore, understanding the challenges faced by a net-importer amid fluctuating fuel prices becomes pivotal and offers insights into how these dynamics can shape the transition process in the face of evolving global events.

3.2 Method

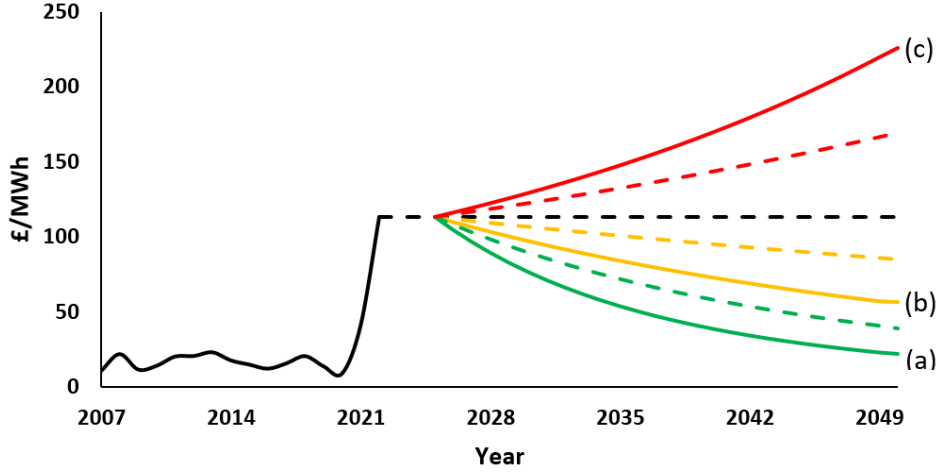


Figure 3.2: An illustration of potential trajectories for future natural gas prices in the UK from 2022 levels [150].

The future trajectory of natural gas prices unfolds through a spectrum of scenarios, presenting a range of potential increases to decreases. Examining the geopolitical dimension reveals a pivotal consideration, where the UK moves towards the international gas market, favoring LNG over natural gas from the European market. This shift implies an augmented reliance on LNG imports and hence, potentially diverting from the existing pipeline infrastructure.

In a hypothetical scenario where the UK shifts to LNG and prices remain unaffected by heightened demand, a consequential reduction in 2022 gas prices can be anticipated. This anticipation can align with the zone occupied by the yellow lines in Figure 3.2. This scenario is contingent on the assumption that LNG prices remain resilient at the levels they were in 2022. However, acknowledging the intricate interplay of market dynamics, there exists a potential for an escalation in LNG prices due to increased demand, a phenomenon tethered to the principles of demand and supply. This could result in a departure from the anticipated trajectory, pushing natural gas prices towards the regions represented by the red lines in Figure 3.2. The manifestation of such fluctuations highlights the com-

plexity of forecasting in the face of dynamic markets. Furthermore, the persistence of geopolitical tensions in Europe and maritime pathways emerge as a critical variable that influences the trajectory of natural gas prices. In the event of ongoing tensions, prices may experience further escalation, projecting as well into the domain occupied by the red lines in Figure 3.2. Given the intricate and uncertain nature of natural gas price dynamics, establishing a strategic pathway forward is imperative. This pathway should navigate potential fluctuations that can mitigate adverse impacts on consumers.

To explore the trajectories of natural gas prices and their potential implications on UK's electricity sector, a case study approach is adopted, focusing on the uncertainties surrounding the decarbonisation process and its relationship with fuel prices. The electricity sector evolution, relative to fuel prices, serves as the focal point by employing the ESO dataset described in Chapter 2. The investigation hinges on modelling different scenarios, considering a range of potential outcomes in natural gas prices. The study period spans from 2022 to 2050, with variations in the years corresponding to when natural gas price are expected to change. The model utilises four selected planning periods: 5, 10, 15, 20 and 25 years for when gas prices change from the baseline year (2022).

3.2.1 Scenario Definition

To capture the complexity of natural gas price dynamics, the study incorporates three levels of price change, each representing a distinct scenario and they are the following:

1. **2019 Price Scenario (2019):** This is an idealised scenario, where gas prices regress to 2019 levels. *22 £/MWh*
2. **Central Price Scenario (Central):** Visualising a shift toward reliance on imported LNG, which is priced based on oil prices. This scenario simulates a transition away from traditional pipeline infrastructure. *56 £/MWh*

3. **Doubled Price Scenario (Double):** This scenario acknowledges the possibility of continued scarcity in natural gas supply through pipelines or continued geopolitical tensions that result in a substantial increase in prices. *226 £/MWh*

All scenarios start with a baseline natural gas price of 113 £/MWh obtained from the National Balance Point (NBP) for the period between March 2022 to September 2022; since the beginning of the Russian-Ukrainian war [151, 152].

For scenario implementation, the model varies the time for when natural gas price changes within the modelled transition period (5, 10, 15, 20 or 25 years). Taking the example of a 15-year case, the study assesses the impacts on decarbonisation assuming a 15-year delay for natural gas prices to change. The variation in prices are contingent upon the predefined levels of natural gas price changes (2019 Price, Central Price, Doubled Price). This approach allows for a comprehensive examination of the potential outcomes and implications under different time frames and price scenarios.

By employing this methodological framework, the study aims to unravel the intricate interplay between natural gas prices and the evolution of the UK's electricity sector, providing valuable insights into the pathways that unfold as fuel prices fluctuate over time on the decarbonisation process. In context of decarbonisation, the model adopts a CDR target of 5 mt-CO₂ by 2030, increasing to 75 mt-CO₂ by 2050 [153]. These targets are incorporated through linear trajectories. The CDR targets are assumed to be achieved through the employment of BECCS technology, as a prior study found that DAC is considered costly in the UK [154]. Regarding carbon pricing, the initial price considered is set at £20/t-CO₂, rising to £312/t-CO₂ by 2050 in a linear trajectory [155, 156].

3.3 Impact of Fuel Prices on Future Transition

3.3.1 Technology Deployment

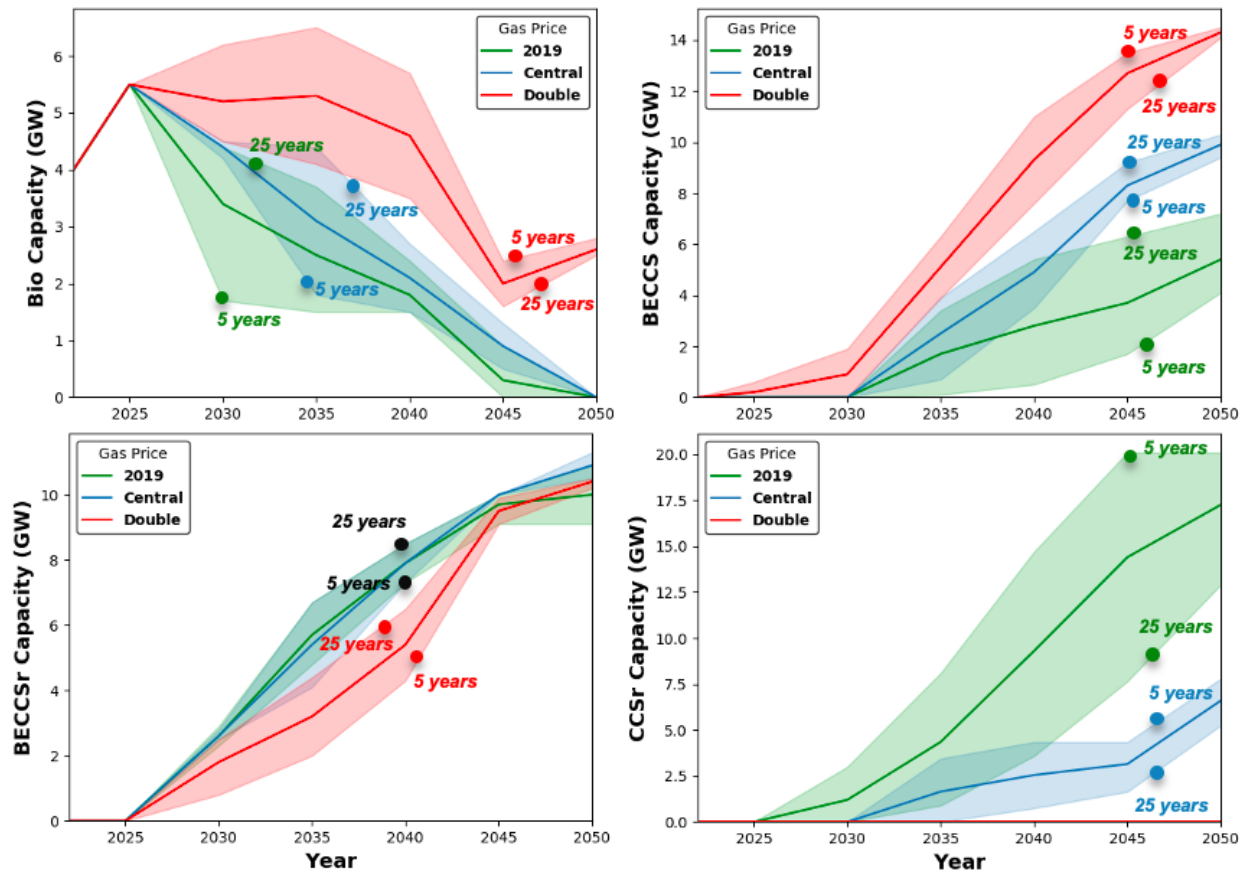


Figure 3.3: Technology deployment for the scenarios used for ESO-UK.

The investigation into various scenarios characterised by distinct natural gas prices yields noteworthy insights into the evolution of the UK's power sector as shown in Figure 3.3. In scenarios marked by high natural gas prices (Double), the integration of CCS consistently aligns with biomass-based (bio) power plants. By 2050, BECCS is projected to achieve a capacity of 14 GW, accompanied by 10 GW of BECCSr and 3 GW of bio-power plants. It is worth emphasising the decrease in bio capacity due to its conversion into BECCSr, as existing bio plants are retrofitted with CCS. Consequently, new bio capacity is built to

replace the retrofitted units, maintaining the overall capacity within BECCSr. Notably, some CCGT capacity from the existing capacity today remains in the system, serving as reserve capacity in 2050 under this scenario.

On the other hand, when natural gas prices decrease from 2022 levels, scenarios unfold with varying capacities of CCGT-CCS. In a scenario where the UK leans towards imported LNG from the international market (Central), there is a reduced demand for CCGT-CCSr capacity compared to 2019 natural gas prices. The projected capacity of CCGT-CCSr at central prices stands at around 5 GW, alongside a corresponding CCGT capacity of approximately 10 GW. In instances where prices revert to 2019 levels, CCGT-CCSr capacity expands to around 17 GW, while CCGT capacity remains at its lowest due to retrofits with CCS. In both scenarios, all the bio-power plant capacity undergoes retrofits with CCS (BECCSr), approximately reaching 10 GW by 2050.

Irrespective of the duration it takes for natural gas prices to change, these prices decisively shape the technological composition within the system. While the endpoint in 2050 remains constant regardless of when the natural gas price begins to change, variations emerge along the trajectory for most technologies. Notably, at extreme price points—whether doubling or dropping to 2019 levels—the deployment of bio-power plants experiences fluctuations between 2025 and 2045. In the scenario where the duration for prices to drop to 2019 levels is beyond 10 years, BECCS gains prominence in the system, overshadowing CCGT-CCSr.

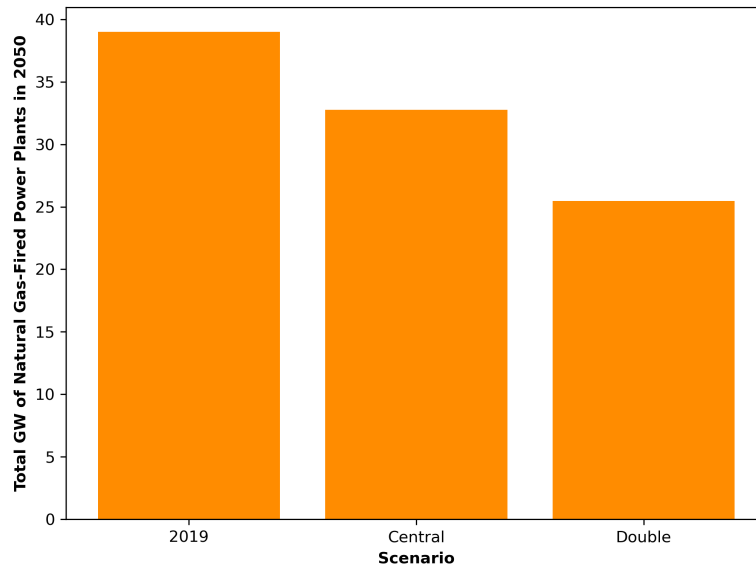


Figure 3.4: Natural Gas Prices and corresponding gas-fired power plant capacities in 2050.

The overarching conclusion is that a complete phase-out of fossil fuels without considering CCS could jeopardise the integrity of the system and it is imperative to promptly consider bio technologies. Previous research by Paratma et al. [157] emphasises the significance of prioritising CCS for decarbonisation and transitioning from the research phase. Regardless of high or low natural gas prices, the results obtained from all scenarios indicate the retention of existing CCGTs, with or without CCS, in 2050, as shown in Figure 3.4. In most scenarios, only 1% to 27% of this capacity is utilised for generation, with the remainder held in reserve, highlighting its crucial role in providing the necessary reserve capacity.

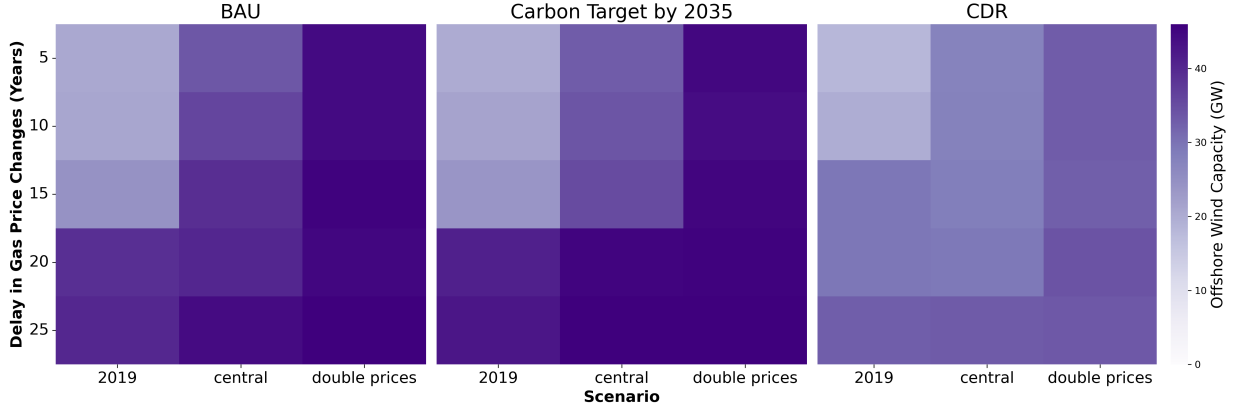


Figure 3.5: Impact of carbon targets and natural gas price variations on offshore wind deployment.

During the analysis, variations in offshore wind deployment were observed in response to changes in carbon targets. To study the impact of these targets, three main conditions were implemented, each varying the carbon target. As shown in Figure 3.5, the first condition, Business as Usual (BAU), maintains emissions at current levels of 58 mt-CO₂ per year until 2050. The second condition introduces a carbon target of net-zero by 2035, a goal established by the UK [158], and maintains this carbon neutrality until 2050 without CDR targets. The third condition applies CDR targets, demonstrating a focused approach toward carbon removal. Each scenario incorporates varying natural gas prices with varied timings for price changes.

From Figure 3.5, it is evident that as the system progresses towards a CDR target, less offshore wind is deployed. This reduction is primarily due to the increased reliance on bioenergy technologies to meet CDR requirements. Moreover, when a CDR target is absent and only a carbon target is applied, the system deploys about 40 GW of offshore wind in most scenarios, closely aligning with the UK's offshore wind target [159]. Importantly, even with a CDR target, offshore wind remains a significant component in the system, with capacities ranging from 15 to 35 GW, dependent on the fluctuations in natural gas prices. In all scenarios, the level of offshore wind deployment is influenced by natural gas prices and the varied timings of their changes.

The interaction between offshore wind capacity and CDR targets in the model highlights the dual role of intermittent renewable energy in reducing operational carbon emissions. As scenarios evolve from BAU to CDR, the increased reliance on offshore wind reflects a strategic shift towards more aggressive decarbonisation and emphasises the crucial role of intermittent renewable infrastructure in achieving future carbon neutrality goals. While the pursuit of 100% renewable energy is advocated for decarbonisation, the intermittent nature of renewables introduces grid stability challenges, as evidenced in numerous studies [160, 161]. Nevertheless, the significance of intermittent renewables, including onshore wind, offshore wind and solar cannot be disregarded. The model projected that these sources are anticipated to account for approximately 60% of the installed capacity in 2050.

3.3.2 Biomass Prices and BECCS Deployment

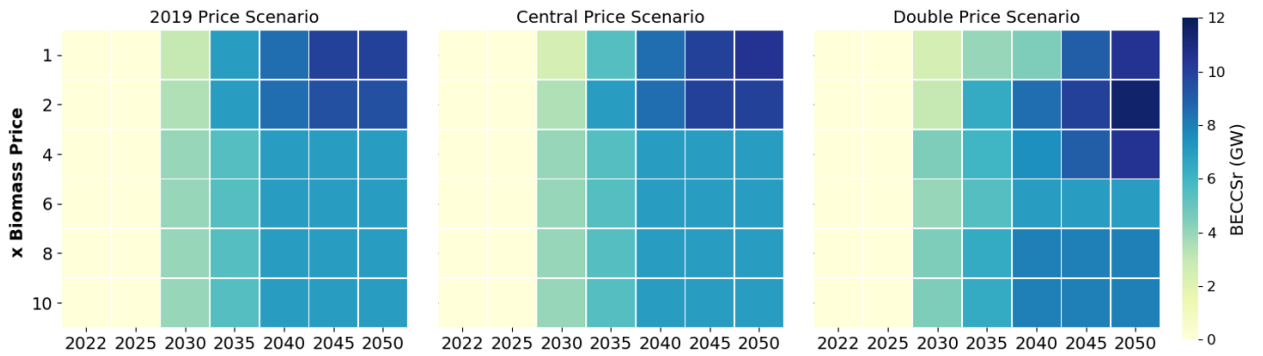


Figure 3.6: The impact of biomass price on BECCS deployment.

In the preceding analysis, the assumption that biomass prices remain unaffected by natural gas price fluctuations led to the preference for biomass over expensive natural gas as a fuel for power generation. However, this assumption requires reconsideration, as economies are impacted by fuel price fluctuations which as a result can influence biomass prices. Thus, a critical question arises regarding the deployment of BECCS in response to changing natural gas and biomass prices. Figure 3.6 was developed to address this question by varying the price of biomass in ESO-UK by multiples of 1 to 10 under dif-

ferent natural gas scenarios over a fixed 15-year duration. BECCSr was chosen for this analysis, as the three natural gas prices reached around the same capacity in 2050.

The analysis reveals that the maximum deployment of BECCSr persists within the system even with a two-fold increase in biomass prices, except when natural gas prices double. In scenarios where natural gas prices rise from 2022 levels, BECCSr remains at its maximum deployment up to a four-fold increase in biomass prices. This highlights the potential of bio technologies in the UK's electricity grid and emphasises the urgency of deploying bio-power plants at the earliest opportunity.

To progress towards carbon neutrality targets in the power sector and offset residual emissions, the UK must stimulate the deployment of BECCS promptly. Following the examples of several European countries, such as Sweden and Finland. Sweden generates 9% of its electricity from bio-resources and this was stimulated by the green schemes implemented since the 1980s [162, 163, 164]. Similarly, Finland, with a bio-focused approach, generates 15.6% of its electricity from bioenergy, driven by feed-in tariffs [165, 166]. The UK intends to introduce more bio-resources into the electricity grid, initially facilitated by public funds to stimulate subsequent private investments. These investments are anticipated to yield social benefits [167], aligning with previous successes in offshore wind projects [168]. In total, the UK is projected to require 14-30 GW of bio technologies to fulfill the CDR policy aimed for the removal of residual emissions from other sectors.

3.3.3 Impact of Fuel Prices on Transition Cost

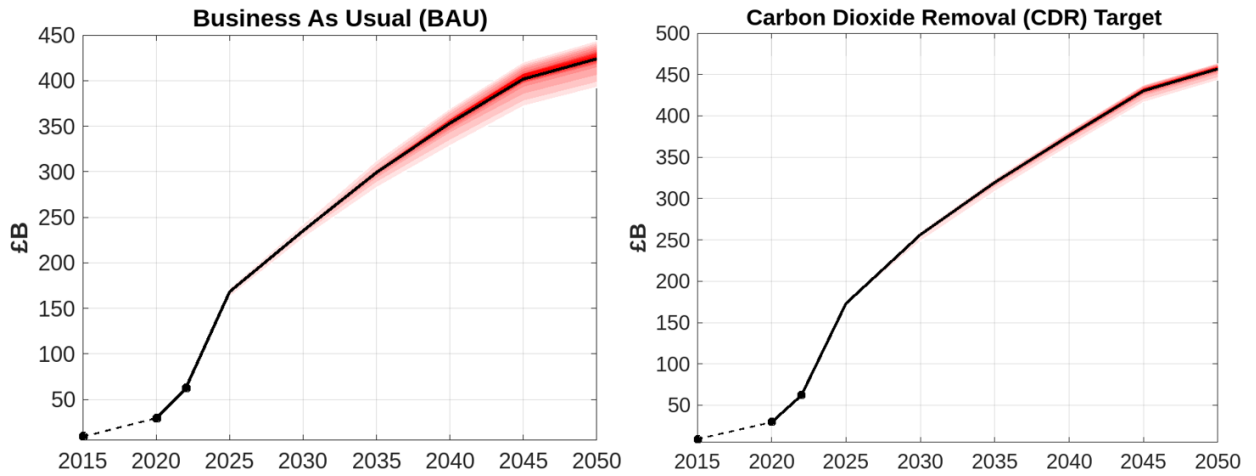


Figure 3.7: Cumulative total system costs for business as usual and CDR decarbonisation conditions across all natural gas scenarios utilised in the ESO-UK model.

The examination of fuel prices has provided valuable insights into the decarbonisation trajectory, particularly concerning the trade-off between relying on natural gas and biomass within the system. Nevertheless, a pivotal inquiry arises regarding the feasibility of sustaining decarbonisation efforts in events of exceptionally high fuel gas prices. To address this crucial question, the cumulative system cost was assessed through a plotted comparison as shown in Figure 3.7 by considering two main conditions. The first condition, denoted as 'Business As Usual (BAU)', involves deviating from decarbonisation goals and maintaining emissions at today's level (58 mt-CO₂) until 2050. This plot incorporates all the delays and variations in natural gas prices outlined earlier. The second condition considers the UK's CDR target.

Figure 3.7 reveals that under a BAU condition, a financial outlay ranging from £392 billion to £445 billion is requisite for the system to transition adequately to meet the power demand in 2050. For a CDR target, an estimated £453 billion is essential, exceeding the upper limit of the BAU range by £8 billion. It is worth noting that under the BAU condition, the electricity sector attains self-sufficiency and reaches near-zero emissions

by 2030, aligning with the 2035 carbon neutrality target. This shift in the model was motivated by the substantial increase in natural gas prices, prompting a system evolution towards greater dependence on bio-resources.

3.4 Chapter Contribution

This chapter makes a contribution to understanding the power landscape in the UK by unraveling historical trajectories, contemporary challenges and future scenarios. The inspection of the UK's past energy policies, shaped by pivotal moments such as the 1970s oil shock and subsequent transitions, provides a comprehensive context for analysing the nation's energy evolution. The chapter highlights the significant shift from being an energy net-exporter to a net-importer, emphasising the impact of global events, particularly the Russian-Ukrainian war of 2022 on the UK's energy dynamics. The vulnerability of a net-importer amid geopolitical uncertainties is explored, revealing the influence of natural gas prices and consequently, the structure of the power mix in 2050.

A key contribution lies in the methodological approach adopted in the model using various natural gas price scenarios. The analysis offers insights into the resilience and adaptability of the UK's energy system under extreme changes of natural gas price. This is with a particular focus on the role of existing CCGT capacity, as a strategic reserve in a decarbonised 2050.

Furthermore, the chapter explores the urgency of deploying bio technologies, specifically BECCS_r, by examining the relationship between biomass prices and deployment under different natural gas scenarios. Comparing scenarios between a BAU condition and the UK's CDR target offers insight into the financial ramifications of maintaining a sustained decarbonisation objective amidst fluctuating fuel prices.

Chapter 4

Assessments of the United Arab Emirates

In December 1971, a pivotal moment unfolded as the distinct Emirates of the United Arab Emirates (UAE) came together to forge a unified nation. Spearheading this monumental effort was the founding father, H.H. Sheikh Zayed bin Sultan Al Nahyan, whose unwavering dedication paved the way for the UAE's transformation into the prosperous country it is renowned for today.

Abu Dhabi, Dubai, Sharjah, Ajman, Fujairah, Ras Al Khaimah and Umm Al Quwain constitute as the distinct emirates that form the UAE. Geographically situated in the southeastern region of the Asian continent and the eastern part of the Arabian Peninsula, the UAE overlooks the Arabian Gulf to the north and northwest, bordered with the Kingdom of Saudi Arabia to the west and the Sultanate of Oman to the south.

Covering a total land area of 71,023 km² and a coastline stretching 1,318 km, the UAE offers a diverse landscape with a population of 9.5 million. The country experiences a warm and sunny winter that transitions to a hot and humid summer [169].

4.1 Political Structure

The government in the UAE is led by the Supreme Council of Rulers that consists of the leaders from its seven emirates. This council is the top policy-making body and has the authority to elect from its members a president and a vice president every five years. Holding legislative and executive powers, the Supreme Council approves the prime minister nominated by the president, who then forms the cabinet that oversees the implementation of federal policies across all governmental institutions. Subsequently, the Federal National Council, a 40-member parliament that is partially elected by the public, examines new legislation and advises cabinet [170, 171]. The government operates with an open-door policy at all levels, facilitating direct interaction between the public and governmental bodies, including rulers, cabinet members and parliamentarians, to address concerns and propose solutions for the community's benefit [172, 173, 174, 175].

In alignment with global climate change initiatives, the UAE has established the Ministry of Climate Change and Environment (MOCCA). The MOCCA is tasked with leading and coordinating efforts to achieve the country's strategic climate change-related targets. The ministry's foremost responsibility is to ensure collaborations at all national levels by engaging stakeholders from key sectors including energy, economy, industry, infrastructure, transport, waste and the environment. These stakeholders report to and update the ministry about their plans and policies on climate change-related initiatives [176]. It is noteworthy that among the ministry's achievements is the development of the Emission Quantification Tool that facilitates the quantification of GHG emissions [177].

4.2 The UAE and Climate Change

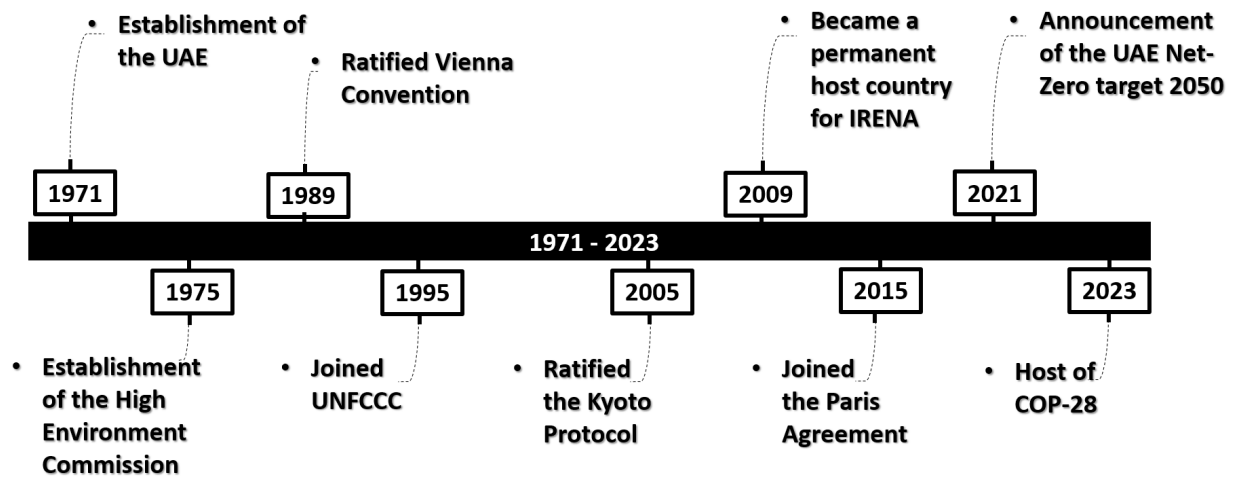


Figure 4.1: A summary of the UAE's environmental evolution during the 1971-2023 period. [176, 178].

Environmental conservation has been a fundamental value in the UAE since its establishment. Founded by H.H. Sheikh Zayed bin Sultan Al Nahyan in 1975, the High Environment Commission led the charge in environmental preservation efforts, evolving into what is known today as the Federal Environment Agency [178, 179]. More recently, the Emirate of Abu Dhabi has emerged as a hub for renewable energy initiatives, hosting the International Renewable Energy Agency (IRENA) in Masdar City, a designated economic zone focused on renewable energy investments. Additionally, the UAE has pioneered a new energy strategy incorporating nuclear and solar power in its energy mix, marking a significant departure from traditional energy sources [176].

Building on this foundation, the UAE became the first country in the Middle East and North Africa (MENA) to commit to a net-zero target by 2050 [50]. Although not mandated by the UNFCCC due to its status as a non-Annex 1 country, the UAE voluntarily chose to monitor and reduce its GHG emissions.

From an economic standpoint, the UAE is an oil net-exporter, yet it has long recognised

the importance of diversifying its revenue streams [180]. Since 2008, the country has pursued a vision of transitioning to a non-oil-based economy, resulting in a notable 17% increase in non-oil revenue in 2022 alone [181, 182]. With a firm commitment to carbon neutrality, the UAE has set ambitious targets for clean ammonia, hydrogen and SAF production. These targets include producing 3 mt/yr of blue or green ammonia by 2030, establishing a blue or green hydrogen production capacity of 15 mt/yr by 2050 and reaching 5 mt/yr of SAF production by 2050 [50, 66, 67].

While transitioning towards alternative fuels, the UAE also plans to increase its oil production to 250 mt/yr by 2030 [183]. Initiatives such as the development of the Hail and Ghasha fields for natural gas processing and LNG export aim to elevate production levels to 27 mt/yr by 2030 from the current 6 mt/yr [184]. Given these ambitious targets, it becomes imperative to consider how the UAE can navigate this transition while ensuring economic stability, particularly considering its role as a fuel supplier to other nations such as Japan and India, both of which have their own net-zero targets [31, 185, 186, 187].

Building upon the insights from Chapter 3, which explored the impact of fuel prices and the effect of a CDR target on technology deployment rates, similar findings were observed in studies by Ganzer et al. when the industrial sector was modeled alongside the power sector [79, 25]. As current literature lacks studies on a net-zero UAE, it is imperative to comprehensively model the interplay between the power, industrial and transport sectors to gain a wholistic understanding of the UAE's transition pathway to net-zero.

4.3 Method

In this chapter, the ESO framework is utilised to derive the results based on the UAE's published emissions reduction plan [188]. The plan outlines a trajectory aiming to decrease current emissions level from 200 mt-CO₂ to 185 mt-CO₂ by the year 2030 and ultimately reaching net-zero emissions by 2050. This trajectory of emissions served as the fundamental input within the ESO framework and is as visualised in Figure 4.2.

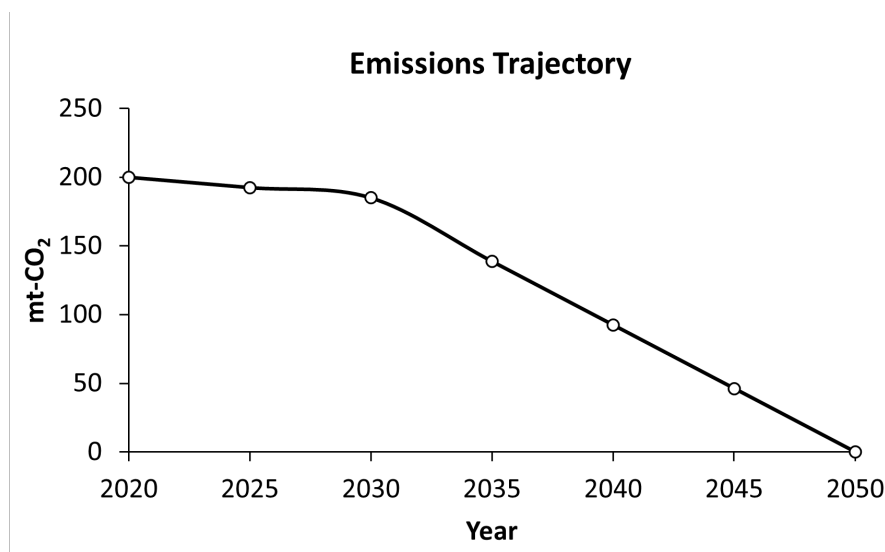


Figure 4.2: Emissions target used in ESO-UAE model.

In terms of maximum allowable capacity for each technology, detailed descriptions can be found in Appendix A (Table A.2). It is important to note that this study exclusively considers commercially available technologies.

As for industrial targets, the analysis assumes an increase in oil production capacity to 250 mt/yr by 2030 from the current level of 160 mt/yr and this capacity is assumed to be maintained until 2050. Similarly, for LNG, the production capacity is projected to rise from 6 mt/yr to 27 mt/yr by 2030 and is assumed to remain constant until 2050. These projections are based on ongoing projects mentioned earlier.

4.3.1 Scenario Definition

In this analysis, four core scenarios are examined, each contingent on resource availability, aiming to simulate transition pathways based on fuel or resource accessibility. This approach extends beyond existing literature precedents and centers on the UAE as the modelled region.

In all scenarios, nuclear capacity is set at 5.4 GW, reflecting the current capacity. However, for representation purposes, the model is initialised at 2.7 GW to match the available capacity in 2022, the starting year of the planning period in the model. The scenarios implemented for this part of the study are the following:

1. **Nuclear + Biomass:** This scenario permits nuclear expansion while utilising imported biomass, assuming the availability of abundant biomass resources.
2. **Biomass Only:** In this scenario, biomass utilisation is restricted to imported sources, assuming they are readily available. The nuclear capacity is capped at the current capacity of 5.4 GW.
3. **Nuclear + Domestic Biomass:** Nuclear expansion is permitted in this scenario, while biomass utilisation is restricted to domestic sources (refer to Table A.2 for more details).
4. **Domestic Biomass:** Here, biomass utilisation is restricted to domestic sources, meaning that only domestically sourced biomass is used. Additionally, the nuclear capacity remains capped at the current level of 5.4 GW.

Furthermore, to project future trajectories, the analysis considers the potential impact of future fuels on the UAE's energy transition. This additional scenario explores the integration of technologies fuelled by these future resources. The costs associated with

these technologies are derived from commercially available data, which is detailed in Appendices A, B and C. Building on the findings presented, this chapter segment (Section 4.9) focuses on a scenario in which the UAE achieves autonomy in fuel resources for its energy transition (Domestic Biomass scenario). Fuels introduced include ammonia, hydrogen and SAF, with production targets outlined in Table 4.1, sourced from the referenced publications.

Table 4.1: Production Targets of Future Fuels [189, 66, 67].

Fuel	2030		2050	
	mt/yr	TJ/yr ¹	mt/yr	TJ/yr ¹
Ammonia	3	67.5	3	67.5
Hydrogen	1.4	198.4	15	2125.5
SAF	0.2	9.24	5.1	235.6

¹Terajoule of energy based on high heating values [?]

4.4 Net-Zero in the Power Sector

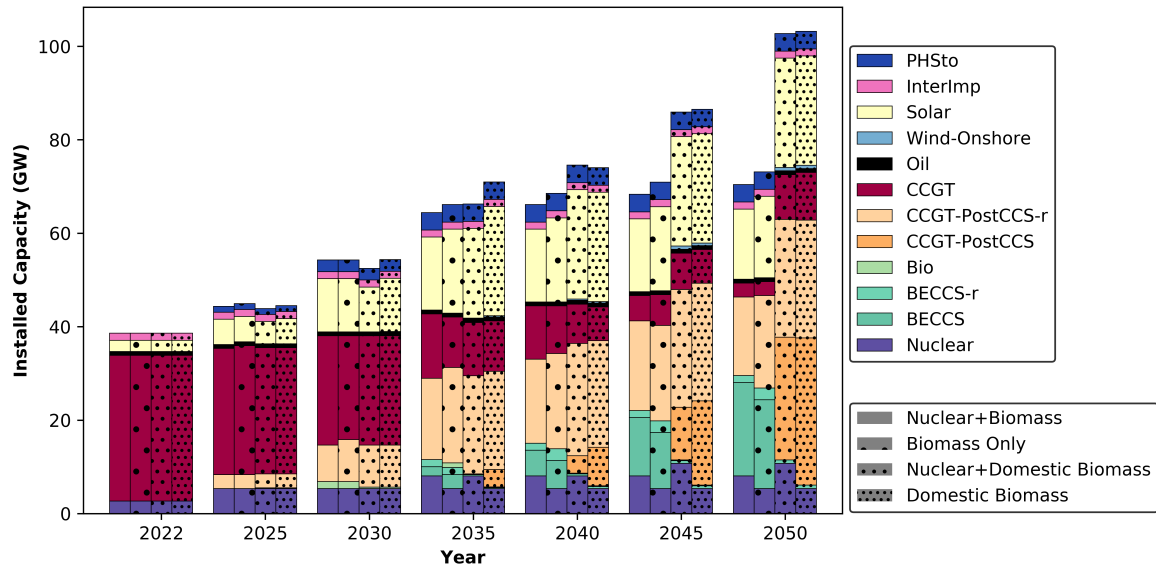


Figure 4.3: Installed capacity design for different resource scenarios in the UAE.

In analysing the evolution of the power sector in the UAE, this study considered the availability of resources as a key theme. As shown on the bottom right side of Figure 4.3, the shading used on the blocks represents the different scenarios introduced in the model, as described in the Method section. The installed capacity in the power sector is plotted based on these scenarios for each planning period.

The integration of nuclear power into the UAE's energy mix significantly influences technology deployment. According to the model output, nuclear capacity can reach a maximum of 8 GW in scenarios allowing imported biomass and 11 GW in scenarios utilising domestic biomass. The presence of nuclear power reduces the system demand for CCGT-CCS by 3 GW in the imported biomass scenario and by 5 GW in the domestic biomass scenario. Additionally, it increases solar capacity by 2.4 GW in the imported biomass scenario compared to the scenario with domestic biomass. Overall, nuclear power contributes as a firm low-carbon capacity to the grid, adding value to the system by lowering

the carbon emissions.

When comparing scenarios using imported versus domestic biomass, significant variations in total installed capacity are observed. In a domestic biomass scenario, an additional 25 GW of installed capacity is required, primarily to support the DAC capacity necessary for emissions removal. In the absence of BECCS, the grid relies heavily on natural gas technologies by 2050. Furthermore, an average of an additional 7 GW of solar capacity is needed when domestic biomass is used. Remarkably, onshore wind emerges as a viable option, with a capacity of 700 MW projected in 2050 if imported biomass is not utilised. Of the total installed capacity, the proportion of clean energy averages 67% with imported biomass and 36% with domestic biomass.

It is worth noting that CCS is introduced into the power sector in all scenarios as early as 2025. Moreover, the allowance of imported biomass results in the deployment of a 1.5 GW bio-power plant by 2030, retrofitted with CCS by 2035 and further expanded thereafter. In contrast, when domestic biomass is utilised, limitations in feedstock availability and plant size lead to the deployment of 150 MW of bio-power capacity by 2025, retrofitted with CCS by 2050 to reach a total capacity of 750 MW.

In terms of solar power, the installed capacity is projected to increase by 4 to 5 times in 2030 compared to 2022 levels. This is exceeding the government's target of tripling the capacity by 2030 [64]. By 2050, the solar capacity is expected to increase by 10 times compared to 2022 levels in scenarios utilising domestic biomass. The share of intermittent renewable is projected to stand at 10-13% in 2050, depending on the scenario.

Overall, the presence of nuclear power in the system favors the deployment of solar capacity, as both technologies have low carbon emissions. However, the feasibility of expanding nuclear capacity in the UAE raises questions due to bureaucratic hurdles and the substantial increase required (a two-fold increase compared to current levels in scenarios with domestic biomass). Additionally, while imported biomass facilitates the deployment of BECCS, it raises concerns about energy security, as the availability of

imported resources may be unpredictable, as demonstrated in Chapter 3. If the UAE is to take the imported biomass path and biomass becomes limited during the transition process, the quickest solution would be to use unabated or abated CCGT plants to deliver power. This approach could impact the country's trajectory towards carbon neutrality, as no other NETs would be available. Hence, to ensure a smooth transition to carbon neutrality, it is recommended to prioritise the domestic biomass path in the power sector. The associated costs and the role of DAC will be further discussed in subsequent sections of this chapter.

4.5 Net-Zero in the Industrial Sector

In this section, the transition of the industrial sector in the UAE is examined. The analysis focuses on the same scenarios presented earlier. The four distinct scenarios are only plotted when a variation is caused due to resource availability in the model. However, in cases where there are no variations in technology deployment, only a single bar is plotted to visualise the transition.

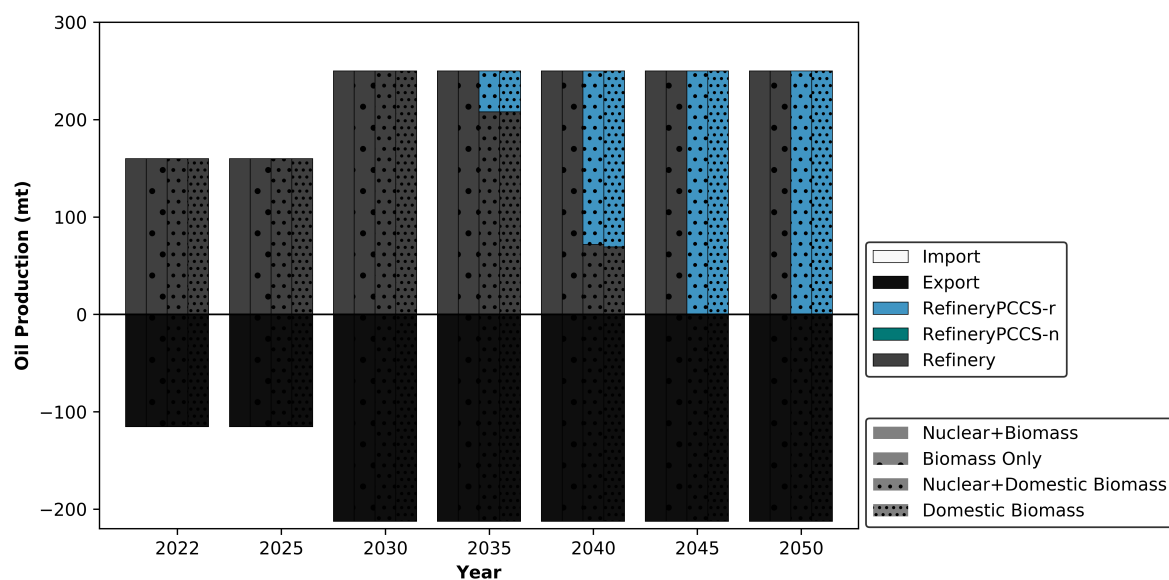


Figure 4.4: The transition of oil refineries in the UAE.

The output of refineries in the UAE plays a pivotal role in the nation's economy. Ensuring the stability of resources derived from these refineries is not only crucial for the UAE's economic prosperity, but also for the countries reliant on the end products. This importance is highlighted by the black bars in Figure 4.4, which represent the refinery output that is predominantly exported.

Across all examined scenarios in Figure 4.4, the implementation of CCS for oil refining in the UAE is not deemed essential until 2035, particularly in scenarios utilising domestic biomass. In these instances, CCS becomes necessary only through retrofitting the capac-

ity. In other words, the capacity developed to accommodate the projected increase in production by 2030 does not necessitate associated CCS facilities until 2035 under domestic biomass scenarios. Conversely, in scenarios utilising imported biomass, CCS is not required throughout the modelled periods, as BECCS removes the associated emissions from the refining processes.

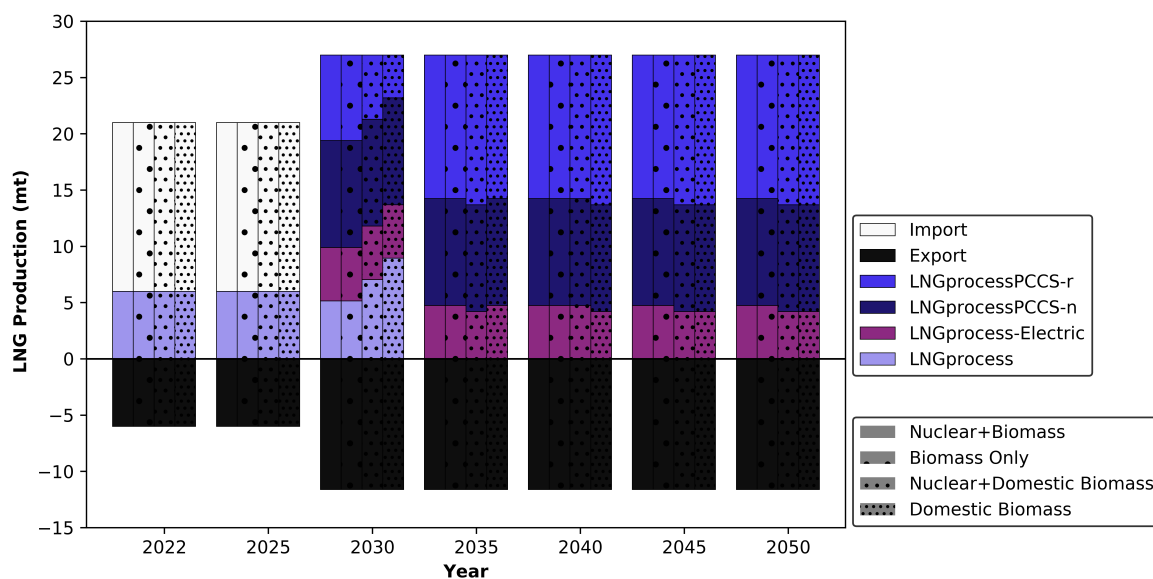


Figure 4.5: The transition of LNG production in the UAE.

For LNG, the transition differs from that of oil refineries. As the capacity increases for LNG production in 2030, new technologies emerge. The newly built capacity to produce 27 mt/yr consists of a blend of technologies. Interestingly, in all scenarios, E-LNG is deployed and it relies on the grid for the refrigeration part of LNG production. The remaining portion of the mix varies depending on the scenario. In terms of existing capacity, all of it is retrofitted with CCS in 2050. The additional share of the 27 mt production target is met by a mix of newly built conventional LNG plants and LNG-CCS plants. Regardless of the scenario, as illustrated in Figure 4.5, the capacity distribution remains the same in 2050, which consists of a mix of E-LNG and LNG-CCS plants.

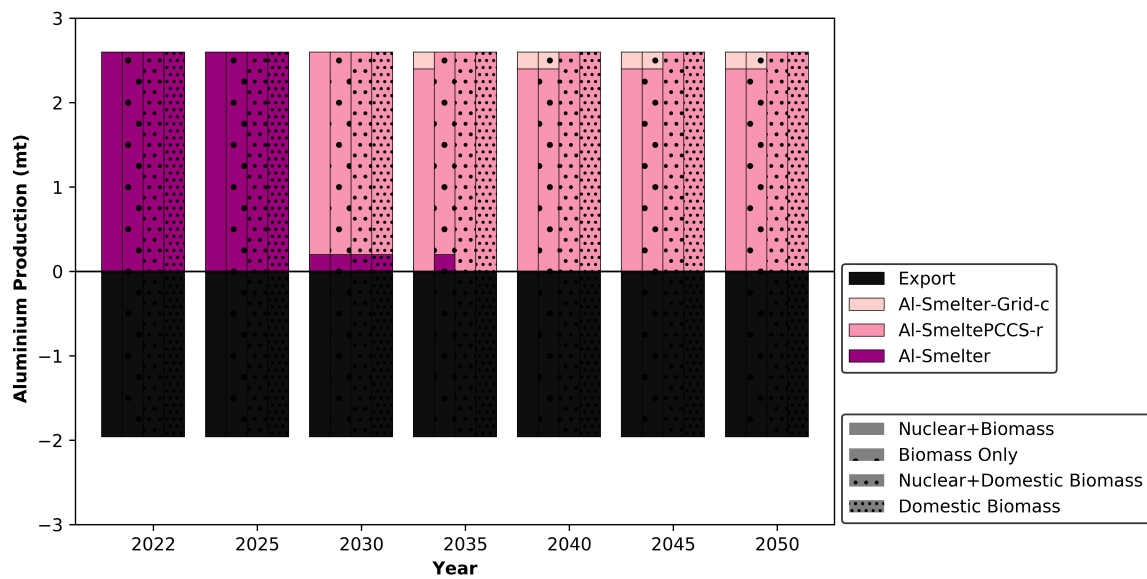


Figure 4.6: The transition of aluminium production in the UAE.

For aluminium production, known for its high carbon intensity [190], understanding the operational dynamics of aluminium smelters in the UAE is crucial before describing the transition process. Typically, an aluminium smelter consists of a CCGT power plant linked to electrolyzers responsible for aluminium production. An important aspect to clarify is the current connection between the existing electrolyzers and the CCGT plants in the model. During the transition process, the model provides the option to either disconnect the electrolyzers from the CCGT plant and connect them directly to the grid or retrofit the existing CCGT plant with CCS. ESO-UAE includes the three existing smelters in the UAE to produce aluminium. Under all circumstances, the assumed operational factor is 80% as stated earlier in Section 2.4.2. As shown in Figure 4.6, two of the plants are retrofitted with CCS by 2030. Beyond that, the fate of the remaining smelter depends on the scenario. In scenarios utilising imported biomass, this plant is connected to the grid, given that nearly 67% of grid generation is derived from clean energy sources. Conversely, in scenarios with domestic biomass, the remaining plant is retrofitted with CCS.

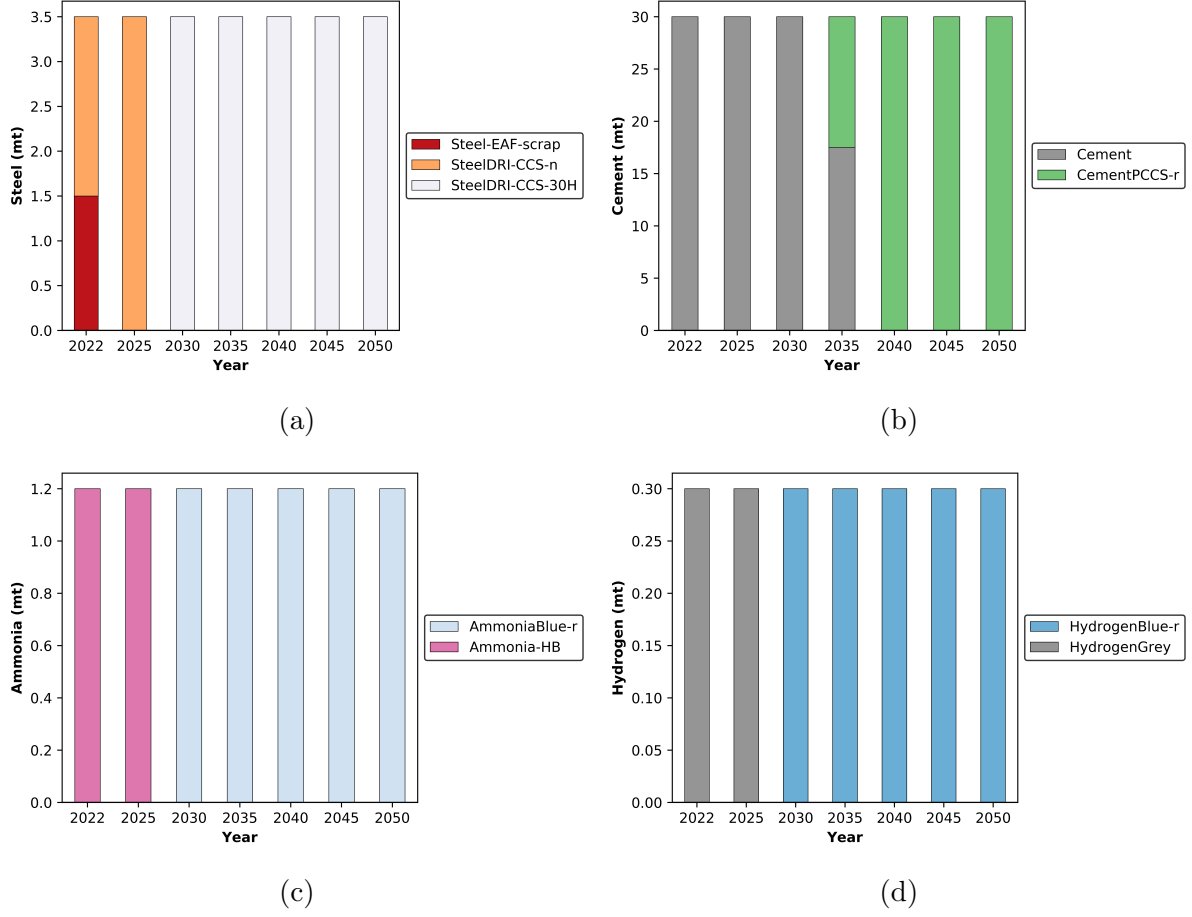


Figure 4.7: The transition of steel, cement, ammonia and hydrogen existing capacities in the UAE

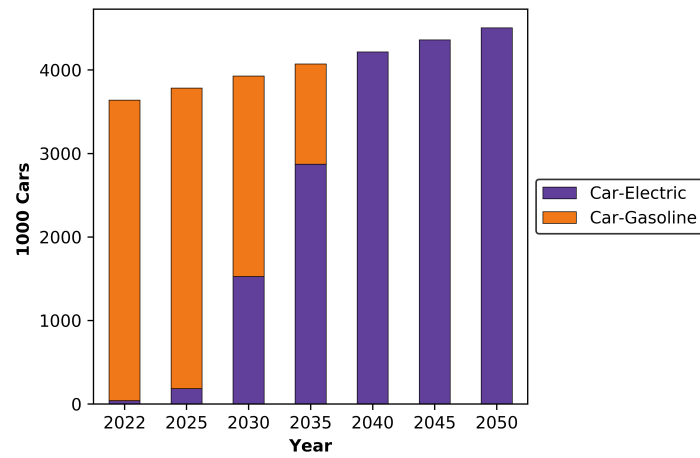
In examining the other commodities considered in this study, variations in deployment were not observed with respect to resource. As shown in Figure 4.7a, the existing steel production capacity is the world's first CCS facility connected to a steel Direct Reduced Iron (DRI) plant, with the captured CO_2 utilised for enhanced oil recovery. This collaboration between ADNOC and Emirates Steel involves capturing the CO_2 in Musaffah area and transferring it via a pipeline to Al Ruwais city [191, 192]. In terms of transition, Figure 4.7a illustrates the initial capacity utilising iron-ore and steel scrap as feedstocks for SteelDRI-CCS and Steel-Electric Arc Furnace (EAF), respectively. Notably, the model suggests replacing Steel-EAF capacity with new SteelDRI-CCS capacity due to the high price of scrap. The price of iron-ore stands at 161 £/ton [193], while scrap costs 322 £/ton [194, 195]. However, if scrap prices decrease to 208 £/ton, Steel-EAF would replace SteelDRI-CCS capacity by 2050. Additionally, the model proposes fuel

switching to reduce emissions further and this is by replacing 100% natural gas feedstock with a blend containing 30% hydrogen. Current DRI technology can accommodate this hydrogen blend without process modifications [90]. This recommendation holds significance not only for the UAE, but also for global steel producers utilising the SteelDRI process, urging them to consider similar blending levels in their processes.

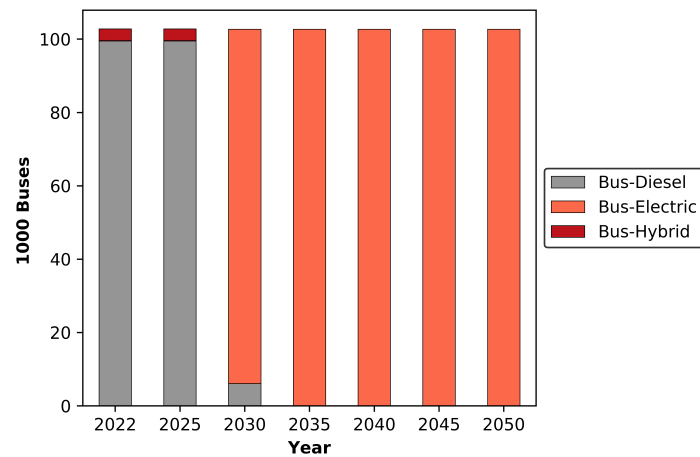
Unlike other technologies, the transition towards retrofitting with CCS in the cement industry begins to emerge around 2035 as shown in Figure 4.7b. Notably, over half of the cement capacity is concentrated in the Emirate of Ras Al Khaimah, located at the far north of the UAE with a coastline overlooking the Arabian Gulf [196]. Retrofitting with CCS in this area would require further analysis to identify the suitable storage areas. However, the assumption of constructing a pipeline to Al Ruwais region is feasible, given the existing infrastructure for natural gas transport between the Emirate of Fujairah and Al Taweela area in Abu Dhabi [197]. Nonetheless, this aspect requires additional research, which falls beyond the scope of this study. Regarding ammonia and hydrogen production in Figure 4.7c and 4.7d, the existing single plants for each are expected to undergo retrofitting by 2030. This aligns with the UAE's current trajectory, exemplified by the initiation of a pilot plant and the shipment of the first batch of blue ammonia to Germany in 2022 [198].

Based on the findings of this study, insights into the allocation of CCS facilities emerge. Under a domestic biomass scenario, complete retrofitting of oil refining capacity is projected to be necessary by 2045. For LNG, CCS implementation occurs more rapidly due to the plant's higher carbon intensity in comparison to oil refining. It is noteworthy that a significant portion of the refining capacity and natural gas processing facilities are situated in Al Ruwais industrial city in the UAE, which is in close proximity to depleted fossil wells that are suitable for CO₂ storage. Regarding other commodities, all except cement will require retrofitting by 2030 due to their higher carbon intensity in producing 1 mt compared to other commodities (for specific emission factors, see Appendix B).

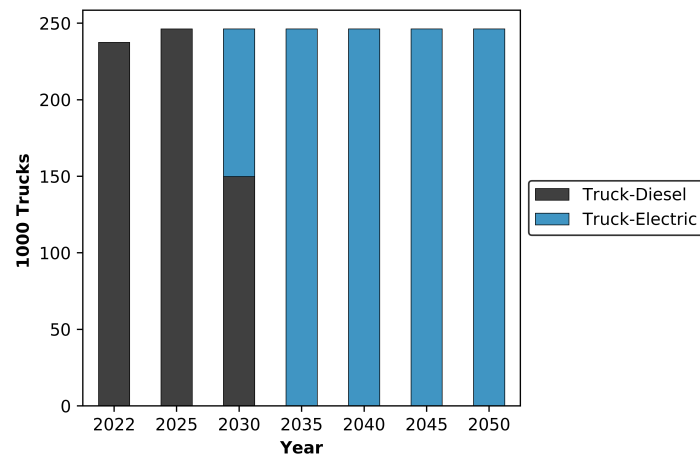
4.6 Net-Zero in the Transport Sector



(a) The transition of individual car vehicles in the UAE.



(b) The transition of mini buses in the UAE.



(c) The transition of heavy-duty vehicles in the UAE.

Figure 4.8: Transition of road vehicles in the UAE

The output of the transport sector remained consistent across the four scenarios analysed. Specifically, this study focused on road vehicles, sea and air transport. Examining road vehicles in particular, Figure 4.8 illustrates a notable trend that is the electrification of all road vehicles by 2050. This shift is primarily attributed to the assumed price of oil, with electric vehicles emerging as a more cost-effective option compared to ICE vehicles. Relative to the UAE's latest targets aiming for electric vehicle adoption of 13.5% in 2030, this analysis suggests a more accelerated approach may be needed to realise the economic benefits of decarbonising the transport sector. Notably, the published targets also indicate ambitions of reaching 53% electric vehicle penetration for cars and 60% for buses by 2050 [188].

In a simulation examining these targets, the model revealed that failing to achieve 100% electrification by 2050 would incur an additional cumulative cost of £25 billion in scenarios involving domestic biomass. This cost covers the deployment of the additional DAC along with its associated power requirements and fuel costs for operating ICE vehicles. Considering potential oil price decreases, it's important to note that in most countries, natural gas prices are typically linked to market oil prices in long-term contracts [199]. Consequently, during oil price fluctuations, transitioning to electric vehicles becomes economically favorable as both fuel prices are expected to move together, given that the grid in the UAE is predominantly powered by natural gas.

This highlights the importance for policymakers to prioritise robust electrification efforts within the transport sector. Regarding vehicle availability to support such a transition, the UAE is already making significant strides in this direction with plans to establish its first electric vehicle manufacturing plant [200]. Furthermore, the UAE hosts one of the largest used car markets globally, valued at \$20 billion in 2021 [201]. Thus, constraints on vehicle availability are unlikely. Moreover, in terms of replacing the existing capacity, as stated in Section 2.4.2, vehicle licenses are typically not renewed after 15 years of operation in the UAE [127].

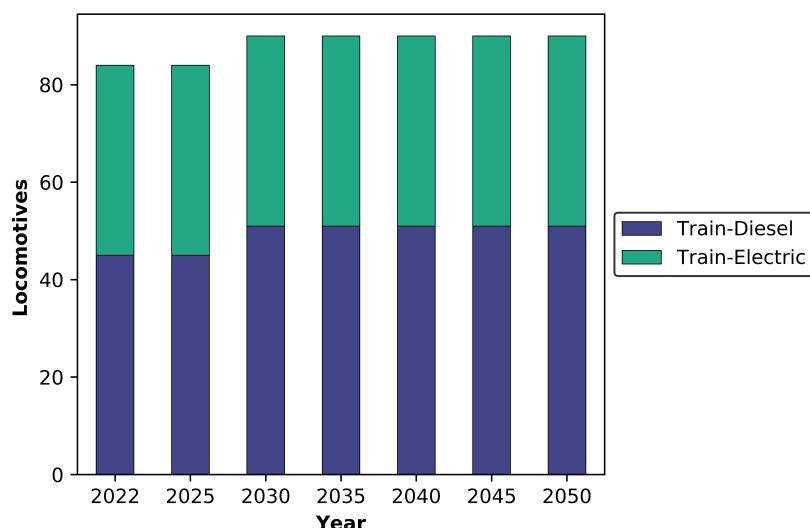


Figure 4.9: The transition of trains in the UAE.

For trains, the current electric capacity represents the existing trains in the Emirate of Dubai, as shown in Figure 4.9. This capacity in the system is dedicated for passenger transport within the Emirate (city) itself and remains as is until 2050 without favoring a switch to diesel trains. When it comes to transportation between the different Emirates of the UAE, the system tends to opt for diesel trains for both passenger and freight transport. This preference arises from the substantial electricity demand that would be placed on the grid by electrified trains, especially considering the long distances traveled. Consequently, given the relatively low cost of natural gas used to power DAC, the model indicates that operating these trains using diesel fuel, is the more economical option. Electrifying train transport would necessitate an additional 2 GW of capacity in the power sector for operating the trains and powering the additional DAC capacity. This would result in an approximate £10 billion increase in the total system cost.

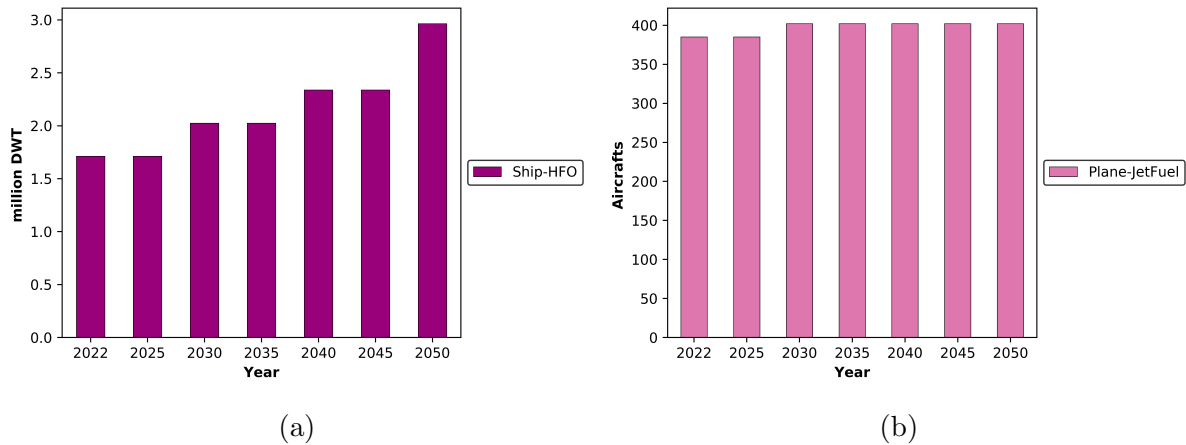


Figure 4.10: The transition of sea and air transport in the UAE.

In the UAE's latest Nationally Determined Contributions (NDC), sea and air transport were not accounted for [188]. However, in this study, these critical components of the transport sector were incorporated to comprehensively assess the total emissions as shown in Figure 4.10. The inclusion of sea and air transport in the model allowed for a more holistic analysis of emissions across sectors. It is noteworthy that the fuel used in these modes of transportation in 2050 consists of low-carbon fuels. In this part of the analysis, the age of each plane and ship was taken into account, along with the associated costs of replacing the old capacity. Transitioning to new technologies or fuels for these modes were further examined in Section 4.9, where the necessary alternative fuels for the power and transport sectors were provided by the industry.

4.7 Sectoral Emissions and Total System Cost

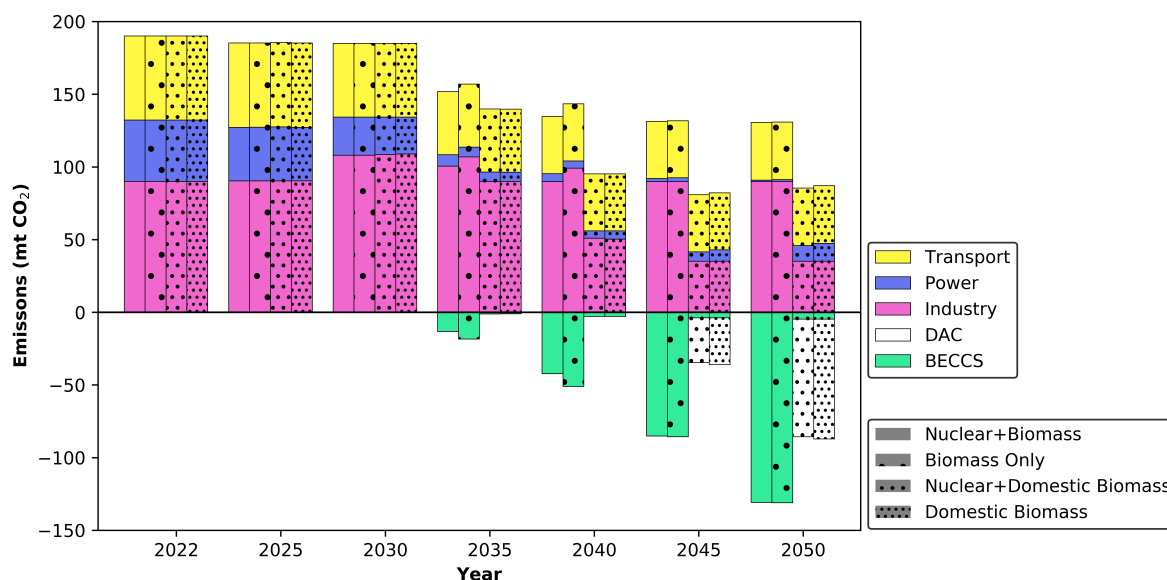


Figure 4.11: The transition of sectoral emissions in the UAE.

The preceding sections have comprehensively addressed the transition within each modelled sector. Analysing the system emissions reveals that the industrial sector emerges as the most carbon-intensive sector among the modelled sectors, as shown in Figure 4.11. Accordingly, the transition within the model initiates with the decarbonisation of the power sector, as previously demonstrated, wherein CCGTs are partially retrofitted with CCS as early as 2025. Transition efforts within the industrial sector commence in 2030, coinciding with the increased production of oil and LNG. In this context, CCS plays a dominant role, particularly in the power sector, thereby facilitating the electrification of LNG refrigeration and road vehicles.

In scenarios where BECCS is deployed to remove emissions, higher emissions from the industrial sector are observed primarily due to not abating the oil refineries. This is because BECCS can remove emissions while simultaneously providing power, making it more economically advantageous to allocate CCS capacity to. In scenarios utilising

domestic biomass, DAC predominantly offsets carbon emissions due to limitations in domestic biomass availability. The residual emissions observed in domestic biomass scenarios in Figure 4.11 represent emissions that cannot be captured. Depending on the commodity, the sources of these emissions are detailed in Tables B.3, B.6, B.9, B.12, B.15, B.18 and B.21. Based on this, the DAC requirement in the UAE is projected to be around 84 mt-CO₂ by 2050. The carbon intensity of the power sector under domestic biomass scenarios is estimated to be at 0.03 t-CO₂/MWh in 2050, with the 2030 level reaching 0.14 t-CO₂/MWh, which is lower than the published NDC value of 0.27 t-CO₂/MWh.

It is worth noting that depending on future collaborations, there may be a possibility of a higher share of BECCS in the system if some imported biomass is integrated. If this becomes available, pursuing this path holds potential, as it is more cost-effective for removing carbon while contributing to the grid demand and its requirements.

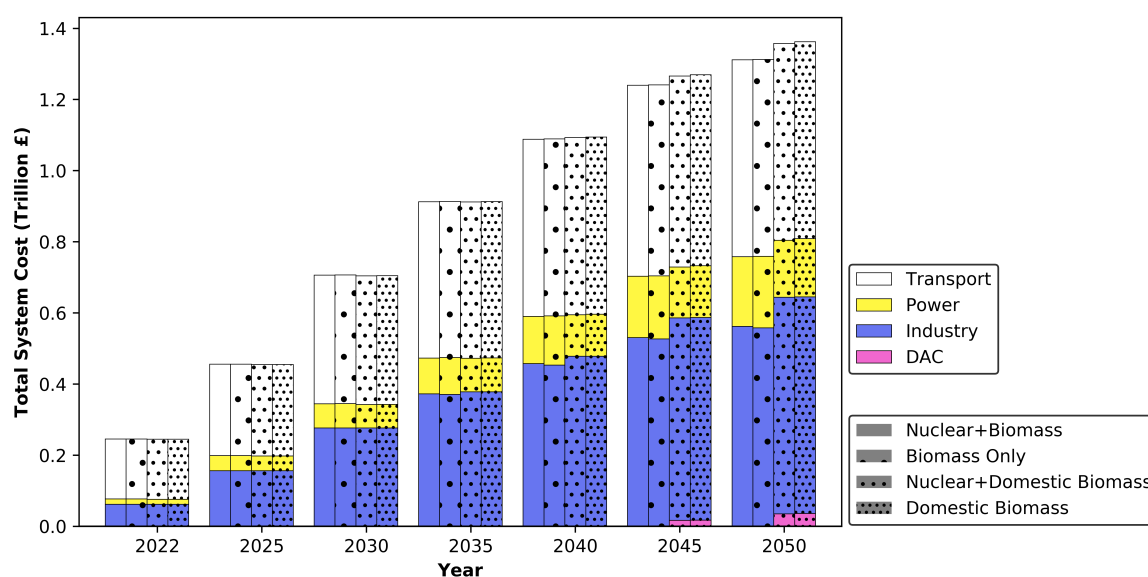


Figure 4.12: Sectoral cumulative total system cost under the four scenarios.

Upon examining the cost implications of the four scenarios, a slight variance in the total system cost is observed. This is with the domestic biomass scenarios proving to be £48 billion more expensive. In a hypothetical scenario where BECCS is employed to remove

emissions, the required biomass in 2050 would amount to 88 mt. The substantial biomass requirement raises concerns regarding energy security, particularly as the UAE lacks local biomass sources. Moreover, relying on international sources via sea routes poses risks of disruption, highlighting the importance of prioritising domestic biomass for energy security. Implementing DAC alongside domestic biomass ensures the UAE's trajectory towards achieving net-zero emissions by 2050. The additional £48 billion investment is therefore deemed necessary to secure net-zero by 2050 in the UAE.

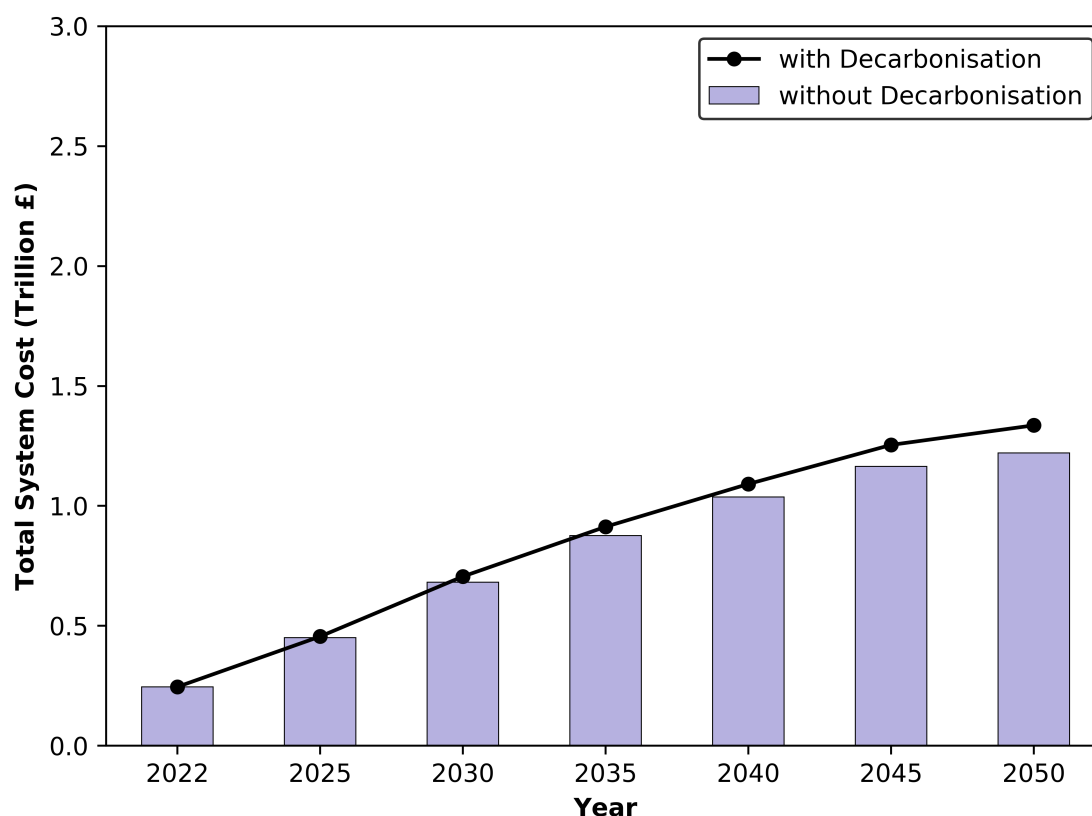


Figure 4.13: Cumulative total system cost comparison between business as usual and decarbonisation scenarios.

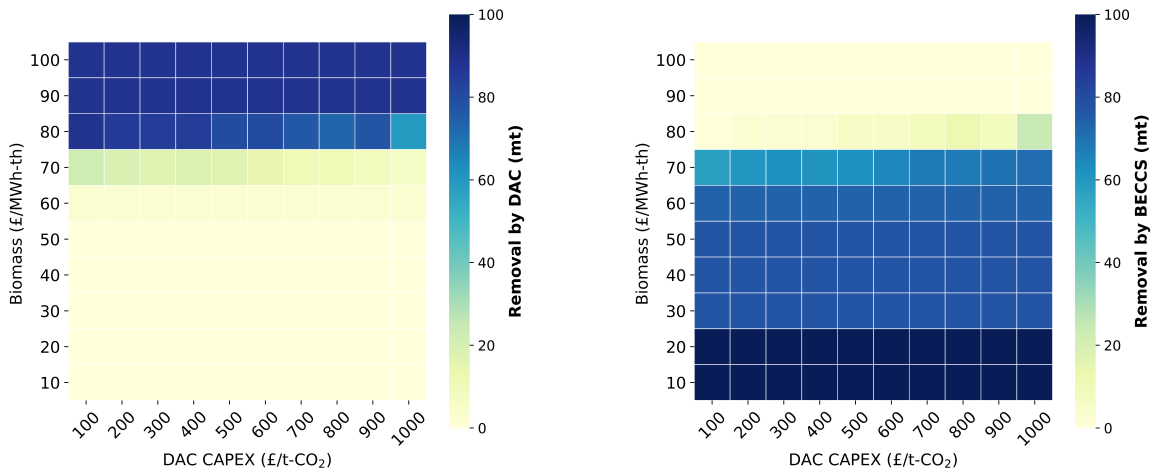
By adhering to future oil and LNG targets, Figure 4.13 illustrates two contrasting scenarios: a BAU approach, which represents the UAE maintaining its current practices without implementing carbon mitigation measures and capping emissions at today's level, contrasting with a decarbonisation scenario. The decarbonisation cost shown in the figure represents the average cost across the four scenarios. It is evident from the figure that the difference in cost between these two scenarios amounts to £115 billion, which is 9.4%

higher than BAU. Therefore, in order to achieve decarbonisation, the UAE would need to allocate approximately £4 billion annually for investments in decarbonisation efforts, that is equivalent to 1.3% of its annual gross value added (GVA) [202].

4.8 Sensitivity

The previous results provide a comprehensive overview of the transition process in the UAE to net-zero by 2050. In the following section, an examination of key technologies pivotal to decarbonising the UAE economy are further analysed. The technologies selected for this section are DAC, BECCS and Solar.

4.8.1 Carbon Removal: Biomass versus Direct Air Capture



(a) The impact of biomass price and DAC CAPEX on carbon removal via DAC.

(b) The impact of biomass price and DAC CAPEX on carbon removal via BECCS.

Figure 4.14: Comparison of carbon removal strategies for 2050.

As previously discussed, the UAE's economy relies heavily on industrial activities, which must be maintained during the net-zero transition to ensure economic stability. In this context, this section evaluates the performance of NETs in the model, focusing on DAC CAPEX and biomass pricing. DAC CAPEX is a key consideration due to the novelty of the technology. In this study, the DAC CAPEX corresponds to the n-th produced technology, with a levelised cost averaging around \$476 per ton of captured CO₂. Table B.23 contains the parameters used to define DAC in the ESO-UAE model. The assessment of

DAC CAPEX aims to identify when DAC becomes competitive with BECCS, which has been consistently favored in imported biomass scenarios. This analysis was conducted under an only biomass scenario.

Analysis shown in Figure 4.14 suggests that the deployment of DAC is largely unaffected by its CAPEX. Instead, it is more influenced by the biomass price. In a scenario where market forces drive biomass prices four times higher than current levels, DAC deployment increases significantly, regardless of its CAPEX. This highlights the importance of investing in research aimed at cultivating environmentally friendly biomass within the UAE at prices below £70/MWh_{th}. Such investments would not only enhance the country's energy security, but also facilitate the widespread adoption of BECCS technology in the UAE. This would enable larger-scale power plants and more effective carbon removal.

4.8.2 Solar Deployment

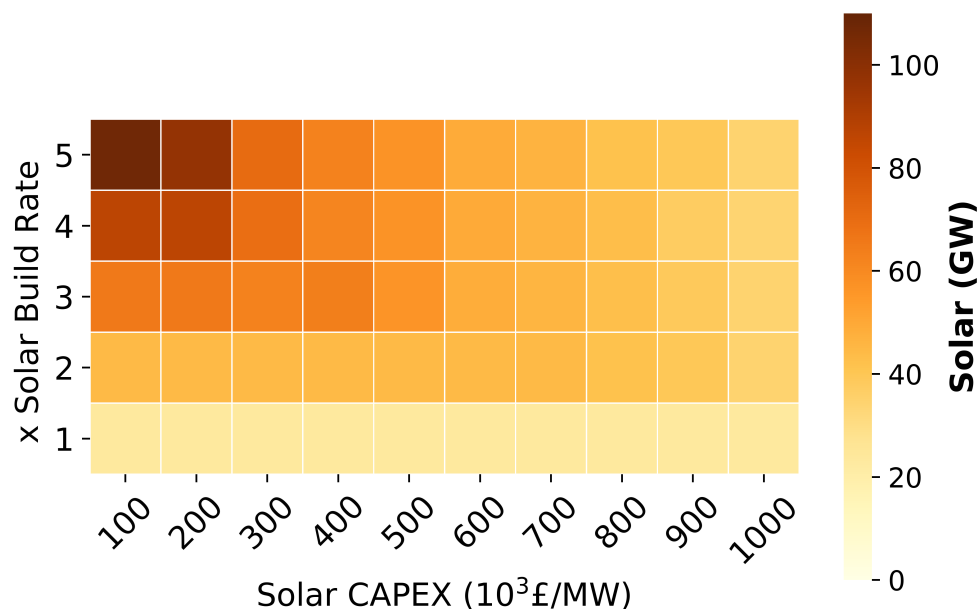


Figure 4.15: The impact of solar build rate and CAPEX on solar installed capacity in 2050.

In the context of domestic biomass scenarios, the deployment of solar energy in the UAE is constrained by the build rate limitations integrated in the model. This build rate is benchmarked against the world's largest solar farm (Noor) that is situated in Abu Dhabi [203].

To evaluate the required solar capacity in a decarbonised UAE, a sensitivity analysis was conducted by varying the build rate of solar farms against their CAPEX as illustrated in Figure 4.15. In all the solar scenarios examined, the capacity of natural gas technologies remained consistent, as per the grid requirement for maintaining reserve (20% back-up) and inertial rotating capacity. As a result, the substitution of natural gas with solar energy was only in power generation. The solar CAPEX utilised in the model approximates around £616 per kW and this is based on current investments in solar farms within the UAE. Analysis of varying CAPEX levels revealed a positive correlation between decreasing prices and increasing build rates for solar infrastructure. Nevertheless, irrespective of CAPEX and at 2x build rate, the deployed solar remained at a 40 GW capacity. This highlights the crucial requirement for the UAE to double its historical build rate to achieve a capacity of 40 GW by 2050 in comparison to the 23.4 GW under the domestic biomass scenario. This expansion would necessitate an area of 156 km² from the current 16 km² [204] that is equivalent to 139 times the land size of Dubai Mall [205].

Notably, despite the significant solar expansion, the reduction in total system costs was marginal with savings of less than 1% at a CAPEX of £100k per kW. Therefore, the justification for such extensive solar deployment hinges on potential reductions in reserve capacity requirements or the availability of commercial-scale storage solutions.

4.9 Future Industries

In addition to the current state-of-the-art, it is important to explore the implications of future deployment of alternative fuels across various sectors. The technologies examined herein are those either commercially available or nearing commercial viability. Consequently, the deployment of these technologies is constrained until the commencement year of fuel production. According to the trajectories outlined in the method section (Table 4.1), deployment is unconstrained from 2030 onwards. As previously explained, ensuring the security of a net-zero transition in the UAE entails predominantly relying on autonomous resources. Hence, for this part of the analysis, the domestic biomass scenario is presumed.

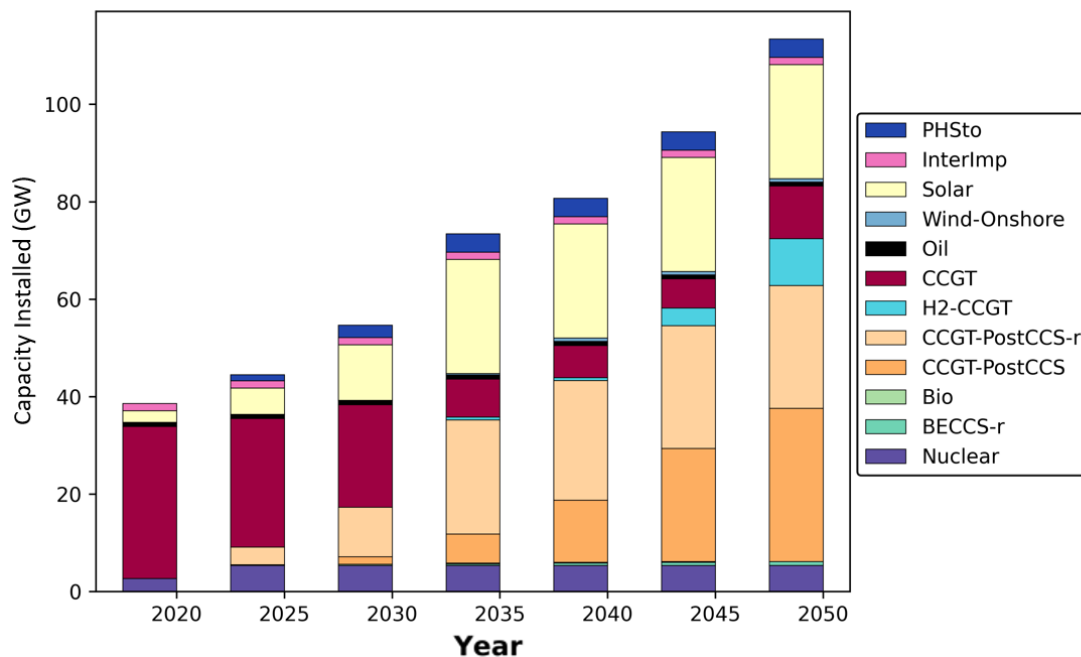
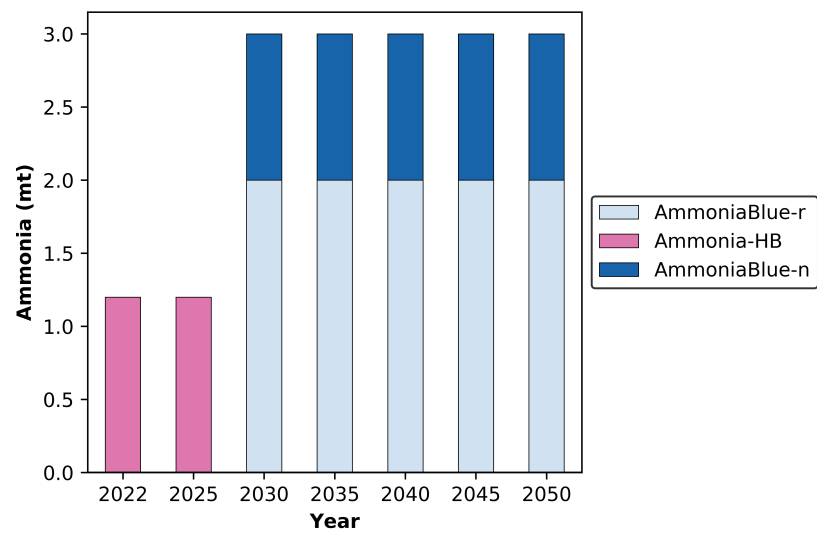


Figure 4.16: The transition of the power sector in the UAE, exploring new fuels.

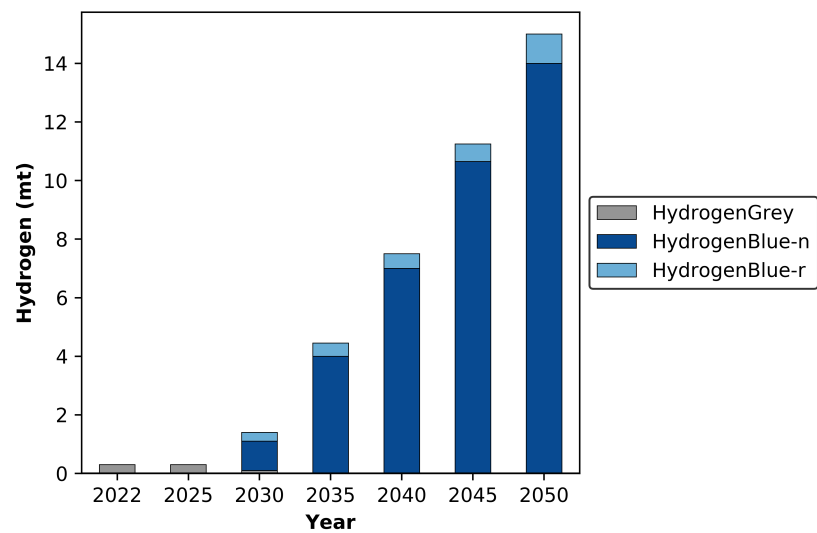
By introducing the demand for alternative fuels in the model, the installed capacity in the power sector increases by a 10% (10 GW) in comparison to the domestic biomass scenario outlined earlier. The primary contributor to this increase is the production of

SAF through the Power-to-Liquid (PtL) route, which relies on green hydrogen production using grid power.

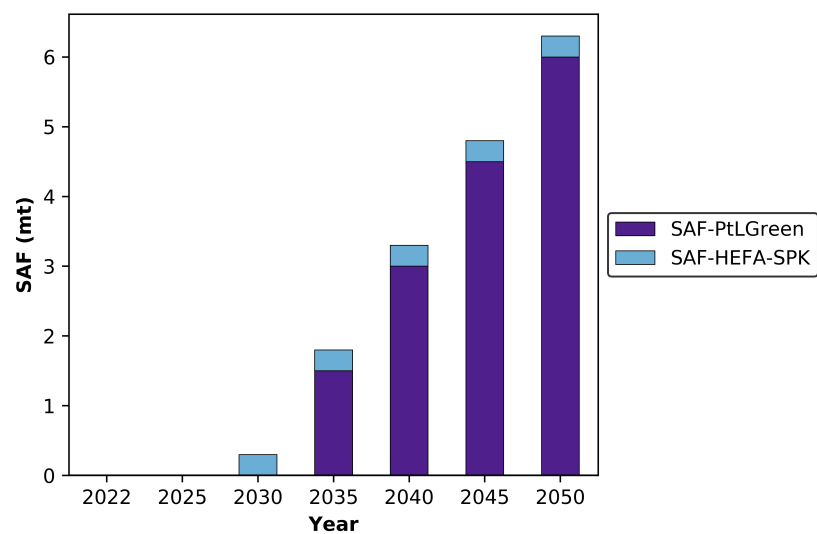
Incorporating hydrogen fuel production into the system allows its utilisation to power the additional 10 GW of H₂-CCGT, as illustrated in Figure 4.16. H₂-CCGT was predominantly utilised during peak-demand periods, especially when cooling demand peaked [110], where it replaced the CCGT-CCS-r generation. The additional H₂-CCGT capacity will require 1.2 mt of clean hydrogen, accounting for 8% of the UAE's projected production target in 2050. Nonetheless, an 18% increase in emissions from the power sector was observed due to the additional power required for SAF production.



(a) The transition of ammonia production in the UAE.



(b) The transition of hydrogen production in the UAE.

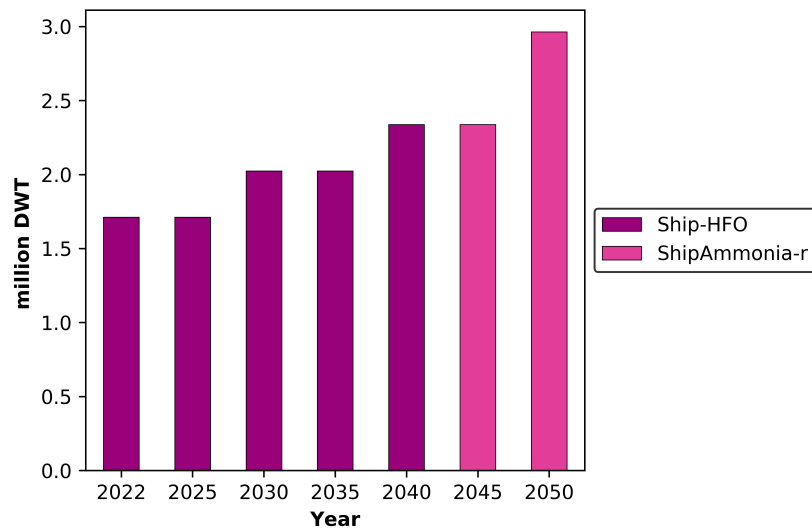


(c) The transition of SAF production in the UAE.

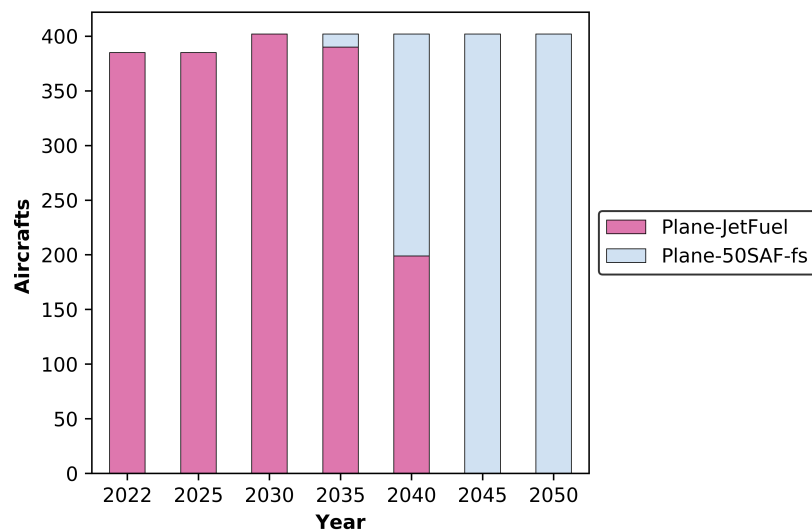
Figure 4.17: Future transitions of industrial production in the UAE.

As illustrated in Figure 4.17, the UAE achieves its targets for clean ammonia and hydrogen through CCS technologies. This approach is favored due to the cost-effectiveness of utilising inexpensive natural gas compared to grid-powered electrolyzers. In this scenario, the levelised cost of blue hydrogen is estimated at 1.2 £/kg-H₂. For SAF, given the limited availability of biomass within the country, the available technology options were Hydroprocessed Esters and Fatty Acids (HEFA) and PtL. The HEFA route is constrained by the availability of domestically used cooking oil, thus the remaining demand is fulfilled using PtL, as shown in Figure 4.17c.

As discussed earlier and to be elaborated on later, the production of ammonia and hydrogen exceeds the national demand. Surplus production is intended for export, particularly to regions such as Europe, where demand for clean hydrogen is anticipated to increase due to regulatory policies [206]. With respect to SAF, the produced quantity will be utilised by Emirati aviation companies, assuming that national airlines will take full responsibility for emissions produced from their fleets. Subsequent analysis will demonstrate the model's inclination toward fuel switching in aviation.



(a) The transition of sea transport in the UAE.



(b) The transition of air transport in the UAE.

Figure 4.18: Future Transitions of Transport in the UAE

For transportation, the transition of road vehicles was as previously described, whereas air and maritime transport favored new fuels. Unlike the power sector, hydrogen fuel was not preferred in road vehicles, mainly due to the high technology cost, which surpasses the price of ICE vehicles (cars, buses, trucks and trains). However, this perception of hydrogen in road transport may shift in the future if lower-cost technologies become available.

Incorporating new fuels into the transport sector, notably ammonia and SAF, played

a pivotal role in this modelling phase. The decision to include ammonia in shipping stemmed from the ongoing trials by Grieg Star, a leading player in the shipping industry [207]. Additionally, the continuous testing of SAF in the UAE, where commercial aircraft have effectively operated using a 50% SAF blend conforming to ASTM standards [208, 209, 210], strengthened the case for SAF integration in the model. The introduction of shipping retrofit with ammonia propulsion engines and fuel switching (incorporating a 50% SAF blend with low carbon jet fuel) demonstrated a preference for these innovative fuels and technologies across both air and sea transportation modes, as shown in Figure 4.18. Consequently, the model projects the feasibility of retrofitting shipping capacity with ammonia propulsion engines by 2045, while SAF is anticipated to enter the UAE airline industry as early as 2035.

For this transformation, the amount of SAF needed is projected to be 8 mt/yr for all national airline companies. This aligns with the 5 mt the UAE plans to produce, assuming that the additional 3 mt are obtained through collaborations similar to the existing one with Shell [211]. Hence, pursuing this route of fuel switching is assumed to be feasible. In terms of ammonia, the transition pertains to the nationally owned vessel fleet, with a projected need of 0.22 mt in 2050, representing 7% of the clean ammonia the UAE plans to produce.

It is noteworthy that the total system cost for this scenario amounts to £1.46 trillion. This represents a 7.4% increase compared to the domestic biomass scenario. The DAC requirement under the future industries scenario remains at a similar level to the domestic biomass scenario. This is attributed to the 52% reduction in transport sector emissions resulting from fuel switching and vessels retrofit.

4.9.1 Scope 3 Emissions

Table 4.2: System design parameters for achieving emissions targets

Emissions Target mt-CO ₂ in 2050	xBR	Installed Capacity GW	DAC Requirement mt-CO ₂	TSC ¹ T£
200 ²	1	64	-	1.22
zero ³	1	113	82	1.46
-231 ³	1	220	495	2.2
-692 ³	4	389	814	3.3

Up to this point, the focus was primarily on scope 1 and 2 emissions (direct and indirect emissions). Nevertheless, this section shifts its attention to scope 3 emissions, specifically, those arising from the use of exported fossil fuels. The aim here is to investigate the feasibility of the UAE taking responsibility for all the emissions linked to exported oil and LNG in 2050. This ultimately sets the emissions target in 2050 to below zero. To evaluate this feasibility, the total emissions resulting from the utilisation of fossil fuels exported by the UAE was calculated. This amounted to approximately 692 mt of CO₂ in 2050.

In Table 4.2, based on the current historical build rate of technologies (xBR=1), it is evident that the UAE can offset one-third of its scope 3 emissions. Any emissions target beyond that renders the model infeasible. To completely offset all scope 3 emissions, the UAE would need to increase its technology build rate by a factor of 4. This is as shown in Table 4.2 would result in an almost 2.5 fold increase in the total system cost. Additionally, it would necessitate close to four times the installed capacity compared to a net-zero domestic biomass scenario. In terms of sold oil, accounting for scope 3 emissions would raise the price by approximately £56 (\$72) per barrel of oil sold in 2050.

¹Cumulative Total System Cost in Trillion £

²Business as usual

³Including future industries under domestic biomass scenario

To effectively combat climate change, incremental measures are essential. It is impractical for the UAE to shoulder the entire burden alone; responsibility must be shared with importing countries to facilitate a smoother path to carbon neutrality. Through collaborative efforts, the UAE can partially offset these scope 3 emissions, with the importing country handling the remainder. This emphasises the necessity for international collaborations to ensure a seamless transition.

4.10 Chapter Contribution

The chapter explores the intricate process of transitioning the UAE to a carbon neutral economy by 2050. It examines various facets of this transformation, with a focus on pivotal sectors: power, industry and transport.

The analysis begins by exploring the path to net-zero emissions in the power sector. It highlights the critical role of CCS in natural gas-fired power plants and the transition towards intermittent renewable energy. In the industrial sector, the chapter investigates the challenges and opportunities entailed in mitigating carbon emissions across key industries, including oil refining, LNG, steel, cement, hydrogen and ammonia production. Notably, emphasis is placed on the adoption of CCS in this sector and the imperative of transitioning towards sustainable practices, exemplified by hydrogen blending in current steel production processes.

In examining the transport sector, the transition of road, air and maritime transportation was thoroughly investigated, with emphasis on the importance of further electrification. Additionally, the chapter explores the implications of deploying alternative fuels across various sectors, highlighting a notable shift towards SAF and ammonia in air and sea transport. The analysis highlights the significance of fuel switching and technological advancements in reducing emissions from aircraft and vessels to pave the way for a sustainable transport paradigm.

In terms of future research, investigating the impact of increasing CCS capture rates on model outcomes is crucial for the various technologies considered in this work. Higher capture rates could reduce reliance on NETs such as BECCS and DAC, though this comes with the trade-off of increased CO₂ capture costs. Conducting scenario analyses to quantify how different CCS rates affect the deployment of BECCS and DAC will provide valuable insights into optimising decarbonisation strategies in a cost-effective manner.

Chapter 5

The Social Impact of Net-Zero Transition

5.1 Lessons from the UK

Decarbonising the UK's economy has been a journey marked by ambition, yielding valuable lessons for economies worldwide. Through comprehensive studies utilising the JEDI tool combined with ESO, the UK's transition provides crucial insights into the social-economic impacts of decarbonisation. One of the fundamental lessons gleaned from the UK's experience is the significant social benefit derived from decarbonising the power and industrial sectors [212]. By transitioning these sectors towards carbon neutrality, not only does the UK reduce its emissions, but also maximises welfare and utilises its domestic assets [16].

Navigating the path to decarbonisation is not without its challenges. The UK's experience highlights the importance of avoiding the offshoring of emissions through deindustrialization and importing commodities, as this can lead to negative economic impacts. Instead, the focus should be on abating emissions domestically and exporting, thereby adding

positive value to the economy [212]. An illustrative example of this principle is the exploration of alternative technologies like auto-thermal reformer-CCS for the production of low-carbon hydrogen in different industrial clusters across the UK. By utilising hydrogen as a fuel within these clusters, social economic benefits were observed to emerge. These benefits were observed to vary regionally; therefore, there is an emphasis on having a tailored strategy that leads to local economic growth [213].

The emphasis on tailoring strategies highlights another critical lesson: the importance of region-specific approaches for decarbonisation. Hence, careful consideration of local conditions and needs is paramount in designing effective decarbonisation strategies. Ultimately, the UK's journey towards decarbonisation highlights the imperative for other nations to evaluate the social-economic impacts of their own decarbonisation efforts. It's crucial to assess whether the chosen path aligns with their economic prosperity or not. By learning from the UK's experience, economies like the UAE can chart a course towards carbon neutrality that balances with economic growth.

5.2 Method

To examine the social impact of decarbonising the energy sectors in the UAE, this study employed the Jobs and Economic Development Impacts (JEDI) model. Developed by the National Renewable Energy Laboratory (NREL), JEDI assesses the GVA and employment levels resulting from changes in the energy sectors by utilising disaggregated technology costs and macroeconomic data [214]. For this analytical segment, macroeconomic ISIC data specific to the UAE were obtained and are as detailed in Table E.1. Following the methodology outlined by Ganzer et al. [79], a database was constructed to incorporate the breakdown of costs associated with the technologies introduced in this thesis. This database facilitated the derivation of GVA ($GVAK_{i,sect}^{cat}$) and employment ($JobsK_{i,sect}^{cat}$) factors across the condensed economic activities from the ISIC. The activities are as follows:

- Agriculture.
- Mining and Extraction.
- Utilities.
- Construction.
- Chemicals products.
- Machinery/electrical equipment.
- Maintenance.
- Other Manufacturing.
- Sales.
- Transportation and Warehousing.
- ICT.
- Finance.
- Professional, scientific and technical activities.
- Administrative and support service activities.
- Other Industries.

Using the above breakdown, associated GVA and jobs data for each category were generated using the model under a domestic biomass scenario that incorporates the production

of alternative fuels.

5.3 The UAE Economy and Carbon Neutrality

The social impact of transitioning to net-zero in the UAE is detailed for the power, industrial and transport sectors. In this section, each sector is individually examined to highlight its distinctive contributions and consequences in the context of social-economics. Following this, a consolidated overview of the aggregate impact across these sectors is provided.

5.3.1 Power Sector

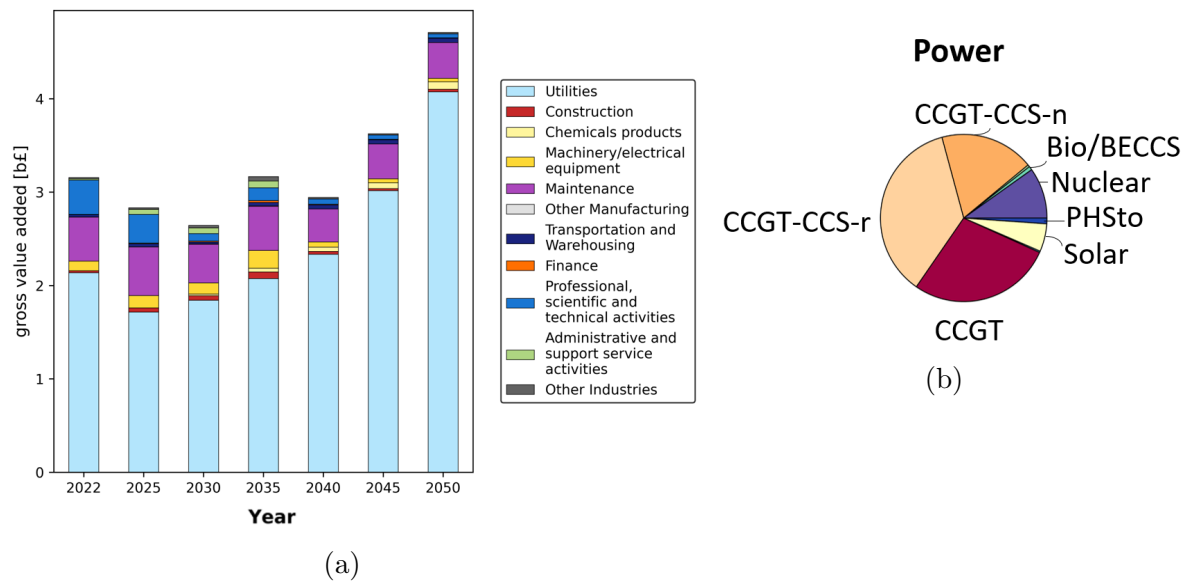


Figure 5.1: GVA produced in the UAE by the power sector.
(a) Annual GVA and (b) Cumulative GVA

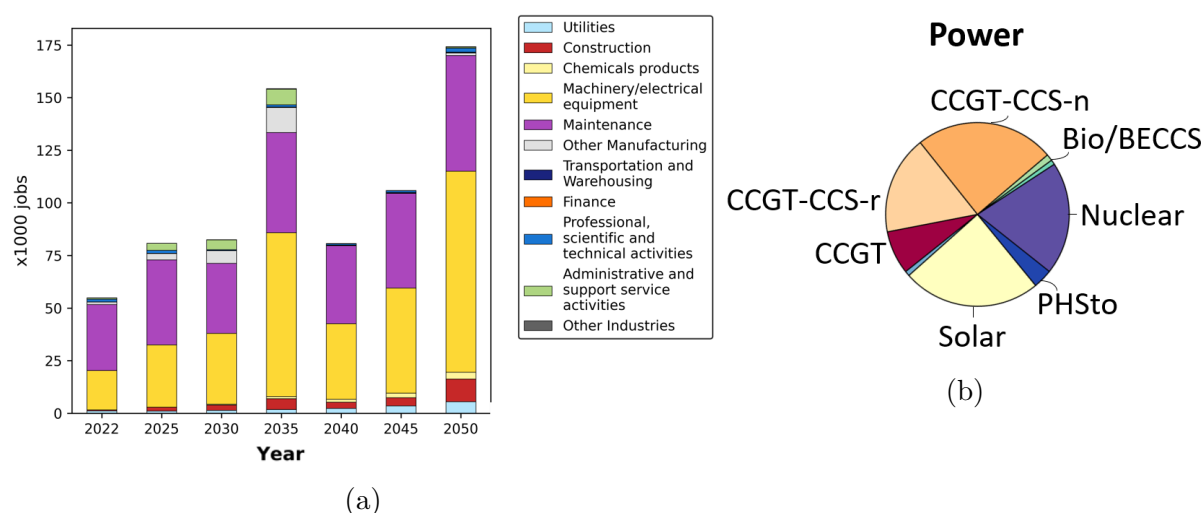


Figure 5.2: Jobs produced in the UAE by the power sector.
(a) Annual jobs and (b) Cumulative jobs

In the context of transition within the power sector, as shown in Figure 5.1a, GVA exhibits fluctuations until a noticeable increase by 2050. Breaking down this progression, the fluctuations post-2022 stem from the completion of construction in nuclear power plants. Between 2022 and 2035, the deployment of additional solar farms capacity commences, leading to a subsequent rise in GVA in 2035 due to increased generation from solar farms and the implementation of onshore wind projects. However, once the model reaches maximum solar capacity (constrained by the S-curve build rate formulation), the GVA experiences a decline. By 2050, the GVA sees a notable increase of 16% from 2022 levels, primarily attributed to additional generation from CCGT-CCS to power the DAC facilities deployed for emissions removal. Throughout these transitions, utility operation remains the dominant economic activity. Further variations are evident in Figure 5.2a, with sharp increases observed in employment by 2035 and 2050. These spikes align with the deployment of solar and onshore wind in 2035, as well as the operation of CCGT-CCS and BECCS in 2050. These increases are predominantly driven by the need for machinery and equipment maintenance throughout the transition.

The deployment of CCS within the power sector is highlighted as contributing to the increased GVA. In Figure 5.1b, the cumulative GVA contribution for each technology

throughout the transition process is illustrated. Notably, natural gas technologies emerge as the primary contributors to the GVA. In comparison to a BAU scenario, the power sector's GVA exhibits a substantial 48% increase by 2050 and this highlights the economic benefits of decarbonising the power sector in the UAE. Regarding employment, as shown in Figure 5.2, nearly half of the new jobs introduced in the economy originate from CCGT-CCS-n/r, with solar and nuclear technologies comprising the remaining quarters during transition.

5.3.2 Industrial Sector

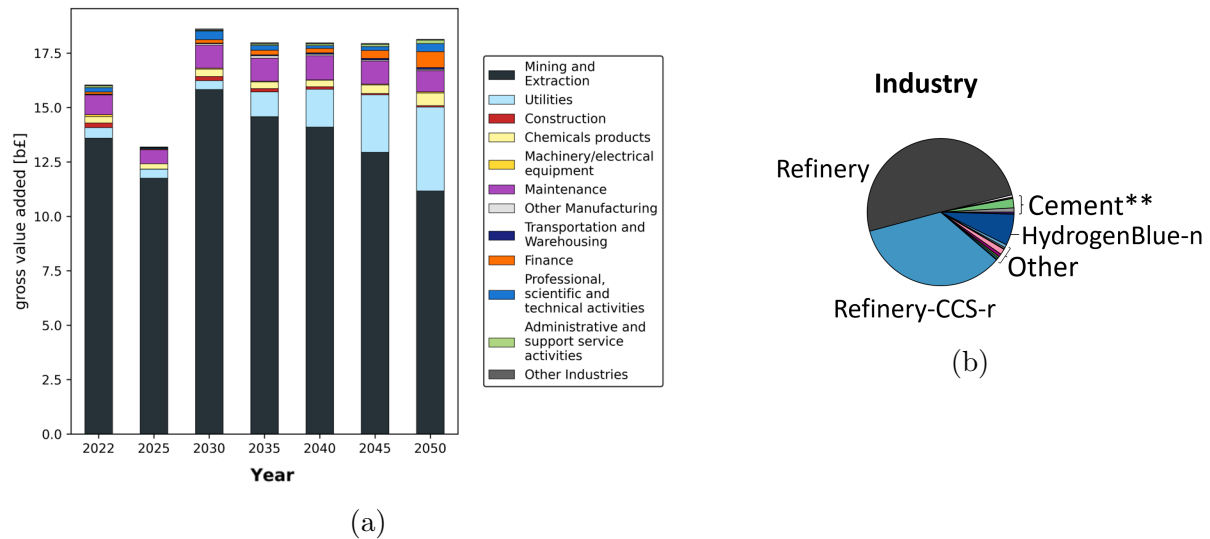


Figure 5.3: GVA produced in the UAE by the industrial sector.

(a) Annual GVA and (b) Cumulative GVA

Cement** stands for Cement and CementPCCS-r.

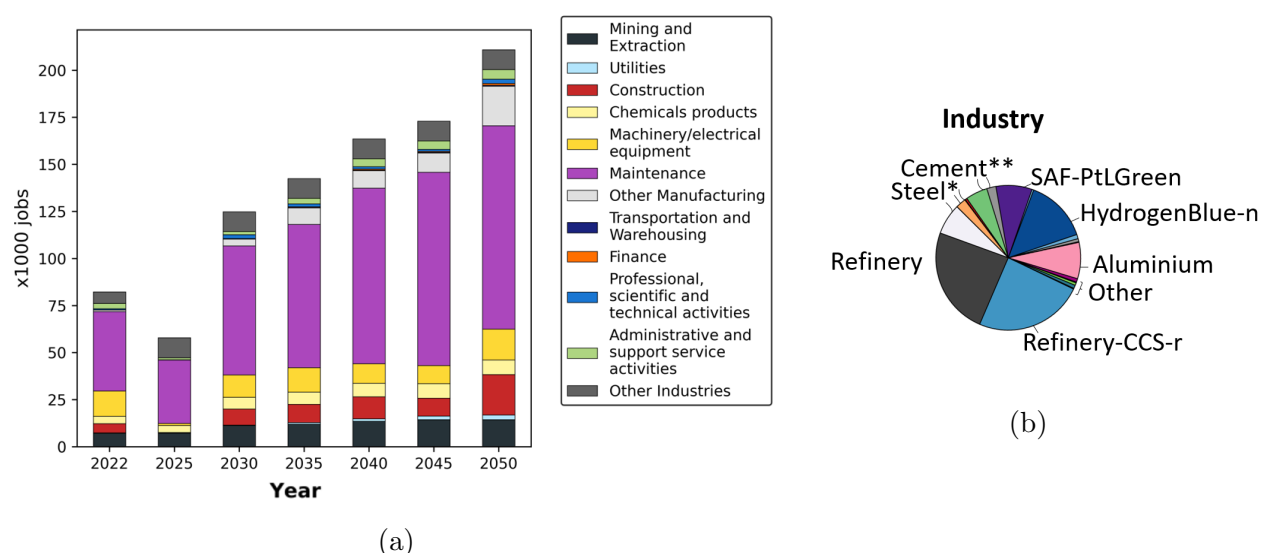


Figure 5.4: Jobs produced in the UAE by the industrial sector.
(a) Annual jobs and (b) Cumulative jobs

Within the industrial sector, the GVA remains relatively stable during the transition period, exhibiting a decrease in 2025 as illustrated in Figure 5.3. The notable increase in GVA observed in 2030 is primarily attributed to the expansion of oil and LNG capacities. Furthermore, in 2030, processes involving aluminum, steel, ammonia and hydrogen undergo retrofitting with CCS, coinciding with the introduction of future fuels. Regarding employment trends, as shown in Figure 5.4a, a sudden surge in employment is observed, correlating with increased oil production and future fuels introduction.

In Figure 5.3b, the cumulative GVA contribution in the UAE's industrial sector is predominantly driven by activities related to oil refining. Conversely, in terms of cumulative employment, as illustrated in Figure 5.4b, oil refining activities account for half of the jobs contributions. The remaining half is associated with various other industrial processes. Remarkably, blue hydrogen and SAF collectively account for one-quarter of the cumulative employment levels, highlighting the notable societal advantages introduced by these fuels.

Steel* stands for SteelDRI-CCS-30H, SteelDRI-CCS-n and Steel-EAF-scrap.
Cement** stands for Cement and CementPCCS-r.

5.3.3 Transport Sector

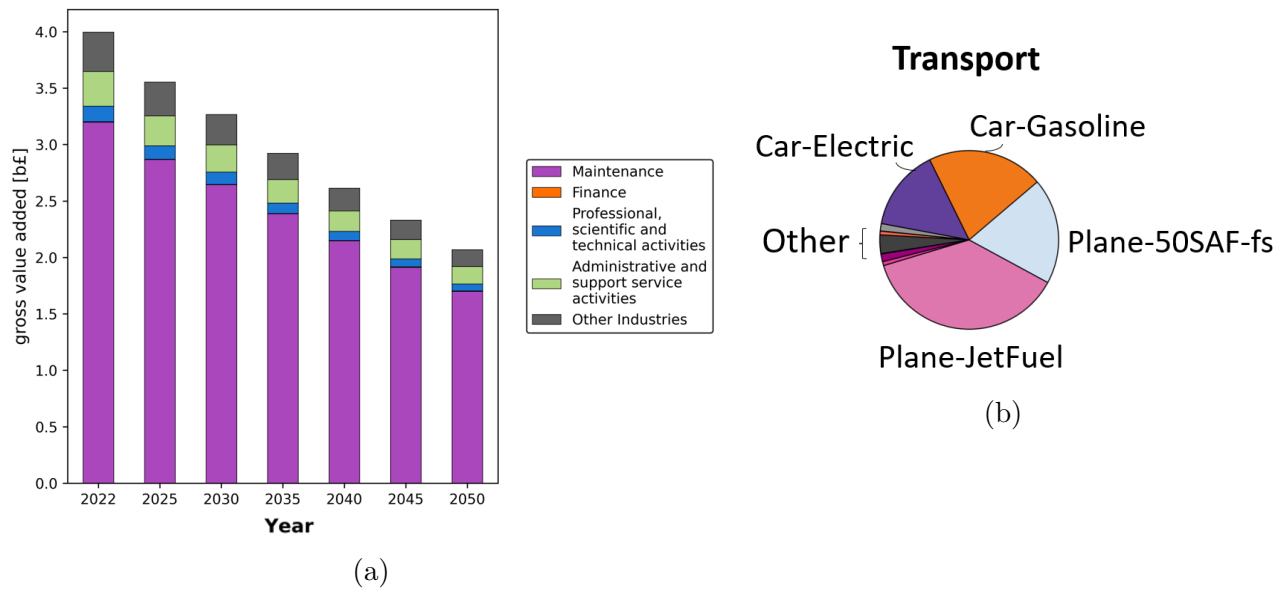


Figure 5.5: GVA produced in the UAE by the transport sector.
(a) Annual GVA and (b) Cumulative GVA

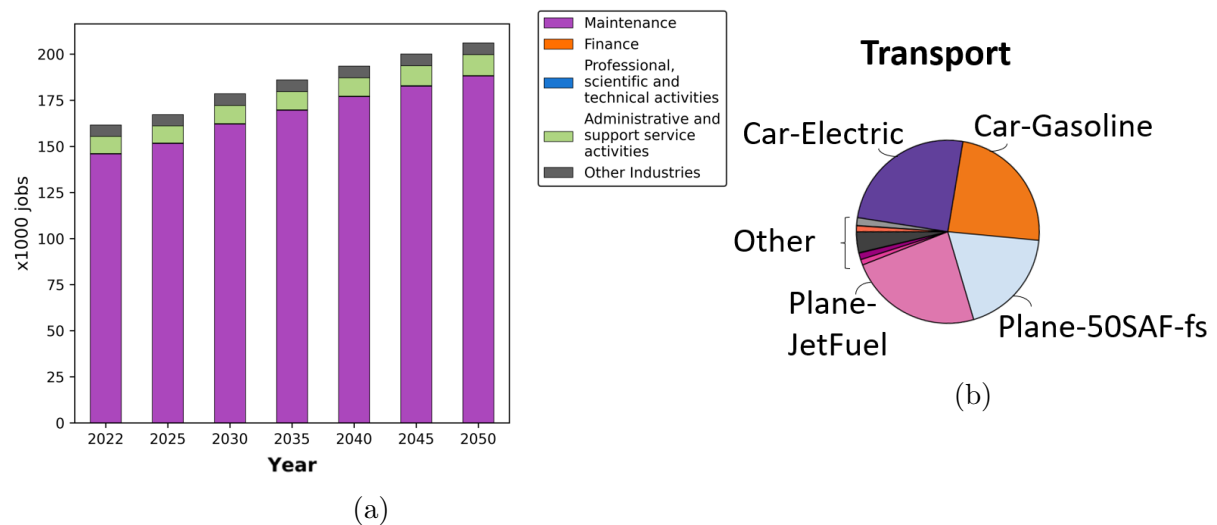


Figure 5.6: Jobs produced in the UAE by the transport sector.
(a) Annual jobs and (b) Cumulative jobs

The gradual electrification of road vehicles in the transport sector has had an observable impact on the power sector, reflecting the evolving dynamics of energy consumption. However, the economic value of this transition within the transport sector itself is not

adequately reflected in terms of GVA, as shown in Figure 5.5a. This is primarily due to the UAE's assumed non-involvement in vehicle manufacturing. Nevertheless, recent initiatives such as the deployment of the NWTN car plant [200] suggest a potential shift in this landscape. Similar opportunities may arise in the domains of air and sea transport, presenting avenues for exploring manufacturing activities that could significantly contribute to the economy. This emphasises the importance of exploring this area to unlock its economic potential.

Regarding employment levels, the observed increase in jobs in the UAE's transport sector is predominantly in maintenance roles as illustrated in Figure 5.6a. This highlights a growing demand for skilled labor within the transport sector. Notably, these jobs primarily revolve around vehicle maintenance in road transport and service provision in air transport, as indicated in Figure 5.6b. This emphasises the importance of developing and sustaining a skilled workforce to support the evolving transportation landscape and capitalise on emerging opportunities.

5.3.4 Overview

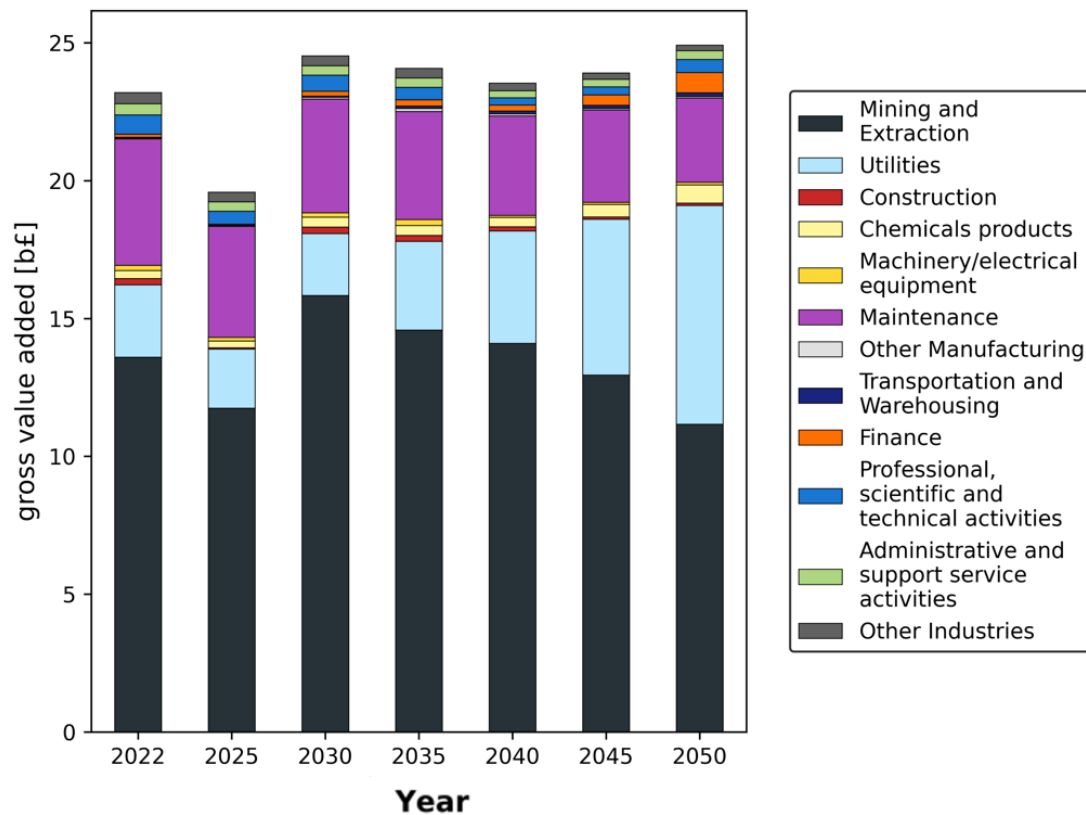


Figure 5.7: The total gross value added by all modeled sectors in ESO-UAE

Throughout the transition period in the UAE, the GVA within the system remains relatively stable, as illustrated in Figure 5.7. Transitioning the UAE to carbon neutrality by 2050 corresponds to a GVA ratio of 47% from the total system cost. Notably, as previously demonstrated, the GVA contributions from the power and industrial sectors predominantly stem from CCS implementation, highlighting the economic significance of CCS in a decarbonised UAE.

In terms of sectoral total system cost, the power sector adds value by 53% in comparison to the amount spent for transitioning this sector, while the industrial sector adds value by 77% and transport by 16%. This breakdown highlights the varying degrees of economic impact across different sectors, with the industrial sector exhibiting particularly high

value addition. Additionally, it emphasises the substantial economic benefits associated with the decarbonisation efforts in these sectors.

Regarding the availability of employees, the region benefits from a pool of skilled workers contracted across the Gulf Cooperation Council (GCC) for similar activities [215, 216]. This availability of skilled labor have the potential to facilitate the implementation of decarbonisation initiatives and support the region's transition towards sustainability.

5.4 Chapter Contribution

This chapter offers several contributions, beginning with drawing lessons from the UK's experience in decarbonisation through highlighting social benefits. This highlighted the importance of avoiding emissions offshoring and emphasised on the need for domestic emissions abatement strategies to maximise economic welfare. Subsequently, the chapter outlines the methodology employed to examine the social impact of decarbonisation in the UAE, utilising the ESO-JEDI framework. This method allows for an in-depth exploration of the social impact of transitioning to net-zero across the power, industrial and transport sectors. Detailed insights into the contributions of each sector are provided, with notable emphasis on the significant contributions from technologies such as CCS.

To summarise, the chapter contributes to understanding the socio-economic implications of transitioning to net-zero, drawing on lessons from the UK's experience and applies an approach to analyse the specific context of the UAE. It provides valuable insights for guiding policy decisions and shaping future research agendas for decarbonisation.

Chapter 6

Conclusion

6.1 Summary of Thesis

Both energy net-importers and net-exporters face the imperative of transitioning to carbon neutrality while simultaneously ensuring their economic stability. Existing literature has predominantly concentrated on the transition challenges encountered by energy net-importers, thereby overlooking the critical perspective of net-exporters. This thesis addresses this gap by examining how the transition in the UK is influenced by the dynamics of an energy net-exporter's economy. Accordingly, the study further explores the transition process specific to energy net-exporter economies with the UAE as the primary focus.

Using the ESO model, the case studies were conducted for the the UK and the UAE. The examination centered on assessing the impact of imported fuel prices on the decarbonisation of the power sector in the UK. Notably, regardless of fluctuations in fuel prices, the presence of bio generating capacities persisted due to the necessity of meeting the CDR targets. The key takeaway from this analysis highlights the UK's requirement for a diversified portfolio of biomass supplies to facilitate its transition. Importantly, the UK

experience highlights the necessity of proactive planning and resource security to ensure the continuity of the transition process and the attainment of targeted goals.

Observing the impact of incorporating a CDR target into the transition process in the UK highlights the necessity for a comprehensive system-level analysis on how a net-exporter can achieve carbon neutrality. To address this, the ESO model underwent an expansion to consider the transport sector, more commodities and additional commercially available decarbonisation technologies. This assessment yielded valuable insights into how an energy net-exporter like the UAE can transition while maintaining economic stability. Notably, projections indicate a significant expansion of the power grid capacity due to the demand from electrified road vehicles in the transport sector and the necessity of DAC to address hard-to-abate emissions. Moreover, analysis revealed the pivotal role of future fuels in mitigating emissions from sea and air transport. Overall, the transition in the UAE differs from that of the UK due to the availability of different resources in each region.

Building upon the socio-economic insights gained from the UK experience, it becomes evident that transitioning can positively impact the economy through increased monetary value and job market growth. Drawing from this premise, a similar socio-economic analysis was conducted on a UAE level. The results of this examination unveiled the favorable effects on the power sector transition within the UAE, highlighting the significance of maintaining a robust industrial sector due to its substantial contribution to the economy.

This thesis has developed a comprehensive model capable of analysing the power, industrial and transport sectors within the context of the UAE. By integrating these sectors into a combined electricity and emission balances, it provides a wholistic view of the decarbonisation process. Moreover, the assessment of technology deployment with reference to fluctuating fuel prices in the UK, adds depth to understanding the dynamics of decarbonisation. By bridging the gap between system-level considerations, techno-economic evaluations and socio-economic analyses, this thesis offers a valuable tool for guiding the

decarbonisation journey of net-exporter economies. As such, it holds significant potential to inform ongoing discussions surrounding the pathways to decarbonise the UAE economy.

6.2 Future Work

This thesis extended the existing ESO framework to include the transport sector, more commodities and technologies for reducing carbon emissions. Potential areas for research and enhancements of the presented work include the framework and data input, as outlined below:

1. Framework:

- The ESO modelling tool developed in this thesis utilises aggregate data inputs to model the cross-sector transition of a country. An extension of this work could involve subdividing the modeled country, such as the UAE, into its seven different zones (Emirates) to account for varying industrial activities.
- Mapping out the precise locations of CCS facilities in the UAE and incorporating this data into an ESO model with the seven emirates could facilitate the analysis of CO₂ flow and identify potential locations for DAC technology.
- Mapping out the exact locations for potential replacement of CO₂-emitting sources in production plants with hydrogen and integrate this data into the model, along with associated costs (e.g., replacing gas boilers in industrial plants with hydrogen boilers).
- Additionally, the thesis could explore the impact of using full hourly data profiles versus clustered data to assess any differences in output, particularly in countries with high cooling demand.
- Moreover, a study on the effects of utilising a rolling horizon modelling approach versus perfect foresight modelling could provide insights into modelling the transi-

tion of a net-exporter more accurately.

- Further expansion of the model to consider additional NETs, such as enhanced weathering could enhance its comprehensiveness.

2. Data Input:

- Extending the thesis to calculate the estimated amounts of steel, cement and aluminum required for constructing new facilities necessary for decarbonising the UAE would provide insight into the sufficiency of existing capacities and the demand for future production capacity increases.
- Incorporating International Civil Aviation Organisation (ICAO) CORSIA regulations for air transport and assessing the cost implications by distributing the emissions burden to enhance the model's accuracy.
- Considering ICAO CORSIA as a carbon price in the model for air transport to determine whether it is more cost-effective to pay emissions fees or invest in emissions reduction within the country.
- Mapping out the exact traveled distances by sea vessels and integrating this data into the model would improve its representation of maritime transport emissions.
- Investigating the impact of increasing CCS capture rates on model outcomes as higher rates could reduce reliance on NETs like BECCS and DAC. Scenario analysis could quantify how different CCS rates affect BECCS and DAC deployment, providing insights into optimising decarbonisation strategies cost-effectively.
- Investigating the different archetypes of DAC, specifically those using natural gas as a fuel, given the UAE's access to inexpensive natural gas. This investigation

could enhance the model outcomes and provide further insights into the competition between different DAC types in the UAE.

Bibliography

- [1] R. J. Andres, D. J. Fielding, G. Marland, T. A. Boden, N. Kumar, and A. T. Kearney, “Carbon dioxide emissions from fossil-fuel use, 1751–1950,” *Tellus B: Chemical and Physical Meteorology*, vol. 51, no. 4, p. 759–765, 1999.
- [2] G. C. Hegerl, S. Brönnimann, A. Schurer, and T. Cowan, “The early 20th century warming: Anomalies, causes, and consequences,” *WIREs Climate Change*, vol. 9, no. 4, p. e522, 2018. Available online at <https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wcc.522>.
- [3] C. Funk, *Drought, Flood, Fire: How Climate Change Contributes to Catastrophes*. Cambridge University Press, 2021.
- [4] S. Mukherjee, A. Mishra, and K. Trenberth, “Climate change and drought: a perspective on drought indices,” *Curr Clim Change Rep*, vol. 4, p. 145–163, 2018. Available online at <https://doi.org/10.1007/s40641-018-0098-x>.
- [5] R. Harding, N. Arnell, N. Reynard, C. Prudhomme, E. Blyth, and C. Taylor, *Climate Change and Hydrology*, ch. 10, pp. 302–323. John Wiley & Sons, Ltd, 2015. Available online at <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119074304.ch10>.
- [6] P. Jackson, “Stockholm to kyoto: A brief history of climate change,” Accessed: 2024-01-01. Available online at <https://www.un.org/en/chronicle/article/stockholm-kyoto-brief-history-climate-change>.

- [7] UNFCCC, “Adoption of the paris agreement,” in *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*, Dec 2015. U.N. Doc. FCCC/CP/2015/10/Add.1.
- [8] United Nations, “Paris agreement: 175 countries sign at un climate headquarters,” 2016. Available online at <https://www.un.org/sustainabledevelopment/blog/2016/04/parisagreementsingatures/>.
- [9] IPCC, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.
- [10] United Nations, “Conference of the parties list,” Accessed: 2024-01-01. Available online at <https://www.downtoearth.org.in/climate-change/coplist>.
- [11] UN, “Climate finance framework - COP28,” 2023. Available online at https://www.cop28.com/en/climate_finance_framework.
- [12] K. Rajendran, B. O’Gallachoir, and J. D. Murphy, “The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane,” *Journal of Cleaner Production*, vol. 219, pp. 278–290, 2019. Available online at <https://doi.org/10.1016/j.jclepro.2019.01.298>.
- [13] A. S. Alamoush, A. I. Ölçer, and F. Ballini, “Ports’ role in shipping decarbonisation: A common port incentive scheme for shipping greenhouse gas emissions reduction,” *Cleaner Logistics and Supply Chain*, vol. 3, p. 100021, 2022. Available online at <https://doi.org/10.1016/j.clscn.2021.100021>.
- [14] S. Hafner, M. Speich, P. Bischofberger, and S. Ulli-Beer, “Governing industry decarbonisation: Policy implications from a firm perspective,” *Journal of Cleaner Production*, vol. 375, p. 133884, 2022. Available online at <https://doi.org/10.1016/j.jclepro.2022.133884>.

- [15] M. Johansson, D. Langlet, O. Larsson, Åsa Löfgren, N. Haring, and S. Jagers, “A risk framework for optimising policies for deep decarbonisation technologies,” *Energy Research Social Science*, vol. 82, p. 102297, 2021. Available online at <https://doi.org/10.1016/j.erss.2021.102297>.
- [16] P. Patrizio, Y. W. Pratama, and N. M. Dowell, “Socially equitable energy system transitions,” *Joule*, vol. 4, no. 8, pp. 1700–1713, 2020. Available online at <https://doi.org/10.1016/j.joule.2020.07.010>.
- [17] European Parliament, “Carbon border adjustment mechanism as part of the European Green Deal - Q2 2021.” Legislative Document, 2021. Available online at <https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-carbon-border-adjustment-mechanism>.
- [18] European Commission - Taxation and Customs Union, “Carbon Border Adjustment Mechanism,” 2023. Available online at https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.
- [19] Eurostat, “Eurostat Energy Database.” Available online at <https://ec.europa.eu/eurostat/web/energy/database> Accessed on: 5 January 2024.
- [20] P. Colbertaldo, F. Parolin, and S. Campanari, “A comprehensive multi-node multi-vector multi-sector modelling framework to investigate integrated energy systems and assess decarbonisation needs,” *Energy Conversion and Management*, vol. 291, p. 117168, 2023. Available online at <https://doi.org/10.1016/j.enconman.2023.117168>.
- [21] M. Yuan, J. Z. Thellufsen, H. Lund, and Y. Liang, “The electrification of transportation in energy transition,” *Energy*, vol. 236, p. 121564, 2021. Available online at <https://doi.org/10.1016/j.energy.2021.121564>.
- [22] N. M. Baid and M. M. Rahman, “The renewable energy sources for electricity generation: A short review,” *Maejo International Journal of Energy and*

- Environmental Communication*, vol. 4, pp. 29–33, Mar. 2022. <https://ph02.tci-thaijo.org/index.php/MIJEEC/article/view/247736>.
- [23] L. Sund, S. Talari, and W. Ketter, “Stochastic wind power generation planning in liberalised electricity markets within a heterogeneous landscape,” *Energies*, vol. 15, no. 21, 2022. Available online at <https://www.mdpi.com/1996-1073/15/21/8109>.
- [24] V. Srikrishnan, D. C. Lafferty, T. E. Wong, J. R. Lamontagne, J. D. Quinn, S. Sharma, N. J. Molla, J. D. Herman, R. L. Sriver, J. F. Morris, and B. S. Lee, “Uncertainty analysis in multi-sector systems: Considerations for risk analysis, projection, and planning for complex systems,” *Earth’s Future*, vol. 10, no. 8, p. e2021EF002644, 2022. Available online at <https://doi.org/10.1029/2021EF002644>.
- [25] C. Ganzer and N. Mac Dowell, “Pathways to net zero for power and industry in the UK,” *International Journal of Greenhouse Gas Control*, vol. 125, p. 103887, 2023. Available online at <https://doi.org/10.1016/j.ijggc.2023.103887>.
- [26] S. Sorrell, “Reducing energy demand: A review of issues, challenges and approaches,” *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 74–82, 2015. Available online at <https://doi.org/10.1016/j.rser.2015.03.002>.
- [27] Element Energy Limited, “Assessment of options to reduce emissions from fossil fuel production and fugitive emissions,” tech. rep., May 2019. Available online at <http://tinyurl.com/538cfh5y>.
- [28] D. W. Keith, G. Holmes, D. St. Angelo, and K. Heidel, “A process for capturing CO₂ from the atmosphere,” *Joule*, vol. 2, no. 8, pp. 1573–1594, 2018. Available online at <https://doi.org/10.1016/j.joule.2018.05.006>.
- [29] S. G. (Ed.), “Illinois basin - decatur project,” *Greenhouse Gases: Science and Technology*, vol. 4, pp. 569–570, Sept. 2014. Available online at <https://www.netl.doe.gov/sites/default/files/2018-11/Illinois-Basin-Decatur-Project.pdf>.

- [30] European Commission, “European green deal,” 2024. Available online at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en Accessed on January 4, 2024.
- [31] T. J. Times, “Uniting paths for carbon neutrality,” November 1 2021. Available online at <https://www.japantimes.co.jp/2021/11/01/special-supplements/uniting-paths-carbon-neutrality/> Accessed on: January 4, 2024.
- [32] “Global commitment on climate action.” Available online at <https://www.greenplan.gov.sg/globalcommitment/> Accessed on: January 4, 2024.
- [33] World Economic Forum, “Davos 2023: Japan to accelerate efforts for a carbon-neutral society,” 2023. Available online at <https://www.weforum.org/agenda/2023/01/davos23-japan-accelerate-efforts-carbon-neutral-society/> Accessed on January 4, 2024.
- [34] National Climate Change Secretariat (NCCS), “Singapore’s carbon tax,” 2023. Available online at <https://www.nccs.gov.sg/singapores-climate-action/mitigation-efforts/carbontax/> Accessed on: January 5, 2024.
- [35] Bloomberg, “Germany returns to coal as energy security trumps climate goals,” 2022. Available online at <https://www.bloomberg.com/news/articles/2022-12-22/germany-returns-to-coal-as-energy-security-trumps-climate-goals> Accessed on: January 5, 2024.
- [36] C. Arlota, “The impact of the COVID-19 pandemic on foreign investment and investment arbitration: from energy transition disrupted to the path forward to a greener future,” *The Journal of World Energy Law Business*, vol. 15, pp. 382–395, 08 2022. Available online at <https://doi.org/10.1093/jwelb/jwac028>.
- [37] M. Mersch, C. N. Markides, and N. Mac Dowell, “The impact of the energy crisis on the UK’s net-zero transition,” *iScience*, vol. 26, no. 4, p. 106491, 2023. Available online at <https://doi.org/10.1016/j.isci.2023.106491>.

- [38] Euronews, “Eu economy loses momentum amid Ukraine war, inflation, natural disasters, and higher interest,” 2023. Available online at <https://www.euronews.com/embed/2367392> Accessed on: January 5, 2024.
- [39] L. Marti and R. Puertas, “Sustainable energy development analysis: Energy trilemma,” *Sustainable Technology and Entrepreneurship*, vol. 1, no. 1, p. 100007, 2022. Available online at <https://doi.org/10.1016/j.stae.2022.100007>.
- [40] A. Pliousis, K. Andriosopoulos, M. Doumpos, and E. Galariotis, “A multicriteria assessment approach to the energy trilemma,” *The Energy Journal*, vol. 40, no. 1_suppl, pp. 143–166, 2019. Available online at 10.5547/01956574.40.SI1.apli.
- [41] BBC News, “Climate change: The rich-poor divide over a green transition,” 2021. Available online at <https://www.bbc.com/news/business-58469238> Accessed on: January 5, 2024.
- [42] H. Liu, I. Khan, A. Zakari, and M. Alharthi, “Roles of trilemma in the world energy sector and transition towards sustainable energy: A study of economic growth and the environment,” *Energy Policy*, vol. 170, p. 113238, 2022. Available online at <https://doi.org/10.1016/j.enpol.2022.113238>.
- [43] C. Panoutsou, A. Bauen, and J. Duffield, “Policy regimes and funding schemes to support investment for next-generation biofuels in the USA and the eu-27,” *Biofuels, Bioproducts and Biorefining*, vol. 7, no. 6, pp. 685–701, 2013. Available online at <https://doi.org/10.1002/bbb.1428>.
- [44] P. Wei, O. Bamisile, H. Adun, D. Cai, S. Obiora, J. Li, and Q. Huang, “Bibliographical progress in hybrid renewable energy systems’ integration, modelling, optimization, and artificial intelligence applications: A critical review and future research perspective,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 1, pp. 2058–2088, 2023. Available online at <https://doi.org/10.1080/15567036.2023.2181888>.

- [45] G. Chehade and I. Dincer, “Progress in green ammonia production as potential carbon-free fuel,” *Fuel*, vol. 299, p. 120845, 2021. Available online at <https://doi.org/10.1016/j.fuel.2021.120845>.
- [46] R. Nandhini, B. Sivaprakash, N. Rajamohan, and D.-V. N. Vo, “Carbon-free hydrogen and bioenergy production through integrated carbon capture and storage technology for achieving sustainable and circular economy– a review,” *Fuel*, vol. 342, p. 126984, 2023. Available online at <https://doi.org/10.1016/j.fuel.2022.126984>.
- [47] O. Mathieu and E. L. Petersen, *Carbon-Free Fuels*. American Chemical Society, June 20 2023. Copyright © 2023 American Chemical Society.
- [48] O. Cavalett and F. Cherubini, “Unraveling the role of biofuels in road transport under rapid electrification,” *Biofuels, Bioproducts and Biorefining*, vol. 16, no. 6, pp. 1495–1510, 2022. Available online at <https://doi.org/10.1002/bbb.2395>.
- [49] R. S. Capaz, E. Guida, J. E. A. Seabra, P. Osseweijer, and J. A. Posada, “Mitigating carbon emissions through sustainable aviation fuels: costs and potential,” *Biofuels, Bioproducts and Biorefining*, vol. 15, no. 2, pp. 502–524, 2021. Available online at <https://doi.org/10.1002/bbb.2168>.
- [50] United Arab Emirates, “UAE Net Zero 2050,” 2023. Available online at <https://u.ae/en/information-and-services/environment-and-energy/climate-change/theuaesresponsetoclimatechange/uae-net-zero-2050>.
- [51] United Arab Emirates Government Portal, “We the UAE 2031 Vision,” 2023. Available online at <https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/innovation-and-future-shaping/we-the-uae-2031-vision>.
- [52] BBC, “Saudi arabia commits to net zero emissions by 2060,” 2021. Available online at <https://www.bbc.com/news/world-middle-east-58955584>.

- [53] Saudi Arabia, “Vision 2030: A Thriving Economy,” 2023. Available online at <https://www.vision2030.gov.sa/en/vision-2030/overview/a-thriving-economy/>.
- [54] N. Buli and N. Adomaitis, “Explainer: How does Norway export its natural gas?,” March 17 2023. Available online at <https://www.reuters.com/business/energy/how-does-norway-export-its-natural-gas-2023-03-17/>.
- [55] Argus Media, “Norway updates 2030 climate targets ahead of COP 27,” November 3 2022. Available online at <https://www.argusmedia.com/en/news/2387279-norway-updates-2030-climate-targets-ahead-of-cop-27>.
- [56] C. Redgwell, *Chapter 11: United Kingdom*, pp. 255 – 277. Cheltenham, UK: Edward Elgar Publishing, 2023. Available online at <https://www.elgaronline.com/view/book/9781802208856/book-part-9781802208856-20.xml>.
- [57] H. Daggash and N. Dowell, “Structural evolution of the UK electricity system in a below 2°c world,” *Joule*, vol. 3, 04 2019. Available online at 10.1016/j.joule.2019.03.009.
- [58] M. Blanch, C. Davies, and A. Roberts, “Offshore wind energy,” in *Building Industries at Sea - 'Blue Growth' and the New Maritime Economy*, p. 18, River Publishers, 1st ed., 2018. OA Funder: European Commission.
- [59] L. Array, “London array: The world’s largest operational offshore wind farm,” *Engineering & Technology Reference*, p. 5, 2015. Available online at 10.1049/etr.2014.0049.
- [60] Department for Energy Security and Net Zero, “Carbon Budget Delivery Plan,” policy paper, Department for Energy Security and Net Zero, March 2023. Available online at <https://www.gov.uk/government/publications/carbon-budget-delivery-plan> Ref: ISBN 978-1-5286-4015-2, E02888032 03/23, HC 1269 2023-24.

- [61] Drax, “The UK needs negative emissions from BECCS to reach net zero – here’s why,” April 7 2020. Available online at <https://www.drax.com/carbon-capture/uk-needs-negative-emissions-beccs-net-zero-why/>.
- [62] OPEC, “UAE Facts and Figures,” 2021. Available online at https://www.opec.org/opec_web/en/about_us/170.htm.
- [63] Statista, “Oil consumption worldwide from 1970 to 2022,” June 2023. Available online at <https://www.statista.com/statistics/265261/global-oil-consumption-in-million-metric-tons/>.
- [64] Embassy of the United Arab Emirates Washington DC, “COP 28,” 2023. Available online at <https://www.uae-embassy.org/discover-uae/climate-energy/cop28>.
- [65] ADNOC, “ADNOC to Build World-Scale Blue Ammonia Project,” May 24 2021. Available online at <https://www.adnoc.ae/news-and-media/press-releases/2021/adnoc-to-build-world-scale-blue-ammonia-project>.
- [66] United Arab Emirates Ministry of Energy & Infrastructure, “UAE Hydrogen Leadership Roadmap,” tech. rep., November 2021. Available online at <https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/environment-and-energy/national-hydrogen-strategy>.
- [67] United Arab Emirates Government, “General Policy for Sustainable Aviation Fuel,” June 2024. Available online at <http://tinyurl.com/prr48a3k>.
- [68] Anthony Di Paola, “UAE Accelerates Plan to Increase Its Oil Production Capacity,” September 2022. Available online at <https://www.bloomberg.com/news/articles/2022-09-19/uae-accelerates-plan-to-increase-its-oil-production-capacity> Published on September 19, 2022, at 11:42 AM GMT+1.

- [69] M. Gargiulo and B. Gallachóir, “Long-term energy models: Principles, characteristics, focus, and limitations,” *WIREs Energy and Environment*, vol. 2, no. 2, pp. 158–177, 2013. Available online at <https://doi.org/10.1002/wene.62>.
- [70] M. Prokopczuk, *Energy Pricing Models: Recent Advances, Methods, and Tools*. Business and Management (R0), Palgrave Macmillan New York, 1 ed., 2014.
- [71] L. M. Hall and A. R. Buckley, “A review of energy systems models in the UK: Prevalent usage and categorisation,” *Applied Energy*, vol. 169, pp. 607–628, 2016.
- [72] H.-K. Ringkjøb, P. M. Haugan, and I. M. Solbrekke, “A review of modelling tools for energy and electricity systems with large shares of variable renewables,” *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 440–459, 2018. Available online at <https://doi.org/10.1016/j.rser.2018.08.002>.
- [73] P. Lopion, P. Markewitz, M. Robinius, and D. Stolten, “A review of current challenges and trends in energy systems modeling,” *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 156–166, 2018.
- [74] A. Herbst, F. Toro, F. Reitze, *et al.*, “Introduction to energy systems modelling,” *Swiss Journal of Economics and Statistics*, vol. 148, pp. 111–135, 2012. 10.1007/BF03399363.
- [75] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, “Classification and challenges of bottom-up energy system models - a review,” *Renewable and Sustainable Energy Reviews*, vol. 129, p. 109917, 2020. Available online at <https://doi.org/10.1016/j.rser.2020.109917>.
- [76] C. F. Heuberger, I. Staffell, N. Shah, and N. Mac Dowell, “Quantifying the value of ccs for the future electricity system,” *Energy & Environmental Science*, vol. 9, no. 8, pp. 2497–2510, 2016.
- [77] C. F. Heuberger, E. S. Rubin, I. Staffell, N. Shah, and N. Mac Dowell, “Power capacity expansion planning considering endogenous technology cost learning,” *Applied Energy*, vol. 204, pp. 831–845, Oct. 2017.

- [78] C. F. Heuberger, P. K. Bains, and N. Mac Dowell, “The evolution of the power system: A spatio-temporal optimisation model to investigate the impact of electric vehicle deployment,” *Applied Energy*, vol. 257, p. 113715, Jan. 2020.
- [79] C. Ganzer, *Pathways to net zero for power and industry in the United Kingdom*. PhD thesis, Imperial College London, Centre for Environmental Policy, Oct 2022. Available online at <http://hdl.handle.net/10044/1/100342>.
- [80] F. Dettner and S. Hilpert, “Modelling CO₂ emissions and mitigation potential of northern european shipping,” *Transportation Research Part D: Transport and Environment*, vol. 119, p. 103745, 2023. Available online at <https://doi.org/10.1016/j.trd.2023.103745>.
- [81] B. A. Zincir, B. Zincir, and Y. Arslanoglu, *SWOT Analysis of Carbon Capture, Storage, and Transportation for Maritime Industry*, pp. 117–140. Singapore: Springer Nature Singapore, 2023. Available online at https://doi.org/10.1007/978-981-99-1677-1_7.
- [82] O. Oguntona, “Longer-term aircraft fleet modelling: narrative review of tools and measures for mitigating carbon emissions from aircraft fleet,” *CEAS Aeronaut J*, vol. 11, pp. 13–31, 2020. Available online at <https://doi.org/10.1007/s13272-019-00424-y>.
- [83] N. Nasrin, I. El-Sayed, and J. García, “A review of simulation models for CO₂ pollution reduction in transportation sector,” in *2022 IEEE Vehicle Power and Propulsion Conference (VPPC)*, pp. 1–6, 2022. 10.1109/VPPC55846.2022.10003288.
- [84] H. Rauf and H. Sikandar, “Transport emission models: A bibliometric and content analysis,” *Journal of Public Value and Administration Insights*, vol. VOL 5 NO 2 (2022), pp. 395–423, 06 2022. 10.31580/jpvai.v5i2.2530.
- [85] J. Huang, Y. Cui, L. Zhang, W. Tong, Y. Shi, and Z. Liu, “An overview of agent-based models for transport simulation and analysis,” *Journal of Advanced Transportation*, vol. 2022, pp. 1–17, 02 2022. 10.1155/2022/1252534.

- [86] B. Li, M. Chen, Z. Ma, G. He, W. Dai, D. Liu, C. Zhang, and H. Zhong, “Modeling integrated power and transportation systems: Impacts of power-to-gas on the deep decarbonization,” *IEEE Transactions on Industry Applications*, vol. 58, no. 2, pp. 2677–2693, 2022. 10.1109/TIA.2021.3116916.
- [87] P. Fu, D. Pudjianto, and G. Strbac, “Integration of power-to-gas and low-carbon road transport in great britain’s future energy system,” *IET Renewable Power Generation*, vol. 14, no. 17, pp. 3393–3400, 2020. Available online at <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-rpg.2020.0595>.
- [88] S. Clegg, L. Zhang, and P. Mancarella, “The role of power-to-transport via hydrogen and natural gas vehicles in decarbonising the power and transportation sector,” in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–6, 2017. 10.1109/ISGTEurope.2017.8260305.
- [89] Z. Fan and S. J. Friedmann, “Low-carbon production of iron and steel: Technology options, economic assessment, and policy,” *Joule*, vol. 5, no. 4, pp. 829–862, 2021. Available online at <https://doi.org/10.1016/j.joule.2021.02.018>.
- [90] T. Astoria, G. Hughes, and N. Mizutani, “MIDREX NG™ with H₂ Addition: Moving from natural gas to hydrogen in decarbonizing ironmaking,” tech. rep., MIDREX Technologies, Inc., 3735 Glen Lake Drive, Suite 400, Charlotte, North Carolina 28208 USA, March 2022. Available online at <https://www.midrex.com/wp-content/uploads/2022/03/MIDREX-NG-with-H2-Addition-1.pdf>.
- [91] IEAGHG, “Techno-economic evaluation of CO₂ capture in lng plants,” Tech. Rep. 2019-07, October 2019. Available online at <http://tinyurl.com/4mf4b65w>.
- [92] R. Skiebe, “All-electric lng maximizes process control in the arctic,” *Gas Processing & LNG*, March/April 2020. Available online at <https://assets.siemens-energy.com/siemens/assets/api/uuid:88cb7d7c-548a-4d8d-b46e-93540d20ddd2/gp-mar-apr2020-electric-lng-article.pdf>.

- [93] A. Sultan, “Power Generation.” Available online at <https://primary.world-aluminium.org/processes/power-generation/>.
- [94] McKinsey & Company and World Economic Forum, “Scaling sustainable aviation fuel today for clean skies tomorrow,” 2020. Available online at <https://www.mckinsey.com/~media/mckinsey/industries/travel%20transport%20and%20logistics/our%20insights/scaling%20sustainable%20aviation%20fuel%20today%20for%20clean%20skies%20tomorrow/clean-skies-for-tomorrow.pdf>.
- [95] NimbleFins, “Average MPG for cars UK (2024),” 2024. Available online at <https://www.nimblefins.co.uk/cheap-car-insurance/average-mpg#:~:text=Petrol%20cars%20average%20around%2036,the%20equivalent%20of%20132%20MPGe>.
- [96] J. O’Dea, “Electric vs. diesel vs. natural gas: Which bus is best for the climate?,” July 19 2018. Available online at <https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-for-the-climate/#:~:text=Fuel%20efficiency&text=Fuel%20efficiencies%20used%20in%20this,a%2090%20percent%20charging%20efficiency>.
- [97] M. T. Parts, “What fuel economy (mpg) does a lorry get?,” Available online at <https://mwtruckparts.co.uk/what-fuel-economy-mpg-does-a-lorry-get#:~:text=Whilst%20modern%20diesel%20cars%20can,over%2033t%20was%207.6mpg>.
- [98] J. Wang and H. A. Rakha, “Electric train energy consumption modeling,” *Applied Energy*, vol. 193, pp. 346–355, 2017. Available online at <https://doi.org/10.1016/j.apenergy.2017.02.058>.
- [99] S. Dermühl and U. Riedel, “A comparison of the most promising low-carbon hydrogen production technologies,” *Fuel*, vol. 340, p. 127478, 2023. Available online at <https://doi.org/10.1016/j.fuel.2023.127478>.

- [100] C. Ganzer, Y. W. Pratama, and N. Mac Dowell, “The role and value of inter-seasonal grid-scale energy storage in net zero electricity systems,” *International Journal of Greenhouse Gas Control*, vol. 120, p. 103740, 2022. Available online at <https://doi.org/10.1016/j.ijggc.2022.103740>.
- [101] S. Pfenninger and I. Staffell, “Renewables ninja,” 2016. Available online at <https://www.renewables.ninja/>.
- [102] European Commission and Directorate-General for Climate Action and Directorate-General for Energy and Directorate-General for Mobility and Transport, A. De Vita, P. Capros, L. Paroussos, K. Fragkiadakis, P. Karkatsoulis, L. Höglund-Isaksson, W. Winiwarter, P. Purohit, A. Gómez-Sanabria, P. Rafaj, L. Warnecke, A. Deppermann, M. Gusti, S. Frank, P. Lauri, F. Fulvio, A. Florou, M. Kannavou, N. Forsell, T. Fotiou, P. Siskos, P. Havlík, I. Tsiropoulos, S. Evangelopoulou, P. Witzke, M. Kesting, N. Katoufa, I. Mitsios, G. Asimakopoulou, and T. Kalokyris, *EU reference scenario 2020 – Energy, transport and GHG emissions – Trends to 2050*. Publications Office, 2021. doi/10.2833/35750.
- [103] M. . Company, *Transformation of Europe’s power system until 2050*. 2010. Available online at https://www.mckinsey.com/~media/mckinsey/dotcom/client_service/epng/pdfs/transformation_of_europes_power_system.ashx.
- [104] International Renewable Energy Agency, “Renewable power generation costs in 2022,” tech. rep., International Renewable Energy Agency, Abu Dhabi, 2023. Available online at <https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022>.
- [105] Department of Business, Energy & Industrial Strategy, “Electricity generation costs 2020,” tech. rep., Department of Business, Energy & Industrial Strategy, 2020. Available online at <https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020>.

- [106] IEAGHG, “Effects of plant location on the costs of CO_2 capture,” Technical Report 2018-04, IEAGHG, April 2018.
- [107] Department of Energy & Climate Change, “Fossil fuel projections: 2015,” tech. rep., November 2015. Available online at <https://www.gov.uk/government/publications/fossil-fuel-price-projections-2015>.
- [108] World Nuclear Association, “Economics of nuclear power.” Updated August 2022, 2022. Available online at <http://www.world-nuclear.org/information-library/economics-of-nuclear-power.aspx>.
- [109] D. Zhang, M. Bui, M. Fajardy, P. Patrizio, F. Kraxner, and N. Mac Dowell, “Unlocking the potential of beccs with indigenous sources of biomass at a national scale,” *Sustainable Energy & Fuels*, vol. 4, no. 1, pp. 226–253, 2020.
- [110] “Generation, analysis, and applications of high resolution electricity load profiles in qatar,” *Journal of Cleaner Production*, vol. 183, pp. 527–543, May 2018. Available online at <https://doi.org/10.1016/j.jclepro.2018.02.084>.
- [111] S. Taqvi, A. Almansoori, A. Maroufmashat, and A. Elkamel, “Utilizing rooftop renewable energy potential for electric vehicle charging infrastructure using multi-energy hub approach,” *Energies*, vol. 15, p. 9572, 12 2022. DOI: 10.3390/en15249572.
- [112] W. Spark, “Compare the climate and weather in doha and Abu Dhabi,” 2021. Available online at <https://weatherspark.com/compare/y/105083~105360/Comparison-of-the-Average-Weather-in-Doha-and-Abu-Dhabi>.
- [113] International Energy Agency, “Qatar.” Available online at <https://www.iea.org/countries/qatar>.
- [114] Masdar, “Masdar launches UAE’s first utility scale wind project with breakthrough low wind speed innovation,” October 5 2023. Available online at <http://tinyurl.com/3jw67ts2>.

- [115] Global Petrol Prices, “Electricity prices in saudi arabia.” Available online at https://www.globalpetrolprices.com/Saudi-Arabia/electricity_prices/.
- [116] Mazoon Electricity Company, “Tariff detail.” Available online at <https://mzec.nama.om/en-us/Pages/tarifftype.aspx>.
- [117] ADE, “Ac voltages & frequencies per country.” Available online at <https://ade-power.com/info/worldwide-voltage-frequency-list>.
- [118] Emirates Green Building Council, “Benchmarking program.” Available online at <https://emiratesgbc.org/technical-programs/benchmarking-program/>.
- [119] ArabianPost, “Power cut plunges Dubai mall into darkness – retail.” Available online at <https://thearabianpost.com/power-cut-plunges-dubai-mall-into-darkness-retail/#:~:text=Dubai%20Mall%2C%20one%20of%20the,the%20mall%20in%20the%20dark>.
- [120] MEED, “UAE to diversify energy supply,” 2011. Available online at <https://www.meed.com/uae-to-diversify-energy-supply/> Published on 16 March 2011.
- [121] Climeworks, “Direct air capture: our technology to capture co₂.” Available online at <https://climeworks.com/direct-air-capture#:~:text=Once%20sucked%20in%2C%20it%20passes,for%20a%20cup%20of%20tea!>
- [122] “Hamriyah combined-cycle independent power project, Sharjah, UAE.” Power Technology, October 2023. Available online at <https://www.power-technology.com/projects/hamriyah-power-project-sharjah-uae/?cf-view>.
- [123] S. Alqahtani, A. Shaher, A. Garada, and L. Cipcigan, “Impact of the high penetration of renewable energy sources on the frequency stability of the saudi grid,” *Electronics*, vol. 12, no. 6, 2023. Available online at <https://www.mdpi.com/2079-9292/12/6/1470>.

- [124] S.-B. Kim and J.-H. Keppler, “The barakah nuclear power plants, the united arab emirates,” 2013. Available online at https://www.oecd-neo.org/ndd/workshops/wpne/presentations/docs/4_2_KIM_%20Barakah%20presentation.pdf.
- [125] M. T. Ashraf, C. Fang, T. Bochenski, I. Cybulska, A. Alassali, A. Sowunmi, R. Husain Farzanah, G. Brudecki, T. Chaturvedi, S. Haris, J. Schmidt, and M. Thomsen, “Estimation of bioenergy potential for local biomass in the united arab emirates,” *Emirates Journal of Food and Agriculture*, vol. 28, p. 1, 01 2016. DOI: 10.9755/ejfa.2015-04-060.
- [126] I. Mubeen and A. Buekens, “Chapter 14 - energy from waste: Future prospects toward sustainable development,” in *Current Developments in Biotechnology and Bioengineering* (S. Kumar, R. Kumar, and A. Pandey, eds.), pp. 283–305, Elsevier, 2019. Available online at <https://www.sciencedirect.com/science/article/pii/B9780444640833000142>.
- [127] A. Ahmed, “UAE no place for old cars,” *Gulf News*, August 2008. Available online at <https://gulfnews.com/uae/transport/uae-no-place-for-old-cars-1.127376>.
- [128] E. Lindstad, D. Polić, A. Rialland, I. Sandaas, and T. Stokke, “Decarbonizing bulk shipping combining ship design and alternative power,” *Ocean Engineering*, vol. 266, p. 112798, 2022. Available online at <https://doi.org/10.1016/j.oceaneng.2022.112798>.
- [129] S. Khan, “AD ports to buy eight bulk carriers and crude tankers in deals worth \$260m,” *The National News*, May 2023. Available online at <http://tinyurl.com/3hnm27x6>.
- [130] M. Grubb and D. Newbery, “UK electricity market reform and the energy transition:emerging lessons,” *The Energy Journal*, vol. 39, no. 6, pp. 1–26, 2018. Available online at <https://doi.org/10.5547/01956574.39.6.mgru>.

- [131] Department for Business, Energy and Industrial Strategy (BEIS), “Historical electricity data: 1920 to 2016,” 2017. Available online at <https://www.gov.uk/government/statistical-data-sets/historical-electricity-data-1920-to-2011>.
- [132] Department for Business, Energy and Industrial Strategy (BEIS), “Digest of UK Energy Statistics,” 2018. Available online at <https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes>.
- [133] Department for Energy Security and Net Zero, “Digest of UK energy statistics (dukes): Foreign trade statistics,” March 28 2014. Available online at <https://www.gov.uk/government/statistics/dukes-foreign-trade-statistics>.
- [134] G. Allen, “Recession and recovery,” 2010. Available online at https://www.parliament.uk/globalassets/documents/commons/lib/research/key_issues/key-issues-recession-and-recovery.pdf.
- [135] S. Pirani, “The Russo-Ukrainian gas dispute of January 2009,” tech. rep., Oxford Institute for Energy Studies, 2010. Available online at <https://www.oxfordenergy.org/2010/11/the-russo-ukrainian-gas-dispute-of-january-2009/>.
- [136] UK Parliament, “Energy price rises and fuel poverty: Key issues for the 2010 parliament,” 2010. Available online at <https://www.parliament.uk/business/publications/research/key-issues-for-the-new-parliament/green-growth/energy-price-rises/>.
- [137] Department of Energy & Climate Change, “Electricity market reform,” 2010. Available online at <https://www.gov.uk/government/consultations/electricity-market-reform>.
- [138] Department of Energy & Climate Change, “Energy act,” 2013. Available online at <https://www.gov.uk/government/collections/energy-act#:~:text=The%20Energy%20Act%20received%20Royal%20Assent%20on%2018%>

- 20December%202013.&text=On%20Thursday%2C%20November%2029th%202012,
alongside%20the%20Annual%20Energy%20StatementThe Energy Act received
Royal Assent on 18 December 2013. Published on 4 October 2013.
- [139] Department for Business, Energy & Industrial Strategy, “Cost of energy review:
Call for evidence,” 2017. Available online at [https://www.gov.uk/government/
calls-for-evidence/cost-of-energy-review-call-for-evidence](https://www.gov.uk/government/calls-for-evidence/cost-of-energy-review-call-for-evidence) Published
on 7 November 2017.
- [140] Great Britain, “The climate change act 2008 (2050 target amendment) order 2019.”
Legislation, June 2019. Available online at [http://www.legislation.gov.uk/
uksi/2019/1056/contents/made](http://www.legislation.gov.uk/ukxi/2019/1056/contents/made). Accessed on 24/12/2019.
- [141] Department for Energy Security and Net Zero and Prime Minister’s Office and
10 Downing Street and Department for Business, Energy & Industrial Strategy
and The Rt Hon Sir Alok Sharma KCMG MP and The Rt Hon Boris Johnson,
“The ten point plan for a green industrial revolution.” Policy Paper, November
18 2020. Available online at [https://www.gov.uk/government/publications/
the-ten-point-plan-for-a-green-industrial-revolution](https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution).
- [142] H. Taylor, “UK coal-burning power facility to stay open two
years longer than planned,” January 11 2023. Available on-
line at [https://www.theguardian.com/environment/2023/jan/11/
uk-coal-burning-power-plant-to-stay-open-two-years-longer-than-planned](https://www.theguardian.com/environment/2023/jan/11/uk-coal-burning-power-plant-to-stay-open-two-years-longer-than-planned).
- [143] J. Crew, “Nearly half of adults struggled to pay energy bills before prices surged –
ons,” April 1 2022. Available online at <http://tinyurl.com/bdc2tukd>.
- [144] P. Bolton, “Imports of fossil fuels from Russia,” March 13 2023. Available online
at <https://commonslibrary.parliament.uk/research-briefings/cbp-9523/>.
- [145] Office for Budget Responsibility, “The changing impact of fossil fuel shocks
on the UK economy,” 2022. Available online at [https://obr.uk/box/
the-changing-impact-of-fossil-fuel-shocks-on-the-uk-economy/](https://obr.uk/box/the-changing-impact-of-fossil-fuel-shocks-on-the-uk-economy/).

- [146] Department for Energy Security and Net Zero, “Digest of UK energy statistics (DUKES): Electricity,” 2023. Available online at <https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes>.
- [147] L. Roberts, “What to do if your business energy supplier goes bust or ceases trading,” *Bionic*, November 2022. Available online at <https://bionic.co.uk/business-energy/guides/what-if-your-business-energy-supplier-goes-bust/>.
- [148] L. Roberts, “What is going on with energy prices in the UK?,” *Bionic Blog*, 2023.
- [149] “Rising cost of living in the UK.” Research Briefing, January 2024.
- [150] “UK NBP natural gas spot price (historical),” 2022. Available online at <https://erce.energy/analytics/5-gas-spot-price/>.
- [151] “UK NBP natural gas futures,” 2022. Available online at <https://www.ice.com/products/910/UK-Natural-Gas-Futures/data?marketId=5508884>.
- [152] N. Walker, “Conflict in ukraine: A timeline (2014 - eve of 2022 invasion),” 2023. Available online at <https://commonslibrary.parliament.uk/research-briefings/cbp-9476/>.
- [153] Department for Business, Energy & Industrial Strategy, “Net zero strategy: Build back greener,” *GOV.UK*, Oct 2021. Available online at <https://www.gov.uk/government/publications/net-zero-strategy>.
- [154] H. A. Daggash, *The Implications of the Paris Agreement on Electric Power Systems Transitions: Technoeconomic and Sociopolitical Assessments of the United Kingdom and Nigeria*. PhD thesis, Imperial College of Science, Technology and Medicine, Centre for Environmental Policy, July 2020.
- [155] M. Greaves, “British carbon tax leads to 93% drop in coal-fired electricity,” January 27 2020. Available online at <https://www.ucl.ac.uk/news/2020/>

- jan/british-carbon-tax-leads-93-drop-coal-fired-electricity#:~: text=The%20Carbon%20Price%20Support%20was,EU%20Emissions%20Trading% 20System%20permits.
- [156] Department for Business, Energy and Industrial Strategy (BEIS), “Valuation of greenhouse gas emissions: For policy appraisal and evaluation,” September 2 2021. Available online at <http://tinyurl.com/4pbrvsxk>.
- [157] Y. W. Pratama and N. Mac Dowell, “Carbon capture and storage investment: Fiddling while the planet burns,” *One Earth*, vol. 5, no. 4, pp. 434–442, 2022. Available online at <https://doi.org/10.1016/j.oneear.2022.03.008>.
- [158] UK Government, “Net zero government: Emissions roadmap,” 2024. Available online at <https://assets.publishing.service.gov.uk/media/6569cb331104cf000dfa7352/net-zero-government-emissions-roadmap.pdf>.
- [159] SP Global Commodity Insights, “Benchmark uk offshore wind load factors seen rising to 57% in 2030: Beis,” 2024. Available online at <https://tinyurl.com/ybh95v72>.
- [160] C. F. Heuberger and N. Mac Dowell, “Real-world challenges with a rapid transition to 100 Available online at <https://doi.org/10.1016/j.joule.2018.02.002>.
- [161] M. O’Malley, “Editorial: Towards 100 DOI: 10.1109/TPWRS.2022.3178170.
- [162] SVEBIO, “About bioenergy,” Apr 2017. Available online at <https://www.svebio.se/en/about-bioenergy/>.
- [163] U. N. C. Change, “Green finance and the aggregation of swedish local government investment projects— sweden.” Available online at https://unfccc.int/files/na/application/pdf/2017_la_fact_sheet_green_bonds_sweden.pdf.
- [164] B. Johansson, “Biomass in sweden - historic development and future potential under new policy regimes,” 05 2004. Available online at <https://portal.research.lu.se/files/5603915/2797226.pdf>.

- [165] L. Pelkmans, L. Similä, and E. Mäki, “Implementation of bioenergy in finland - 2021 update,” *IEA Bioenergy*, 2021. Available online at https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_Finland_final.pdf.
- [166] M. of Economic Affairs and Employment, “Feed-in tariff for renewable energy.” Available online at <https://tem.fi/en/feed-in-tariff-for-renewable-energy>.
- [167] A. Markandya, I. Arto, M. González-Eguino, and M. V. Román, “Towards a green energy economy? tracking the employment effects of low-carbon technologies in the european union,” *Applied Energy*, vol. 179, pp. 1342–1350, 2016. Available online at <https://doi.org/10.1016/j.apenergy.2016.02.122>.
- [168] G. Allan, K. Connolly, P. McGregor, and A. G. Ross, “A new method to estimate the economic activity supported by offshore wind: A hypothetical extraction study for the united kingdom,” *Wind Energy*, vol. 24, no. 8, pp. 887–900, 2021. Available online at <https://doi.org/10.1002/we.2607>.
- [169] The United Arab Emirates’ Government Portal, “Fact sheet.” Available online at <https://u.ae/en/about-the-uae/fact-sheet>.
- [170] Embassy of the United Arab Emirates - Washington, DC, “Political system & governance.” Available online at <https://www.uae-embassy.org/discover-uae/governance/political-system-governance>.
- [171] The United Arab Emirates’ Government Portal, “The federal national council.” Available online at <https://u.ae/en/about-the-uae/the-uae-government/the-federal-national-council->.
- [172] HE Chancellor Ali Mohammed Alblooshi, Abu Dhabi Attorney General, “Attorney general message.” Available online at <https://www.adjd.gov.ae/sites/Authoring/Pages/Attorney-General-Message.aspx>.

- [173] Emirates News Agency-WAM, “Open-door policy was the hallmark of zayed’s rule,” November 8 2004. Available online at <https://wam.ae/en/details/1395227312993>.
- [174] S. R. Anjana Sankar, “Abu Dhabi municipality adopts open-door policy,” *Gulf News*, May 2016. Available online at <https://gulfnews.com/uae/abu-dhabi-municipality-adopts-open-door-policy-1.1834933>.
- [175] K. T. Abdurabb, “UAE open door policy triggers investment flow,” March 2013. Available online at <https://www.arabnews.com/economy/uae-open-door-policy-triggers-investment-flow>.
- [176] The United Arab Emirates’ Government Portal, “The UAE’s response to climate change.” Available online at <https://u.ae/en/information-and-services/environment-and-energy/climate-change/theuaesresponsetoclimatechange>.
- [177] United Arab Emirates Ministry of Climate Change & Environment, “HE Mariam Almheiri launches UAE’s ‘integrated emission quantification tool’ to track emissions and air quality,” December 2023. Available online at <http://tinyurl.com/2ats85jz>.
- [178] Emirates News Agency - WAM, “Zayed considered environment as,” April 2005. Available online at <https://wam.ae/ru/details/1395227411559>.
- [179] United Arab Emirates, “Federal law no.7 of 1993 establishing federal environment authority.” UNEP - LEAP, 1993. Available online at <https://leap.unep.org/en/countries/ae/national-legislation/federal-law-no7-1993-establishing-federal-environment-authority>.
- [180] LSE Middle East Centre, “Export composition and economic growth in the UAE.” in collaboration with the American University of Sharjah. Available online at <https://www.lse.ac.uk/middle-east-centre/research/>

- collaboration-programme/2019-20/athanasia-kalaitzi LSE PI: Dr. Athanasia Kalaitzi, Co-PI: Dr. Samer Kherfi, Duration: August 2019 – October 2021.
- [181] Government of Abu Dhabi, *The Abu Dhabi Economic Vision 2030*. 2008. Available online at <https://www.actvet.gov.ae/en/Media/Lists/ELibraryLD/economic-vision-2030-full-versionEn.pdf>.
- [182] R. Uppal, “UAE’s non-oil foreign trade jumps 17% in 2022,” February 2023. Available online at <https://www.reuters.com/markets/uaes-non-oil-foreign-trade-jumps-17-2022-2023-02-06/>.
- [183] A. D. Paola, “UAE accelerates plan to increase its oil production capacity,” 2022. Available online at <https://www.bloomberg.com/news/articles/2022-09-19/uae-accelerates-plan-to-increase-its-oil-production-capacity?leadSource=uverify%20wall>.
- [184] GlobalData, “Oil & gas field profile: Hail & ghasha conventional gas field, UAE.” Updated July 30, 2023. Available online at <https://www.offshore-technology.com/data-insights/oil-gas-field-profile-hail-ghasha-conventional-gas-field-uae/>.
- [185] C. Klein, “Crude oil imports from the u.a.e. to japan fy 2022, by oil type,” June 2023. Available online at <https://www.statista.com/statistics/761790/japan-crude-oil-imports-from-uae-by-oil-type/#:~:text=In%20the%20fiscal%20year%202022,at%20around%2017.7%20million%20kiloliters>.
- [186] Ministry of Environment, Forest and Climate Change, “Net zero emissions target.” Posted On: 03 AUG 2023 5:04PM by PIB Delhi, 2023. Available online at <https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1945472#:~:text=India%20C%20at%20the%2026th%20session,achieve%20net%20zero%20by%202070>.
- [187] India Briefing from Dezan Shira & Associates, “India, UAE commence crude oil trade using local currency settlement (lcs) framework,” Available online at <http://tinyurl.com/y9t5sust>.

- [188] Ministry of Climate Change and Environment, UAE, “Accelerating action towards a green, inclusive, determined contribution for the UAE: Third update of second nationally determined contribution for a sustainable and resilient economy,” 2023. Available online at <http://www.moccae.gov.ae>.
- [189] Zawya, “TA’ZIZ progresses with low-carbon ammonia shareholder agreement,” January 18 2023. Available online at <https://www.zawya.com/en/press-release/companies-news/taziz-progresses-with-low-carbon-ammonia-shareholder-agreement-a0zxqo6i>.
- [190] B. Cushman-Roisin and B. T. Cremonini, “Chapter 1 - materials,” in *Data, Statistics, and Useful Numbers for Environmental Sustainability* (B. Cushman-Roisin and B. T. Cremonini, eds.), pp. 1–16, Elsevier, 2021. Available online at <https://doi.org/10.1016/B978-0-12-822958-3.00012-1>.
- [191] ADNOC, “ADNOC and Masdar’s carbon capture facility holds key to limiting industrial CO₂ emissions,” Jan. 2017. Available online at <https://t.ly/m-1W6>.
- [192] A. Henni, “ADNOC harnesses CO₂ to increase oil recovery,” *Hart Energy*, Feb. 2018. Available online at <https://www.hartenergy.com/exclusives/adnoc-harnesses-co2-increase-oil-recovery-30742>.
- [193] J. Mayer, G. Bachner, and K. Steininger, “Macroeconomic implications of switching to process-emission-free iron and steel production in europe,” *Journal of Cleaner Production*, vol. 210, 11 2018. DOI: 10.1016/j.jclepro.2018.11.118.
- [194] S. on the Net, “Electric arc furnace steelmaking costs 2023.” Available online at <https://www.steelonthenet.com/cost-eaf.html> Accessed: February 9, 2024.
- [195] TradeKey, “Hms 1 scrap exporters.” Available online at <https://uae.tradekey.com/hms-1-scrap.htm> Accessed: February 9, 2024.
- [196] G. of Ras Al Khaimah, “About the emirate.” Available online at [https://mun.rak.ae/en/pages/about-rak.aspx#:~:text=Ras%20Al%](https://mun.rak.ae/en/pages/about-rak.aspx#:~:text=Ras%20Al%20Khaimah)

- 20Khaimah%20is%20located, and%20overlooks%20the%20Arabian%20Gulf.
Accessed: February 9, 2024.
- [197] D. Energy, “Operations.” Available online at <https://www.dolphinenergy.com/operations> Accessed: February 9, 2024.
- [198] ADNOC, “ADNOC sends first low-carbon ammonia shipment from the UAE to Germany.” Available online at <https://adnoc.ae/en/news-and-media/press-releases/2022/adnoc-sends-first-low-carbon-ammonia-shipment-from-the-uae-to-germany#:~:text=Abu%20Dhabi%20%E2%80%93%20September%201%2C%202022,to%20be%20shipped%20to%20Germany>.
- [199] A. Ason, “International gas contracts,” *The Oxford Institute For Energy Studies*, 2022. Available online at <https://www.oxfordenergy.org/publications/international-gas-contracts/>.
- [200] A. R. Cabral, “Electric car maker NWTN to expand Abu Dhabi factory in green automotive push,” *The National*, July 2023. Available online at <https://shorturl.at/ipq0V>.
- [201] M. Intelligence, “Used cars market in UAE size & share analysis - growth trends & forecasts (2024 - 2029).” Online. Available online at <https://www.mordorintelligence.com/industry-reports/united-arab-emirates-used-car-market>.
- [202] U. Nations, “Gross value added by kind of economic activity at constant (2015) prices - national currency,” 2019. Available online at <https://data.un.org/Data.aspx?q=united+arab+emirates&d=SNAAMA&f=grID%3A202%3BcurrID%3ANCU%3BpcFlag%3A0%3BcrID%3A784>.
- [203] ITP, “Emirates water and electricity company targets 50% reduction in co₂ emissions by 2025,” *Arabian Business*, May 3 2021. Available online at <https://shorturl.at/ayzZ2>.

- [204] Emirates Water and Electricity Company, “Noor Abu Dhabi.” Available online at <https://www.ewec.ae/en/power-plants/noor-abu-dhabi#:~:text=Located%20at%20Sweihan%2C%20Abu%20Dhabi,%20features%203.2%20million%20solar%20panels>.
- [205] Square Yards, “Unfolding 10 mind blowing facts about dubai mall,” *Square Yards Blog*, October 19 2022. Available online at <https://www.squareyards.ae/blog/dubai-mall-facts-ttart#:~:text=The%20mall%20spans%20an%20area,%20km>.
- [206] Clean Hydrogen Partnership - European Commission, “Study on hydrogen in ports and industrial coastal areas,” March 2023. Available online at <https://shorturl.at/fuyIJ>.
- [207] C. Jallal, “Pilot projects prepare the path to a greener future,” Aug 2023. Available online at <https://www.rivieramm.com/news-content-hub/news-content-hub/pilot-projects-prepare-the-path-to-a-greener-future-77219>.
- [208] Fly Emirates, “Emirates operates milestone demonstration flight powered with 100% sustainable aviation fuel,” January 2023. Available online at <https://shorturl.at/ag1TZ>.
- [209] IATA, “Developing sustainable aviation fuel (SAF).” Available online at <https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/>.
- [210] U.S. Department of Energy, “Sustainable aviation fuel.” Available online at https://afdc.energy.gov/fuels/sustainable_aviation_fuel.html#:~:text=ASTM%20approved%20in%20June%202009%20with%20a%2050%25%20blend%20limit.&text=Triglyceride%20feedstocks%20such%20as%20plant,followed%20by%20hydroisomerization%20and%20hydrocracking.
- [211] G. C. Congress, “Emirates, shell aviation sign agreement for SAF supply at airline’s dubai hub; tracking via blockchain,” October 2023. Available online at <https://www.greencarcongress.com/2023/10/20231003-emirates.html>.

- [212] C. Ganzer and N. M. Dowell, “Pathways to net zero for UK power and industry – technologies, emissions, GVA, jobs,” in *6th International Conference on Greenhouse Gas Control Technologies, GHGT-16*, (Lyon, France), Sargent Centre for Process Systems Engineering, Imperial College London, UK and Centre for Environmental Policy, Imperial College London, UK, October 2022.
- [213] P. Patrizio, N. Sunny, and N. Mac Dowell, “Inefficient investments as a key to narrowing regional economic imbalances,” *iScience*, vol. 25, no. 3, p. 103911, 2022. Available online at <https://doi.org/10.1016/j.isci.2022.103911>.
- [214] National Renewable Energy Laboratory (NREL), “JEDI: Jobs & economic development impact models.” Website. Available online at <https://www.nrel.gov/analysis/jedi/international.html>.
- [215] “Number of construction workers in the united arab emirates from 2014 with forecasts to 2021 (in 1,000s).” Statista, 2024. Available online at <https://www.statista.com/statistics/1351180/uae-number-of-construction-workers/>.
- [216] “Number of construction workers in saudi arabia from 2014 with a forecast for 2020 (in 1,000s).” Statista, 2024. Available online at <https://www.statista.com/statistics/1351197/saudi-arabia-number-of-construction-workers/#:~:text=In%202020%2C%20it%20was%20estimated,decrease%20to%20about%20.1%20million.>
- [217] A. S. Matthew Martin, “Abu dhabi said to revive debt plan for first nuclear power plant,” September 2015. Available online at <https://shorturl.at/KMW02>.
- [218] “Nuclear power in the united arab emirates.” Updated January 2024, 2024. Available online at <https://world-nuclear.org/information-library/country-profiles/countries-t-z/united-arab-emirates.aspx>.
- [219] PJSC, “Hassyan power complex, dubai, UAE.” Available online at <https://www.power-technology.com/projects/hassyan-clean-coal-project-dubai/?cf-view&cf-closed>.

- [220] United Arab Emirates Ministry of Cabinet Affairs, “Agriculture environment and energy.” Federal Competitiveness and Statistics Centre, 2020. Available online at <https://fcsc.gov.ae/en-us/Pages/Statistics/Statistics-by-Subject.aspx>.
- [221] NS Energy, “Noor Abu Dhabi Solar Power Project.” Available online at <https://www.nsenergybusiness.com/projects/noor-abu-dhabi-solar-power-project/>.
- [222] Gulf Cooperation Council Interconnection Authority, “The interconnection project.” Available online at https://www.gccia.com.sa/P/the_interconnection_project/55.
- [223] Power Technology, “Hatta Pumped Storage Hydropower Plant, UAE.” Available online at <https://www.power-technology.com/projects/hatta-pumped-storage-hydropower-plant-uae/?cf-view> Accessed on: Insert Access Date.
- [224] S. Öberg, M. Odenberger, and F. Johnsson, “Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems,” *International Journal of Hydrogen Energy*, vol. 47, no. 1, pp. 624–644, 2022. Available online at <https://doi.org/10.1016/j.ijhydene.2021.10.035>.
- [225] S. A. Alnaqbi, S. Alasad, H. Aljaghoub, A. H. Alami, M. A. Abdelkareem, and A. G. Olabi, “Applicability of hydropower generation and pumped hydro energy storage in the middle east and north africa,” *Energies*, vol. 15, no. 7, p. 2412, 2022. Available online at <https://doi.org/10.3390/en15072412>.
- [226] B. Standard, “Ultratech invests \$101.1 mn in UAE-based rakwct, acquires 29.39% share.” Business Standard, January 27 2024. Available online at <https://t.ly/-2jk9>.
- [227] “Ccs from cement production.” Available online at <https://www.ctc-n.org/technologies/ccs-cement-production> Accessed: 27th January 2024.

- [228] Global Cement Magazine, “Total installed capacity of cement plants in the united arab emirates (UAE) 2019, by producer.” Statistic as Excel data file, 2019.
- [229] P. S. Fennell, S. J. Davis, and A. Mohammed, “Decarbonizing cement production,” *Joule*, vol. 5, no. 6, pp. 1305–1311, 2021. Available online at <https://doi.org/10.1016/j.joule.2021.04.011>.
- [230] T. Hills, D. Leeson, N. Florin, and P. Fennell, “Carbon capture in the cement industry: Technologies, progress, and retrofitting,” *Environmental Science & Technology*, vol. 50, no. 1, pp. 368–377, 2016. Available online at <https://doi.org/10.1021/acs.est.5b03508> PMID: 26630247.
- [231] M. Watts, “United iron & steel company to invest \$138m in UAE rolling mill,” *MEED*, April 15 2014. Available online at <https://www.meed.com/united-iron-steel-company-to-invest-138m-in-uae-rolling-mill/>.
- [232] International Energy Agency, “Iron and steel technology roadmap: Towards more sustainable steelmaking.” This publication is subject to specific restrictions that limit its use and distribution. The terms and conditions are available online at www.iea.org/t&c/. Source: IEA. All rights reserved.
- [233] G. E. Monitor, “Ghc emirates steel industries Abu Dhabi plant,” 2023. Available online at https://www.gem.wiki/GHC_Emirates_Steel_Industries_Abu_Dhabi_plant.
- [234] Element Energy Limited, “Industrial carbon capture business models,” tech. rep., The Department for Business, Energy and Industrial Strategy, Suite 1, Bishop Bateman Court, Thompson’s Lane, Cambridge CB5 8AQ, October 2018. Supported by: Element Energy Limited, Tel: 01223 852499.
- [235] S. S. Tam, “Gasification plant cost and performance optimization,” 5 2002. Available online at <https://www.osti.gov/biblio/837331>.
- [236] P. E. Duarte, “HYL direct reduction technology: Adaptations for the indian market,” *HYL*. Available online

- at <https://www.energiron.com/wp-content/uploads/2019/05/2004-HYL-Direct-Reduction-Technology-Adaptations-for-the-Indian-Market.pdf>.
- [237] Y. Cao, Z. Gao, J. Jin, H. Zhou, M. Cohron, H. Zhao, H. Liu, and W. Pan, “Synthesis gas production with an adjustable H_2/CO ratio through the coal gasification process: Effects of coal ranks and methane addition,” *Energy & Fuels*, vol. 22, no. 3, pp. 1720–1730, 2008. 10.1021/ef7005707.
- [238] M. De Santis, A. Di Donato, T. Kempken, T. Hauck, M. Draxler, A. Sormann, P. Queipo, W. Szulc, D. Croon, J.-T. Ghenda, C. Wang, J.-C. Pierret, and J. Borlee, “Green steel for europe investment needs,” tech. rep., March 2021. This project has received funding from the European Union under grant agreement NUMBER — 882151 — GREENSTEEL.
- [239] WAM, “Emirates steel’s exports expand to 56 international markets,” Mar. 2022. Available online at <https://www.wam.ae/en/details/1395303030757#:~:text=Emirates%20Steel%20has%20a%20capacity,diversification%20by%20boosting%20its%20exports>. Accessed on January 28, 2024.
- [240] COSASTEEL, “Steel company in UAE.” Available online at <https://www.cosasteel.com/steel-company-uae/> Accessed on March 18, 2022.
- [241] Emirates Steel Arkan, “Our journey: A history of looking to the future.” Available online at <https://www.emiratessteelarkan.com/our-journey/#:~:text=Its%20capacity%20of%20500%2C000%20metric,and%20the%20UAE’s%20steel%20industry>.
- [242] A. Rauwerdink, “Steel production through electrolysis: Impacts for electricity consumption.” VP, Business Development, October 2019.
- [243] “ESFC: International investment, global engineering and financial consulting.” Website, 2024. Available online at <https://esfcinvestment.com/> Accessed on January 28, 2024.

- [244] D. Johansson, P. Åke Franck, and T. Berntsson, “CO₂ capture in oil refineries: Assessment of the capture avoidance costs associated with different heat supply options in a future energy market,” *Energy Conversion and Management*, vol. 66, pp. 127–142, 2013. Available online at <https://doi.org/10.1016/j.enconman.2012.09.026>.
- [245] Organization of the Petroleum Exporting Countries, “UAE facts and figures.” Website, 2024. Available online at <https://www.opec.org/uae-facts-and-figures> Accessed on January 28, 2024.
- [246] Y. Saba, “UAE oil giant raises climate goal ahead of key UN summit,” *Reuters*, July 2023. Available online at <https://www.reuters.com/article/us-emirates-oil-climatechange-idUSKBN2F20QK> Accessed on January 28, 2024.
- [247] J. van Straelen, F. Geuzebroek, N. Goodchild, G. Protopapas, and L. Mahony, “CO₂ capture for refineries, a practical approach,” in *Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9)*, (Amsterdam, The Netherlands), Shell Global Solutions, Shell Global Solutions, 2008.
- [248] Q. Zou, C. Yi, K. Wang, X. Yin, and Y. Zhang, “Global LNG market: supply-demand and economic analysis,” *IOP Conference Series: Earth and Environmental Science*, vol. 983, p. 012051, mar 2022. Available online at <https://doi.org/10.1088/1755-1315/983/1/012051>.
- [249] Staff Writer, “ADNOC awards \$80 million contract for Hail and Ghasha gas development,” *Oil & Gas Middle East*, Jan 2023. Available online at <https://www.oilandgasmiddleeast.com/news/adnoc-awards-80-million-contract-for-hail-and-ghasha-gas-development>.
- [250] B. Songhurst, “LNG plant cost reduction 2014–18,” tech. rep., The Oxford Institute for Energy Studies, 2019. <https://www.oxfordenergy.org/publications/lng-plant-cost-reduction-2014-18/>.

- [251] European Technology Platform for Zero Emission Fossil Fuel Power Plants, “The costs of CO₂ capture, transport and storage,” tech. rep., Advisory Council of the European Technology Platform for Zero Emission Fossil Fuel Power Plants, Year.
- [252] S&P Global Commodity Insights, “FEATURE: ADNOC’s new Fujairah LNG project seeks to capitalize on global thirst for energy,” *SP Global Commodity Insights*, Jul 2022. Available online at <https://t.ly/DNrtK>.
- [253] “Chapter 5 - natural gas liquefaction cycle enhancements and optimization,” in *Handbook of Liquefied Natural Gas* (S. Mokhatab, J. Y. Mak, J. V. Valappil, and D. A. Wood, eds.), pp. 229–257, Boston: Gulf Professional Publishing, 2014. Available online at <https://doi.org/10.1016/B978-0-12-404585-9.00005-2>.
- [254] Timera Energy, “The value impact of LNG carbon emissions,” *Timera Energy*, Mar 2021. Available online at <https://timera-energy.com/the-value-impact-of-lng-carbon-emissions/> Accessed on March 29, 2021.
- [255] K. Singh, “Vedanta aluminium sets capex target of \$300 m for current fiscal,” *Businessline*, May 2021. Available online at <https://www.thehindubusinessline.com/companies/vedanta-aluminium-sets-capex-target-of-300-m-for-current-fiscal/article34557268.ece> Updated - May 18, 2021.
- [256] “Climate and carbon footprint.” Available online at <https://aluminium.fr/en/climate-and-carbon-footprint/>.
- [257] GlobalData, “Asia to lead global ammonia capacity additions.” News Analysis, September 2022. Available online at <https://www.offshore-technology.com/news/asia-to-lead-global-ammonia-capacity-additions/>.
- [258] International Energy Agency (IEA), “The future of hydrogen assumptions annex,” YEAR. Available online at <https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf>.

- [259] A. Puri-Mirza, “Production nitrogen content of ammonia in UAE by type 2010-2018.” Statista, 2021. Available online at <https://www.statista.com/statistics/761200/uae-nitrogen-content-of-ammonia-production-by-type/>.
- [260] I. Sen, “Shareholders sign taziz blue ammonia agreement,” *MEED*, January 2023. Available online at <https://www.meed.com/shareholders-sign-agreement-for-taziz-blue-ammonia-facility>.
- [261] “Methodology and specifications guide: Global hydrogen & ammonia.” Available online at www.spglobal.com/commodityinsights Latest update: October 2023.
- [262] IEAGHG, “Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS,” technical report, IEAGHG, 2017. Available online at https://www.ieaghg.org/docs/General_Docs/2017-02.pdf.
- [263] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, “Hydrogen supply chain: Evidence base.” GOV.UK, November 30 2018. Available online at <https://www.gov.uk/government/publications/hydrogen-supply-chain-evidence-base>.
- [264] P. Fragiaco and M. Genovese, “Numerical simulations of the energy performance of a pem water electrolysis based high-pressure hydrogen refueling station,” *International Journal of Hydrogen Energy*, vol. 45, no. 51, pp. 27457–27470, 2020. Available online at <https://doi.org/10.1016/j.ijhydene.2020.07.007>.
- [265] J. Benny, “Site preparation under way for first phase of multi-billion dollar projects at ta’ziz,” November 4 2022. Available online at <https://t.ly/0n2mq>.
- [266] M. Sendi, M. Bui, N. Mac Dowell, and P. Fennell, “Geospatial analysis of regional climate impacts to accelerate cost-efficient direct air capture deployment,” *One Earth*, vol. 5, no. 10, pp. 1153–1164, 2022. Available online at <https://doi.org/10.1016/j.oneear.2022.09.003>.

- [267] Seez, “Average car listing price in the united arab emirates in 2018 and 2019 (in emirati dirhams),” 2020, March 1. Available online at <https://www.statista.com/statistics/1156189/uae-average-car-listing-price/>.
- [268] P. Bazaar, “What is the cost of car insurance in Dubai?.” Available online at <https://www.policybazaar.ae/what-is-the-cost-of-car-insurance-in-dubai-ciart/#:~:text=How%20Much%20Does%20Car%20Insurance,driving%20history%2C%20driving%20experience%20etc.>
- [269] H. Zhang, W. Chen, and W. Huang, “Times modelling of transport sector in China and USA: Comparisons from a decarbonization perspective,” *Applied Energy*, vol. 162, pp. 1505–1514, 2016. Available online at <https://doi.org/10.1016/j.apenergy.2015.08.124>.
- [270] Statista, “Electric vehicles - united arab emirates.” Available online at <https://www.statista.com/outlook/mmo/electric-vehicles/united-arab-emirates>.
- [271] D. Cars, “Used hybrid cars for sale in UAE.” Available online at <https://www.dubicars.com/uae/used/hybrid-cars>.
- [272] Phys.org, “Hybrid cars – pros and cons,” January 19 2006. Available online at [https://phys.org/news/2006-01-hybrid-cars-pros-cons.html#:~:text=Hybrids%20are%20the%20most%20gasoline,to%2060%20mpg%20\(claimed\)](https://phys.org/news/2006-01-hybrid-cars-pros-cons.html#:~:text=Hybrids%20are%20the%20most%20gasoline,to%2060%20mpg%20(claimed)).
- [273] J. Fossdyke, “Toyota mirai hydrogen UK pricing.” motor1.com, May 5 2021. Available online at <https://uk.motor1.com/news/505291/toyota-mirai-hydrogen-uk-pricing/>.
- [274] “Toyota coaster toyota coaster 2023 diesel 4.2l.” Available online at <https://www.dubicars.com/2024-toyota-coaster-toyota-coaster-2023-diesel-42l-528354.html> Updated: 28 Jan, 2024.

- [275] Sustainable Bus Editorial, “Major fuel cell bus order for solaris from rvk cologne: 15 solaris hydrogen on delivery,” March 13 2020. Available online at <https://t.ly/1qrzp>.
- [276] L. Collins, “Europe’s largest ever order for hydrogen buses awarded to poland’s solaris after €272m tender,” September 12 2023. Available online at <https://rb.gy/rwg2ub>.
- [277] R. Lydall, “Won’t get fuelled again! london electric buses powered by ‘world-first’ rapid charging technology,” October 28 2022. Available online at <https://www.standard.co.uk/news/transport/london-buses-electric-rapid-charging-bexleyheath-b1035299.html#:~:text=The%20buses%20cost%20about%20%C2%A3,diesel%20or%20hybrid%20double%20decker>.
- [278] T. Nguyen, “Australia’s first electric bus hits the market! 2022 joylong e6 priced above ford transit, mercedes sprinter, toyota hiace commuter and volkswagen crafter minibus,” June 3 2022. Available online at <https://rb.gy/cfkkji>.
- [279] S. Visawanathan, “Best commercial vehicles in UAE 2021-22: Price, specifications, mileage, colors, images,” August 16 2021. Available online at <https://www.cars24.com/ae/blog/best-commercial-vehicles-in-uae/>.
- [280] Toyota, “Proace verso.” Available online at <https://www.toyota.co.uk/new-cars/proace-verso>.
- [281] S. Ranganathan, “Hybrid buses costs and benefits,” Available online at https://www.eesi.org/files/eesi_hybrid_bus_032007.pdf.
- [282] C. Barnet, “Tesla opens order book for its semi to UK buyers,” May 16 2022. Available online at <https://www.commercialmotor.com/product-news/article/tesla-opens-order-book-its-semi-uk-buyers>.
- [283] dubizzle, “Buy & sell cars online in all cities (UAE), UAE.” Available online at <https://uae.dubizzle.com/motors/used-cars/>.

- [284] D. Hawley, “How much does it cost to charge an ev?,” 2022, September 20. Available online at <https://www.jdpower.com/cars/shopping-guides/how-much-does-it-cost-to-charge-an-ev#:~:text=Most%20EVs%20can%20generally%20travel,and%20cost%20%2410%2D%2414>.
- [285] T. Moloughney, “2023 toyota prius prime: Insideevs 70 mph range test.” InsideEVs, April 5 2023. Available online at <https://insideevs.com/reviews/660293/2023-toyota-prius-prime-range-test/#:~:text=In%20addition%20to%20the%20great,of%2025%20miles%20per%20charge>.
- [286] S. B. Editorial, “Electric bus range, focus on electricity consumption. a sum-up,” November 28 2023. Available online at <https://www.sustainable-bus.com/news/electric-bus-range-electricity-consumption/>.
- [287] Tesla, “Semi: The future of trucking is electric.” Available online at https://www.tesla.com/en_gb/semi#:~:text=With%20less%20than%202%20kWh,miles%20on%20a%20single%20charge.
- [288] Ministry of Energy Infrastructure, “Updated UAE energy strategy 2050,” tech. rep., July 2030.
- [289] S. T., “Automotive fleet market size - UAE,” September 6 2021. Available online at <https://askwonder.com/research/automotive-fleet-market-size-uae-5h1c3e9m8>.
- [290] United States Environmental Protection Agency (EPA), “Greenhouse gas emissions from a typical passenger vehicle,” 2023. Available online at <https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle> Last updated on August 28, 2023.
- [291] R. Technology, “Etihad rail, united arab emirates (UAE),” September 8 2022. Available online at <https://www.railway-technology.com/projects/etihad-rail/?cf-view>.

- [292] A. Talaiekhosani, O. Ghaffarpasand, M. R. Talaie khosani, N. Neshat, and B. Eydivandi, "Evaluation of emission inventory of air pollutants from railroad and air transportation in isfahan metropolitan in 2016," *Journal of Air Pollution and Health*, vol. 2, pp. 1–18, 03 2017.
- [293] MEED Editorial, "ADNOC axes plan for shah sulphur pipeline," May 5 2010. Available online at <https://www.meed.com/adnoc-axes-plan-for-shah-sulphur-pipeline/>.
- [294] mydubaistay, "Dubai metro time table." Available online at <http://www.mydubaistay.com/en/dubai-metro-routes.aspx>.
- [295] R. Gopalan, M. Ravibabu, and S. Sahu, "Alternative approach to costing on indian railways: Linking outputs and expenses to activity centres," *Asian Transport Studies*, vol. 6, p. 100001, 2020. Available online at <https://doi.org/10.1016/j.eastsj.2020.100001>.
- [296] Global Railway Review, "Etihad rail boosts its fleet size with order for 38 emd locomotives," February 27 2020. Available online at <https://www.globalrailwayreview.com/news/97440/etihad-rail-38-locomotives-progress-rail/>.
- [297] A. Business, "Fifty new Dubai metro trains set to be deployed," November 8 2020. Available online at <https://www.arabianbusiness.com/industries/transport/454266-fifty-new-dubai-metro-trains-set-to-be-deployed#:~:text=Seats%20in%20the%20new%20trains,643%20riders%20to%20696%20riders>.
- [298] Mitsubishi Heavy Industries Technical Review, "The Dubai metro, the world's longest fully automated metro network," vol. 49, June 2012. Available online at <https://www.mhi.co.jp/technology/review/pdf/e492/e492001.pdf>.
- [299] Made-in-China, "Vessel price," 2023.

- [300] J. Atchison, “Retrofitting vessels for ammonia fuel: New technical study from grieg star,” March 21 2023. Available online at <https://rb.gy/wufpwp>.
- [301] D. Shafran, “How much fuel does a cargo ship use? ship fuel consumption explained with examples,” 2023. Available online at <https://maritimepage.com/fuel-consumption-how-much-fuel-cargo-ship-use/#:~:text=For%20example%2C%20a%20cargo%20ship%20with%20a%20capacity%20of%2050%2C000,also%20increase%20fuel%20consumption%20rates.> Updated on November 16, 2023.
- [302] J. Dawson, L. Pizzolato, S. Howell, L. Copland, and M. Johnston, “Temporal and spatial patterns of ship traffic in the canadian arctic from 1990 to 2015 + supplementary appendix 1: Figs. s1–s7 (see article tools),” *ARCTIC*, vol. 71, p. 15, 02 2018. DOI: 10.14430/arctic4698.
- [303] SeaPlace, “Ship maintenance cost: How can owners reduce it?.” Available online at <https://www.seaplace.es/maintenance-cost-how-can-owners-reduce-it/> Accessed in 2023.
- [304] “Sea route & distance,” 2023.
- [305] UNCTAD, “Maritime profile: United arab emirates,” 2022. Available online at <https://unctadstat.unctad.org/CountryProfile/MaritimeProfile/en-GB/784/index.html>.
- [306] U.S. Energy Information Administration (EIA), “Carbon dioxide emissions coefficients.”
- [307] Pilot Institute, “From gliders to jumbos: How much do airplanes cost?.” Available online at <https://pilotinstitute.com/how-much-do-airplanes-cost/> Posted on February 16, 2023.
- [308] M. Fioriti, V. Vercella, and N. Viola, “Cost-estimating model for aircraft maintenance,” *Journal of Aircraft*, vol. 55, no. 4, pp. 1564–1575, 2018. Available online at <https://doi.org/10.2514/1.C034664>.

- [309] Epic Flight Academy, “How fast do commercial planes fly?.” Available online at <https://epicflightacademy.com/flight-school-faq/how-fast-do-commercial-planes-fly/#:~:text=FAQ%20%C2%BB%20Careers%20%20General%20FAQs%20%C2%BB,%3B%20547%E2%80%9393575%20mph>.
- [310] Fly Emirates, “Emirates aircraft cover 432 million kilometres across the globe in six months,” July 28 2016. Available online at <https://rb.gy/utnn01>.
- [311] PlaneSpotters.NET, “Emirates fleet details and history.” Available online at <https://www.planespotters.net/airline/Emirates>.
- [312] PlaneSpotters.NET, “Etihad airways fleet details and history.” Available online at <https://www.planespotters.net/airline/Etihad-Airways>.
- [313] PlaneSpotters.NET, “Air arabia fleet details and history.” Available online at <https://www.planespotters.net/airline/Air-Arabia>.
- [314] T. Robinson, “ADNOC natural gas, lng ipo seen as ‘highly feasible’ amid broader expansion plans,” February 9 2023. Available online at <https://rb.gy/xqc1yw>.
- [315] MEED Editorial, “UAE purchases gas from Dolphin pipeline at reduced rate,” May 16 2008. Available online at <https://www.meed.com/uae-purchases-gas-from-dolphin-pipeline-at-reduced-rate/>.
- [316] “United arab emirates gasoline prices,” 2023. Available online at https://www.globalpetrolprices.com/United-Arab-Emirates/gasoline_prices/.
- [317] “United arab emirates diesel prices,” 2023. Available online at https://www.globalpetrolprices.com/United-Arab-Emirates/diesel_prices/.
- [318] Jet-A1-Fuel.com, “Jet a1 price united arab emirates.” Available online at <https://jet-a1-fuel.com/price/united-arab-emirates>.
- [319] H. N. Psaraftis and C. A. Kontovas, “Speed models for energy-efficient maritime transportation: A taxonomy and survey,” *Transportation Research Part C*:

- Emerging Technologies*, vol. 26, pp. 331–351, 2013. Available online at <https://doi.org/10.1016/j.trc.2012.09.012>.
- [320] LiveBunkers, “Heavy fuel oil (HFO).” Available online at <https://livebunkers.com/heavy-fuel-oil-hfo#:~:text=Density%3A,m3%20to%20facilitate%20efficient%20centrifuging>.
- [321] W. E. Forum, “Dubai has just increased the cost of landfill. can it hit zero waste by 2030?,” February 9 2022.
- [322] Argus, “Argus biomass markets,” tech. rep., 2023. Available online at <https://www.argusmedia.com/-/media/Files/sample-reports/argus-biomass-markets.ashx>.
- [323] United Nations Industrial Development Organization, “Indstat 4 2023, isic revision 4,” 2023. Available online at <https://stat.unido.org/database/INDSTAT%204%202023,%20ISIC%20Revision%204>.
- [324] P. Pearson and J. Watson, “UK energy policy 1980-2010: A history and lessons to be learnt,” tech. rep., Low Carbon Research Institute of Wales, Cardiff University and Sussex Energy Group, University of Sussex. Available online at <https://www.theiet.org/impact-society/factfiles/energy-factfiles/energy-generation-and-policy/uk-energy-policy-1980-2010/>.
- [325] Department of Energy and Climate Change, “2010 to 2015 government policy: UK energy security,” tech. rep., Department of Energy and Climate Change, 2015. Available online at <https://www.gov.uk/government/publications/2010-to-2015-government-policy-uk-energy-security/2010-to-2015-government-policy-uk-energy-security> Updated 8 May 2015.

Appendix A

Power Sector Data (ESO-UAE)

Table A.1: Power generation technology costs and parameters in the ESO-UAE model.

Technology	CAPEX (£/kW)	Unit Size (MW/unit)	Build Rate (Unit(s)/year)	Capacity (MW)	Ref.
Nuclear	3604	1345	0.4	2690	[217, 218]
Coal	1540	500	0	0	[219]
Bio	2250	500*	0.6	0	[102, 103, 104, 105]
CCGT	721	600	5	31200	[220, 219]
CCGT-PostCCS	1531	750	1.2	0	
CCGT-PostCCS-r	811	600	1.2	0	[106]
BECCS	3826	500	1.2	0	[102, 105]
BECCS-r	1827	500*	1.2	0	[106]
Wind-Onshore	981	20	1	0	[102, 103, 104, 105]
Wind-Offshore	2047	50	1	0	[102, 103, 104, 105]
Solar	616	600	1	2400	[220, 221]
InterImp	1001	500	0	1500	[222]

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Power generation technology costs and parameters in the ESO-UAE model (continued)

Technology	CAPEX (£/kW)	Unit Size (MW/unit)	Max. Build Rate (MW/year)	Capacity (MW)	Ref.
PHSto	1211	125	2	0	[223]
Oil	803	75	0	825	[220]
H ₂ -CCGT	1550	600	1	0	[224]

*50 MW if the scenario is considering domestic biomass only.

Table A.2: Power generation maximum allowable capacity in the ESO-UAE model.

Technology	Maximum Capacity
Nuclear	Unlimited or zero depending on the scenario
Coal	None - The area is rich with natural gas. The country used to have a coal capacity for a short period of time. This plant was converted to operate on natural gas [219].
Bio	Unlimited or constrained based on nationally available biomass
CCGT	Unlimited
CCGT-PostCCS	Unlimited
CCGT-PostCCS-r	Unlimited
BECCS	Unlimited or zero depending on the scenario
BECCS-r	Unlimited or constrained based on nationally available biomass
Wind-Onshore	Unlimited
Wind-Offshore	Unlimited
Solar	Unlimited
InterImp	None assuming the existing capacity is enough. This is based on the fact that Abu Dhabi operated as reserve capacity for the Gulf region
PHSto	Limited based on dam availability in the UAE [225]
Oil	None as recent ones have been converted into natural gas power plants
H ₂ -CCGT	Unlimited or 0 depending on the scenario

Appendix B

Industrial Sector Data (ESO-UAE)

Table B.1: Cost input for cement production used technologies in the ESO-UAE model [79, 226, 227].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
Cement Plant	Cement	250	41
CementPCCS-r	Cement	12	66
CementPCCS-n	Cement	263	66
CementOxy-r	Cement	114	37
CementOxy-n	Cement	296	37

Table B.2: Existing capacity for cement production used in the ESO-UAE model [228].

Technology	Product (X)	Capacity (mt-X/year)
Cement	Cement	30
CementPCCS-r	Cement	
CementPCCS-n	Cement	
CementOxy-r	Cement	
CementOxy-n	Cement	

Table B.3: Emissions and their sources for cement production technologies used in the ESO-UAE model [79, 229, 230].

Technology	Emissions (t-CO ₂ /mt-X)	Source
Cement	591500	
CementPCCS-r	59150	Capture is from clinker flue gas
CementPCCS-n	59150	Capture is from clinker flue gas
CementOxy-r	88000	
CementOxy-n	88000	

Table B.4: Cost input for steel production technologies used in the ESO-UAE model [79, 90, 231, 232, 233, 234, 235, 236, 237, 238].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
Steel-DRI	Steel	204	148
SteelDRI-CCS-n	Steel	253	150
SteelDRI-CCS-r	Steel	49	150
SteelDRI-30H-n	Steel	204	148
SteelDRI-30H	Steel		148
SteelDRI-CCS-30H-n	Steel	253	148
SteelDRI-CCS-30H	Steel		148
SteelDRI-CCS-30H-r	Steel	49	150
Steel-BioGasif.-DR-n	Steel	3071828	215
SteelDRI-BioGasif.-CCS-n	Steel	3071877	217
SteelDRI-BioGasif.-CCS-r	Steel	3071662	217
SteelDRI-BioGasif.-CCS-rg	Steel	3071613	217
Steel-MOE	Steel	1000	601
Steel-EAF-scrap	Steel	115	390
Steel-EW	Steel	548	601

Table B.5: Existing capacity and power requirement for steel production used in the ESO-UAE model [79, 239, 240, 241, 242].

Technology	Product (X)	Capacity (mt-X/year)	Power (TWh/mt-X)
Steel-DRI	Steel		
SteelDRI-CCS-n	Steel	2	
SteelDRI-CCS-r	Steel		
SteelDRI-30H-n	Steel		
SteelDRI-30H	Steel		
SteelDRI-CCS-30H-n	Steel		

Continued on next page

Table B.5 – continued from previous page

Technology	Product	Capacity	Power
	(X)	(mt-X/year)	(TWh/mt-X)
SteelDRI-CCS-30H	Steel		
SteelDRI-CCS-30H-r	Steel		
SteelDRI-BioGasif.-n	Steel		
SteelDRI-BioGasif.-CCS-n	Steel		
SteelDRI-BioGasif.-CCS-r	Steel		
SteelDRI-BioGasif.-CCS-rg	Steel		
Steel-MOE	Steel		4000
Steel-EAF-scrap	Steel	2	563
Steel-EW	Steel		2583

Table B.6: Emission sources for steel production using various technologies in the ESO-UAE model [89, 90].

Technology	Emissions (t-CO ₂ /mt-X)	Source
Steel-DRI	804000	Emissions from DRI and pre-treatment reactors
SteelDRI-CCS-n	356700	Emissions are from pre-treatment reactors and 90% is captured from the DRI.
SteelDRI-CCS-r	356700	Emissions are from pre-treatment reactors and 90% is captured from the DRI.
SteelDRI-30H-n	739000	Emissions from DRI and pre-treatment reactors
SteelDRI-30H	739000	Emissions from DRI and pre-treatment reactors
SteelDRI-CCS-30H-n	350200	Emissions are from pre-treatment reactors and 90% is captured from the DRI.
SteelDRI-CCS-30H	350200	Emissions are from pre-treatment reactors and 90% is captured from the DRI.
SteelDRI-CCS-30H-r	350200	Emissions are from pre-treatment reactors and 90% is captured from the DRI.
SteelDRI-BioGasif.-n	-430699	The negative emissions result from utilizing biomass, primarily from 90% of DRI capture, while accounting for supply chain emissions, gasifier emissions and pretreatment reactors.
SteelDRI-BioGasif.-CCS-n	-430699	The negative emissions result from utilizing biomass, primarily from 90% of DRI capture, while accounting for supply chain emissions, gasifier emissions and pretreatment reactors.
SteelDRI-BioGasif.-CCS-r	-430699	The negative emissions result from utilizing biomass, primarily from 90% of DRI capture, while accounting for supply chain emissions, gasifier emissions and pretreatment reactors.
SteelDRI-BioGasif.-CCS-rg	-430699	The negative emissions result from utilizing biomass, primarily from 90% of DRI capture, while accounting for supply chain emissions, gasifier emissions and pretreatment reactors.
Steel-MOE	-	-
Steel-EAF-scrap	-	-
Steel-EW	-	-

Table B.7: Cost input for oil-refining technologies used in the ESO-UAE model [79, 243, 244].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
Refinery	Refined-Oil	94	108
Refinery-PCCS-r	Refined-Oil	31	137
Refinery-PCCS-n	Refined-Oil	124	137

Table B.8: Existing capacity for oil-refining used in the ESO-UAE model [245].

Technology	Product (X)	Capacity (mt-X/year)
Refinery	Refined-Oil	169
Refinery-PCCS-r	Refined-Oil	
Refinery-PCCS-n	Refined-Oil	

Table B.9: Emission sources for oil-refining using various technologies in the ESO-UAE model [246, 247].

Technology	Emissions (t-CO ₂ /mt-X)	Source
Refinery	300587	Emissions are from upstream and downstream operations
Refinery-PCCS-r	81378	90% capture of downstream emissions
Refinery-PCCS-n	81378	90% capture of downstream emissions

Table B.10: Cost input for LNG technologies used in the ESO-UAE model [91, 248, 249, 250, 251].

Technology	Product	CAPEX	OPEX
	(X)	(m£/mt-X)	(m£/mt-X)
LNGprocess	LNG	141	18
LNGprocess-PCCS-r	LNG	141	18
LNGprocess-PCCS-n	LNG	788	18
LNGprocess-Electric	LNG	647	4

Table B.11: Existing capacity and power requirement for LNG production used in the ESO-UAE model [252, 253].

Technology	Product	Capacity	Power
	(X)	(mt-X/year)	(MWh/mt-X)
LNGprocess	LNG	8	
LNGprocess-highPCC-r	LNG		
LNGprocess-highPCC-n	LNG		
LNGprocess-Electric	LNG		330000

Table B.12: Emission sources for LNG production using various technologies in the ESO-UAE model [91, 254].

Technology	Emissions (t-CO ₂ /mt-X)	Source
LNGprocess	600000	
LNGprocess - CCS - n	372000	Post-combustion capture from gas turbine for LNG refrigeration. The remaining emissions are from natural gas pre-treatment and exploration
LNGprocess - CCS - r	372000	Post-combustion capture from gas turbine for LNG refrigeration. The remaining emissions are from natural gas pre-treatment and exploration.
E-LNG	360000	Emissions are from upstream and exploration.

Table B.13: Cost input for Aluminium technologies used in the ESO-UAE model [219, 255].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
Al-Smelter	Aluminium	1563	229
Al-Smelter-CCS-n	Aluminium	3183	259
Al-Smelter-CCS-r	Aluminium	1743	259
Al-Smelter-Grid-c	Aluminium		27
Al-Smelter-Grid	Aluminium	123	27

Table B.14: Existing capacity and power requirement for Aluminium production used in the ESO-UAE model [93].

Technology	Product (X)	Capacity (mt-X/year)	Power (TWh/mt-X)
Al-Smelter	Aluminium	4.5	
Al-Smelter-CCS-n	Aluminium		
Al-Smelter-CCS-r	Aluminium		
Al-Smelter-Grid-c	Aluminium		14000
Al-Smelter-Grid	Aluminium		14000

Table B.15: Emission sources for Aluminium production using various technologies in the ESO-UAE model [256].

Technology	Emissions (t-CO ₂ /mt-X)	Source
Al-Smelter	5437385	Processing and CCGT plant
Al-Smelter-CCS	543739	90% Capture from CCGT power plant
Al-Smelter-CCS-r	543739	90% Capture from CCGT power plant
Al-Smelter-Grid-c		
Al-Smelter-Grid		

Table B.16: Cost input for Ammonia technologies used in the ESO-UAE model [257, 258].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
Ammonia-HB	Ammonia	374	9
AmmoniaBlue-r	Ammonia	169	19
AmmoniaBlue-n	Ammonia	543	19
AmmoniaGreen	Ammonia	2576	

Table B.17: Existing capacity and power requirement for Ammonia production used in the ESO-UAE model [258, 259, 260].

Technology	Product (X)	Capacity (mt-X/year)	Power (MWh/mt-X)
Ammonia-HB	Ammonia	2	83333
AmmoniaBlue-r	Ammonia		361111
AmmoniaBlue-n	Ammonia		361111
AmmoniaGreen	Ammonia		10500000

Table B.18: Emission sources for Ammonia production using various technologies in the ESO-UAE model [258].

Technology	Emissions (t-CO ₂ /mt-X)	Source
Ammonia-HB	2350000	
AmmoniaBlue-r	120000	95% capture
AmmoniaBlue-n	120000	95% capture
AmmoniaGreen		

Table B.19: Cost input for Hydrogen technologies used in the ESO-UAE model [261, 262, 263, 264].

Technology	Product (X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
HydrogenGrey	Hydrogen	4003	524
HydrogenBlue-r	Hydrogen	2685	586
HydrogenBlue-n	Hydrogen	6688	586
HydrogenGreen	Hydrogen	5239	191

Table B.20: Existing capacity and power requirement for Hydrogen production used in the ESO-UAE model [264, 265].

Technology	Product (X)	Capacity (mt-X/year)	Power (TWh/mt-X)
HydrogenGrey	Hydrogen	0.3	
HydrogenBlue-r	Hydrogen		
HydrogenBlue-n	Hydrogen		
HydrogenGreen	Hydrogen		56300

Table B.21: Emission sources for Hydrogen production using various technologies in the ESO-UAE model [258, 262].

Technology	Emissions (t-CO ₂ /mt-X)	Source
HydrogenGrey	9305786	
HydrogenBlue - n	987989	90% capture from SMR furnace flue gas. Capture is based on MEA chemical absorption
HydrogenBlue - r	987989	90% capture from SMR furnace flue gas. Capture is based on MEA chemical absorption
HydrogenGreen	-	

Table B.22: Cost input for SAF technologies used in the ESO-UAE model [94].

Technology	Power (MWh/mt-X)	CAPEX (m£/mt-X)	OPEX (m£/mt-X)
SAF-HEFA-SPK		90	220
SAF-PtL-Green	17461574	1600	121

Table B.23: Cost input for DAC technologies used in the ESO-UAE model [266].

Technology	Power	CAPEX	OPEX
	(MWh/t-CO ₂)	(£/t-CO ₂)	(£/t-CO ₂)
DAC	2.03	389	213

Appendix C

Transport Sector Data (ESO-UAE)

Table C.1: Cost input for road transport vehicles used in the ESO-UAE model [95, 96, 97, 99, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283].

Vehicle	CAPEX	OPEX
	(£/vehicle)	(£/vehicle)
Car-Gasoline	21213	2420
Car-Hybrid	40658	2040
Car-Electric	44240	1490
Car-Hydrogen	49214	2049
Bus-Diesel	39708	8150
Bus-Hybrid	24855	8230
Bus-Electric	71100	2130
Bus-Hydrogen	531250	20778
Truck-Diesel	48765	6532
Truck-Electric	142200	
Truck-Hydrogen	400000	7149

Table C.2: Capacity and power requirement for road transport vehicles used in the ESO-UAE model [284, 285, 286, 287, 288, 289].

Vehicle	Capacity (vehicles)	Power (kWh/vehicle)
Car-Gasoline	3600000	
Car-Hybrid		252
Car-Electric	39000	4258
Car-Hydrogen		
Bus-Diesel	99490	
Bus-Hybrid	3189	2536
Bus-Electric	100	29484
Bus-Hydrogen		
Truck-Diesel	237427	
Truck-Hybrid		
Truck-Electric		29193
Truck-Hydrogen		

Table C.3: Emission from road transport vehicles in the ESO-UAE model
[95, 96, 97, 272, 283, 290].

Vehicles	Emissions
	(t-CO ₂ /vehicle per year)
Car-Gasoline	4
Car-Hybrid	2.4
Car-Electric	
Car-Hydrogen	
Bus-Diesel	31
Bus-Hybrid	28
Bus-Electric	
Bus-Hydrogen	
Truck-Diesel	19
Truck-Electric	
Truck-Hydrogen	

Table C.4: Cost input for train transport used in the ESO-UAE model
[291, 292, 293, 294, 295].

Train Type	CAPEX	OPEX
	(£/train)	(£/train)
Train-Diesel	1537114	213111
Metro	1537114	100328
Train-Electric-r		100328
Train-Electric	1537114	100328
Train-Hydrogen	81840000	5360588

Table C.5: Capacity and power requirement for road transport vehicles used in the ESO-UAE model [98, 290, 292, 293, 296, 297, 298].

Train Type	Capacity (Trains)	Emissions (t-CO ₂ /train)	Power (GWh/train per year)
Train-Diesel	45	705	
Metro	39		190
Train-Electric-r			190
Train-Electric			190
Train-Hydrogen			

Table C.6: Cost input for maritime transportation used in the ESO-UAE model [299, 300, 301, 128, 302, 303, 304].

Ship Type	CAPEX (£/DWT*)	OPEX (£/DWT)
Ship-HFO	755	153
Ship-Ammonia-r	387	304
Ship-Ammonia	1142	304

Table C.7: Maritime transportation capacity and emissions data used in the ESO-UAE model [128, 301, 302, 303, 304, 305, 306].

Ship Type	Capacity (DWT)	Emissions (t-CO ₂ /DWT)
Ship-HFO	1711700	0.66
Ship-Ammonia-r		
Ship-Ammonia		

Table C.8: Cost input for aviation used in the ESO-UAE model [307, 308, 309, 310].

Plane Type	CAPEX	OPEX
	(£/plane)	(£/plane)
Plane-JetFuel	110600000	20206321
Plane-50SAF-fs		30974777
Plane-50SAF	110600000	30974777

Table C.9: Airplane capacity and emissions data used in the ESO-UAE model [306, 309, 311, 312, 313].

Plane Type	Capacity	Emissions
	(planes)	(t-CO ₂ /plane per year)
Plane-JetFuel	385	93736
Plane-50SAF-fs		46868
Plane-50SAF		46868

Appendix D

Fuel Prices (ESO-UAE)

Table D.1: Fuel prices used in the ESO-UAE model.

Fuel	Price	Units	Note	Ref.
Natural Gas	8	£/MWh		[314, 315]
Gasoline	0.7	£/L		[316]
Diesel	0.7	£/L		[317]
JetFuel	0.4	£/L		[318]
Heavy Fuel Oil	11	£/L		[319, 320]
Uranium	5	£/MWh		[108]
Biomass	5	£/MWh	Domestic	[321, 125]
Biomass	20	£/MWh	Imported	[322]
Hydrogen	2	£/kg	Averaged levelised cost of green and blue hydrogen	
Cooking Oil	43	£/ton		

Appendix E

Social-Economic Data (ESO-UAE)

Table E.1: Model input data for the JEDI segment of ESO-UAE model [323].

OECD	Sector	GVA/output (m£/m£) - %	GVA (m£)	Compensation (m£)	Wages (£)
1	Agriculture, forestry and fishing	56	2502	85	12908
2	Mining and quarrying	90	75927	2565	63792
3	Manufacture of food, beverages and tobacco	11	601	1967	25049
4	Manufacture of textiles, wearing apparel and leather	0	8	1967	25049
5	Manufacture of wood and paper products and printing	39	1012	1967	25049
6	Manufacture of coke, refined petroleum and chemicals	20	5888	1967	25049
7	Manufacture of pharmaceutical products	26	73	1967	25049
8	Manufacture of rubber, plastic and non-metallic minerals	32	2581	1967	25049
9	Manufacture of basic and fabricated metal products	22	3827	1967	25049
10	Manufacture of computer, electronic and optical products	35	66	1967	25049
11	Manufacture of electrical equipment	30	616	1967	25049
12	Manufacture of machinery and equipment	12	745	1967	25049
13	Manufacture of transport equipment	32	185	1967	25049
14	Other manufacturing, repair and installation	54	1722	1967	25049
15	Electricity, gas, steam and air-conditioning supply	69	13508	358	59637
16	Water supply; sewerage and waste management	0	0	0	46093
17	Construction	41	29306	8423	17083
18	Wholesale and retail trade; repair of motor vehicles	63	44239	2800	20654
19	Transportation and storage	44	28964	2864	40826
20	Accommodation and food service activities	63	7115	631	16670
21	Information and communication	73	10073	533	74664
22	Financial and insurance activities	57	29671	1568	69588
23	Real estate activities	90	22155	356	46536
24	Professional, scientific and technical activities	79	12855	1361	53591
25	Administrative and support service activities	69	1740	922	17527
26	Public administration and defence	65	22934	8313	75376
27	Education	47	5647	1908	63119
28	Human health and social work activities	47	4704	2369	56115
29	Arts, entertainment and recreation	43	148	1163	54231
30	Other service activities	53	251	2113	24109
31	Activities of households	100	2361	950	8079

Appendix F

UK Electricity Sector Evolution Timeline

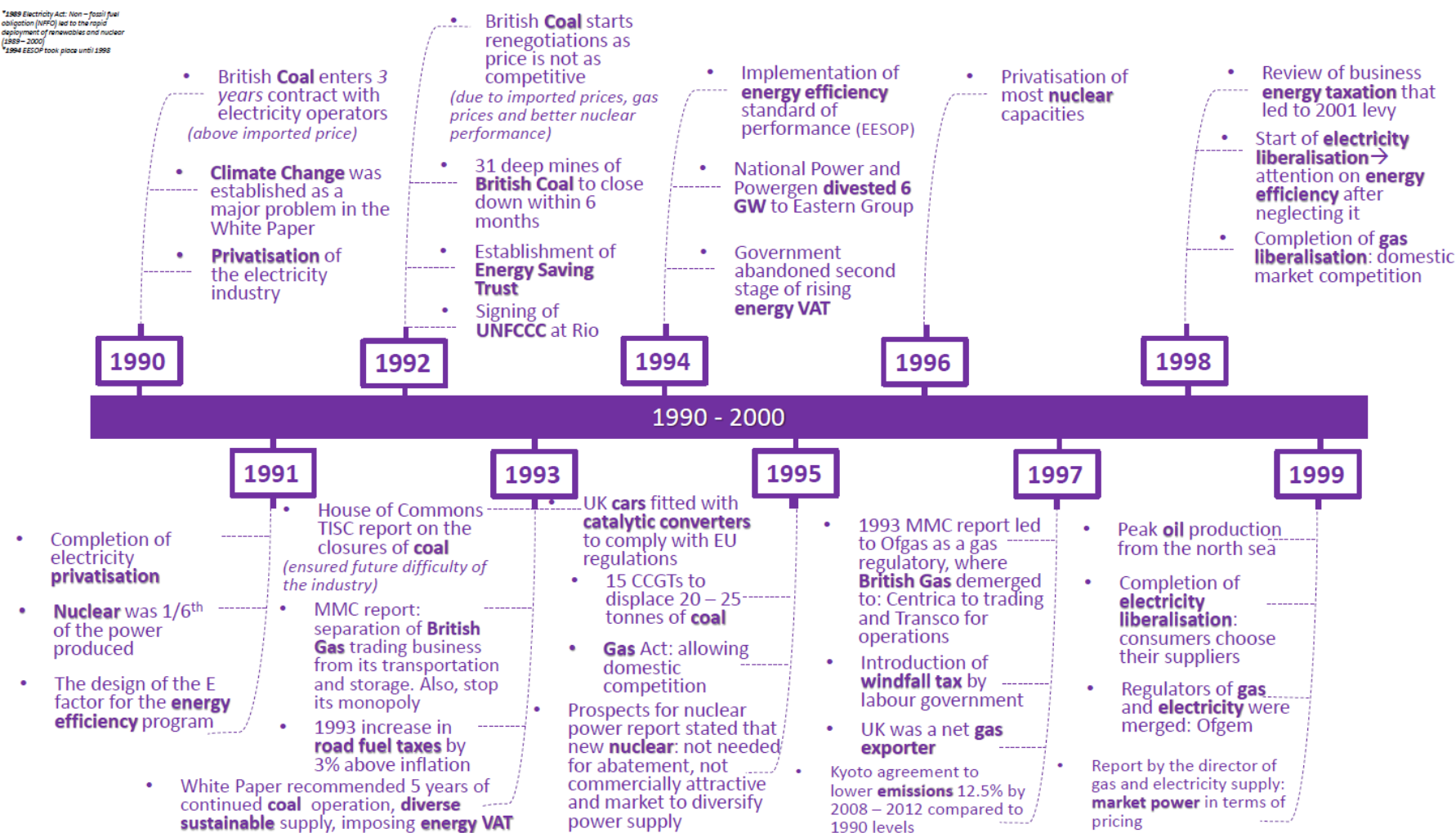


Figure F.1: Detailed UK electricity sector evolution timeline during the 1990-1999 [324, 325].

*2002 energy efficiency commitment (2002 - 2005)

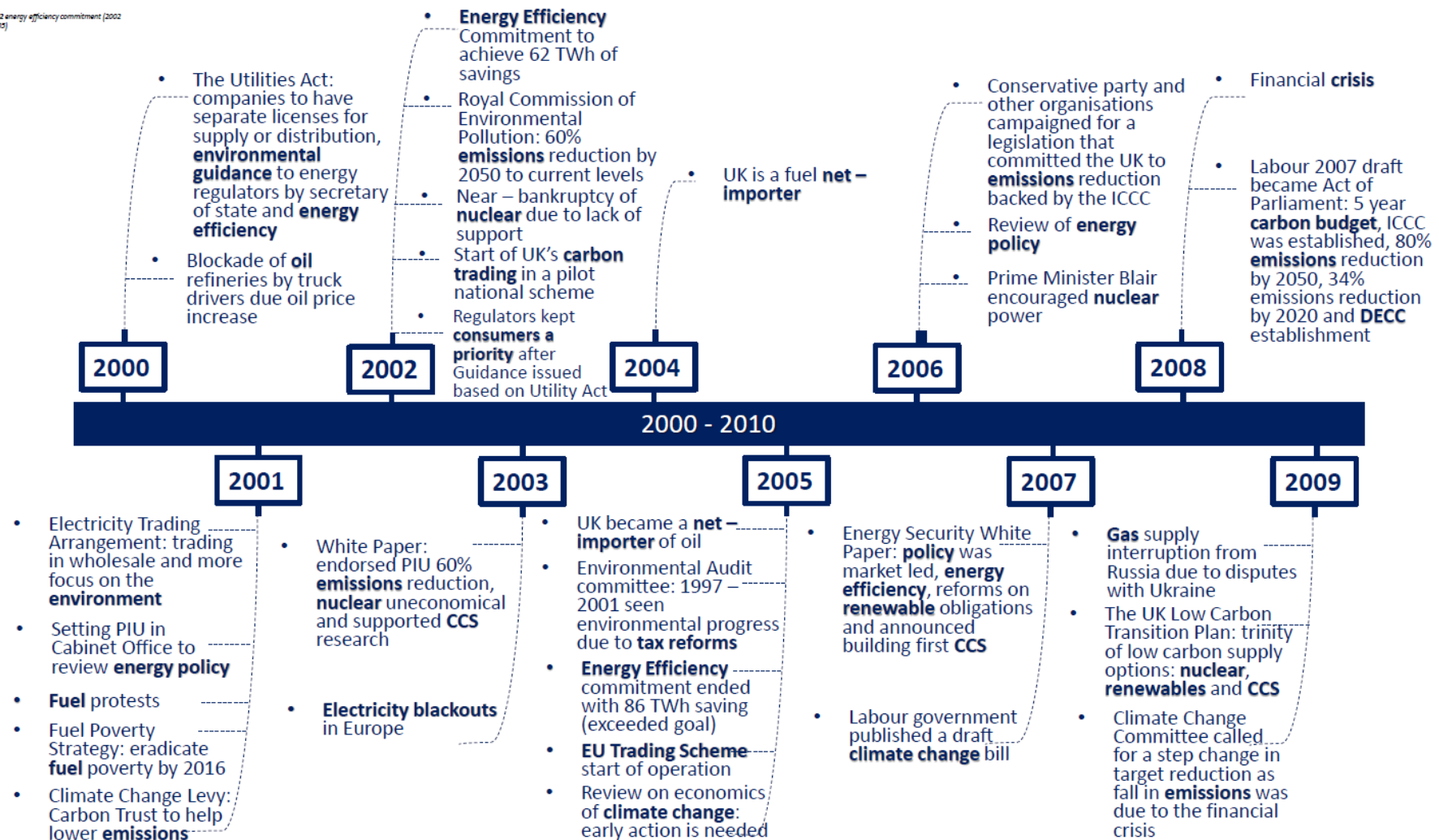


Figure F.2: Detailed UK electricity sector evolution timeline during the 2000-2009 [324, 325].

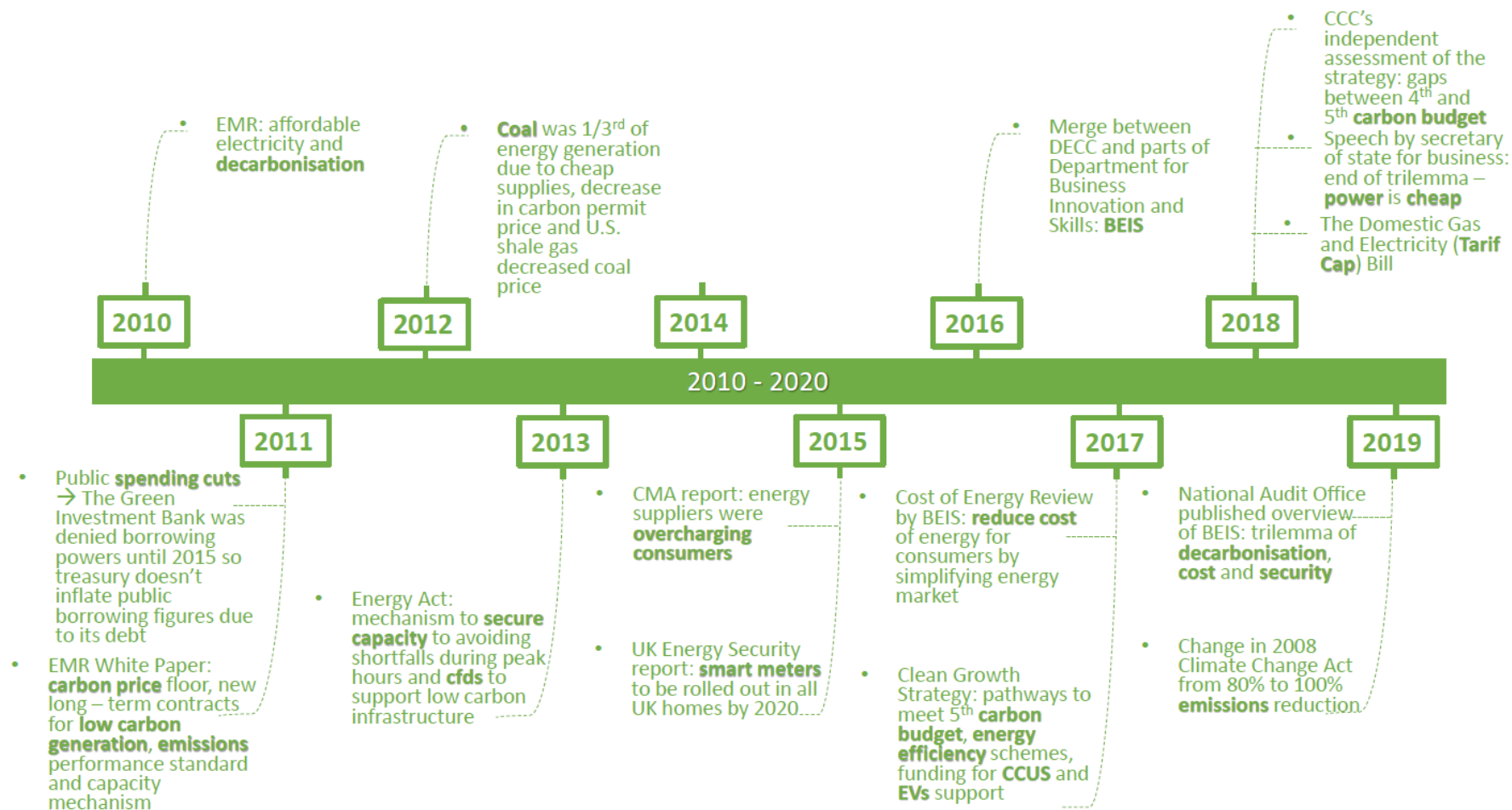


Figure F.3: Detailed UK electricity sector evolution timeline during the 2010-2019 [324, 325].