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Integrated Assessment Model (Simulation) for Qatar Energy Transition: Energy and Environmental Implications for Resilient Decarbonisation Pathways

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Declaration of Originality

I confirm that this thesis is entirely my own work with the exception of that which has been properly referenced.

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Abstract

The energy transition in hydrocarbon-rich economies presents a dual challenge of mitigating its environmental footprint while safeguarding economic stability and sustaining system resilience. For Qatar, however, the transition is not only a matter of domestic benefit. As one of the world's largest energy exporters, leading the decarbonisation agenda among fossil fuel-dependent countries offers an opportunity to enhance the international perception of its export commodities, thereby opening a wider window for investment and market access.

Addressing these challenges requires a robust policy discourse, which can be strengthened through energy system modelling tools. This thesis contributes to the knowledge base on Qatar sustainable transition by examining the likely evolution of its energy system under alternative decarbonisation pathways. The research is organised into three principal components: a novel simulation model using MUSE platform for Qatar energy system transition under BAU, NDC, and NZ50 scenarios targeting accounting-based emissions reductions; a comparative analysis with an optimisation-based framework using TIMES platform; and a modelled assessment of Qatar's potential transition towards a hydrogen-based export future as a potential pathway to reduce global emissions.

The novelty of this work is rooted in creating a partial-equilibrium simulation model for Qatar energy system which is unprecedented in the literature using a state-of-the-art simulation framework. The work is designed to be extensible, not only offering insights for energy policy but also serving as a basis for exploring related research areas such as carbon pricing strategies, market evolution uncertainties, or trade competitiveness of low-carbon fuels. Since the modelling framework is open-source and relies on publicly available datasets, it is replicable and adaptable for comparative studies. Moreover, the approach can be extended to other hydrocarbon-dependent countries in the region, providing a transferable framework for assessing pathways towards sustainable energy transitions in similar contexts.

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To my mother, who has been a mother to my little children for long years,
To my father, who has travelled across the world to make the pursuit of my dreams possible,
I dedicate this thesis entirely to you.

The right to a quality education is, I believe, the perfect path to bridge the gap between different cultures and to reconcile various civilizations. Without such a right, the values of liberty, justice and equality will have no meaning. Ignorance is by far the biggest danger and threat to humankind.

H.H. Sheikha Moza bint Nasser

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Chapter 1

Introduction

1.1 Motivation

The abundance of natural gas endowment laid the foundation for a long-lasting era of welfare for young Qatar. This advantage was reinforced by the nation's relatively small population and modest domestic demand which has remained nearly constant over the past decade (EIA, 2023a). Ultimately, it is global demand that continues to fuel this prosperity. Asia has consistently remained the principal customer of Qatari LNG, acting as the key driver of its market growth (QatarEnergy News, 2024a). Furthermore, Qatar's attentiveness to the broader geopolitical landscape has recently enabled the country to secure several long-term gas supply contracts with Europe (Saba, 2023). This is following a sharp curtailment of Russian gas imports in 2023, which dropped by 80% in two years increasing Qatar's share of total EU gas imports to 5.3% in 2023 (Council of the European Union, 2025b).

This accelerated growth in the hydrocarbon export sector has been accompanied by an unprecedented increase in the country's carbon footprint, placing it amongst the highest global emitters on per capita basis (Boyle, 2024). Continued reliance on LNG exports exposes the economy to price and demand volatility under mounting global climate pressures. Beyond fluctuations in oil and gas markets, carbon tax proposals targeting carbon-intensive imports are taking shape, most notably the EU's Carbon Border Adjustment Mechanism (CBAM) under the Fit for 55 Policy Framework (Council of the European Union, 2025a). In parallel, the long-term viability of hydrocarbon demand faces further uncertainty, as the phasing out of fossil fuels has been explicitly highlighted in the COP28 report (Climate Change Committee, 2024).

Aware of the current energy and environmental landscape, Qatar has signalled its commitment by ratifying at the Paris Agreement and introducing emissions reduction

plans as a climate response (QNRES, 2024; PSA, 2024). This transition, while necessary, introduces inevitable economic uncertainty.

The analysis of economic uncertainties using energy system models has become a key instrument for anticipating the implications of investment decisions on the overall energy system (Pfenninger, et al., 2014). Over time, a wide range of energy system models has been developed to assess prospective energy pathways. Model-based analysis captures underlying nuances and delivers valuable insights and recommendations for energy policy drafting (Pfenninger, et al., 2014). Particularly for Qatar, the pressing environmental crisis, deeply intertwined with its hydrocarbon-dependent economy, underscores the urgency of enacting policies that chart a future which is both environmentally responsible and economically sustainable. Extending beyond the national context, this modelling approach also offers a transferable prototype for application in similar settings and regional case studies.

1.2 Problem Statement

Climate mitigation measures are likely to impose the largest adverse impact on developing economies which are highly dependent on carbon-intensive fuels, as stated in article 4.8 and 4.10 of the Kyoto protocol. Therefore, countries reserve the right to sustain its economic growth, while encouraged to participate in this global movement (UNFCCC, 1995).

In this regard, the research gap in this thesis concerns how the energy transition can be translated for a mega oil and gas producer like Qatar at economic and environmental dimensions and how system resilience can be maintained while recognising the central role of oil and gas in the socio-economic welfare of its population. This challenge, as declared in the Nationally Determined Contribution (NDC), must be met without jeopardizing economic stability (NDC, 2021).

For Qatar, the use of energy system models to inform policy planning has gained momentum only recently, with a predominant focus on cost-optimal planning approaches aimed at sectoral-level decarbonisation, particularly within energy demand sectors such as industry and transport. However, reliance on a single modelling perspective fails to capture the complex interdependencies between supply- and demand-side components of the energy system, which collectively determine the timing, sequencing, scale, and pace of the transition.

Model-based policy guidance is therefore susceptible to biases arising from assumptions of perfect foresight, immediate infrastructure flexibility, and homogeneous investment behaviour. Assumptions regarding perfect knowledge of future energy commodities prices, technologies costs, and market evolution risk underestimating infrastructure inertia, technology adoption frictions, and heterogeneity of real-world investment decision-making. Addressing these limitations requires complementary modelling approaches, including partial-equilibrium simulation frameworks capable of representing system dynamics under imperfect foresight and uncertainty, thereby enabling the identification of more realistic transition pathways for Qatar energy system.

Qatar energy system Transition is particularly sensitive to modelling assumptions due to its strong dependence on hydrocarbon revenues and the concentration of capital in long-lived energy infrastructure, which constrains diversification and increases risk of technology lock-in. Furthermore, the country's close integration with global energy export markets exposes it to external climate-policy shocks and uncertainties surrounding emerging hydrogen trade dynamics, both of which may significantly affect future competitiveness. Consequently, modelling the energy system under myopic foresight is key for developing policy strategies that are robust to market, technology, and policy variability.

Qatar, as a member country of the Gulf Corporation Council (GCC), shares a multitude of economic and social characteristics with its neighbouring countries, most notably a strong dependence on oil and gas production. The scenario formulation and insights developed in this study can therefore contribute to strategy design for countries with

similar contexts, particularly in shaping emissions mitigation pathways. This simulation model for Qatar can serve as a knowledge-sharing tool, leveraging Qatar energy industry expertise to inform and support regional approaches to decarbonisation.

1.3 Research aim and questions

The aim of this research is to identify possible decarbonisation scenarios for Qatar energy system and evaluate the trade-offs between economic growth and environmental performance. It aims to generate policy-relevant insights to support long-term strategy development for a sustainable future. This involves the deployment of a simulation platform to model Qatar energy system across varying climate policy scenarios, while examining the interplay of the energy trilemma: economy, environment, and resilience.

This research aim is answered through three main questions which supports evaluating the transition and evolution of Qatar energy system under specific emission reduction targets. It introduces a novel simulation model for Qatar, then it compares it with a well-established optimisation model, and lastly it investigates energy export opportunity under potential changes in international energy markets. This orderly structure ensures in-depth analysis of the evolution of the current energy system under varying scenarios for robust policy recommendation.

By doing so, this research advances energy transition modelling by systematically examining the intricacies of the energy system that shape the timing, sequencing, and pace of transition. This will identify decision-making failure modes arising from model-result divergence, planning assumptions, and the pursuit of overly optimistic targets without adequately accounting for uncertainty and potential cost shocks. This triggers time sensitivity of mitigation pathways distinguishing between early or delayed intervention strategies; and evaluates the associated risks of infrastructure lock-in and stranded assets.

Research Question 1: How the current energy system of Qatar corresponds to short-term and long-term mitigation targets on basis of a simulation model, and what are the economic and environmental implications?

Research Question 2: How can this simulation model be compared and validated against an optimisation model, and what are the areas of distinction that can explain convergence and divergence that affect economic decision-making and emissions trajectory to inform balanced policy making?

Research Question 3: How can Qatar maintain its prime position as an LNG exporter under decarbonisation targets and what is the impact on its current energy system to meet a change in energy demand exports particularly towards clean fuels?

To answer these questions, a ModUlar energy system Simulation Environment (MUSE), which is an integrated assessment modelling (IAM) framework developed at Imperial College London, will be used to create a simulation model for the energy system of Qatar. To our knowledge, this is unprecedented work which will add to the literature base to support Qatar, and similar contexts, in their pursuit of a low-carbon future. This model will be utilised to audit current policies and propose evidence-based recommendations.

1.4 Conclusion

Qatar energy and emissions intensive economy is under the mounting pressure to reduce its environmental footprint and actively contribute to global climate change mitigation. Enhancing its environmental performance will not only directly improve the welfare of its citizens but will also position Qatar at the forefront of the energy industry, strengthening its claim to leadership in the global transition to a low-carbon future.

The evaluation of Qatar current energy system through a simulation model provides valuable insights into the implications of emissions reduction targets on system

performance. This novel approach offers a distinct perspective on system evolution highlighting the trade-offs between investment decisions and emissions trajectories, and establishing the foundation for the following chapters.

The subsequent comparison between the simulation and optimisation models elevates the analysis by identifying areas of similarities and differences that drives the endogenous decision-making in both models and shape emissions pathways. This comparative approach serves as a validation tool, thereby enhancing the robustness of the resulting policy recommendation.

Lastly, the outlook is broadened to consider shifts in Qatar's export capacity by proposing scenarios that integrate climate-aligned constraints. This analysis captures the impact of external levers on an energy system that is deeply intertwined with global energy export market, delivering strategic insights to inform policy development.

Together, these approaches constitute a coherent and comprehensive framework for energy system modelling that addresses uncertainties surrounding the implications of climate mitigation strategies. They offer rigorous assessment of present dynamics and future projections, underscoring the role of modelling as a key tool for advancing research, strengthening policy discourse, and guiding Qatar toward the realisation of its climate goals.

1.5 Contribution of the thesis

This thesis is part of the research initiative under the Qatar National Environment and Climate Strategy (QNE), organised by Qatar Environment and Energy Research Institute (QEERI) and funded by Qatar Research Leadership Program (QRLP). This thesis was showcased in academic events to discuss findings and share knowledge for capacity building. Aimed at tackling the issues discussed in the research main questions; distinct chapters have contributed as follows:

Chapter 3 (Qatar simulation model and scenario analysis):

Oral presentation at the SDEWES – 2021 conference

Oral presentation at the ICSEWEN – 21 conference

Poster presentation for the H.E. the Minister of Education of Qatar at the Qatar Cultural Attaché in London

Chapter 4 (Dual model comparison for Qatar system evolution under decarbonisation targets):

Oral presentation at the IAEE MECA – 2025 conference

Submitted under review for publication in Q1 journal

Chapter 5 (Implications on Qatar export capacity for potential change in international market away from LNG towards clean fuels):

Oral presentation at the ICAE – 2025 conference

Published in Energy Proceedings (Al-Qassabi et al., 2026)

Contributed as a work package (WP5) in an extended project at Qatar Environment and Energy Research Institute (QEERI) on *Analysing energy transition pathways for Qatar (PATH-QA)*

1.6 Structure of the thesis

The thesis is structured into seven chapters, exploring the complexity of mitigating global climate change for a distinguished energy system, and working in tandem to provide a holistic perspective on system transition.

Chapter 1: Introduction

This chapter lays the grounds for the research framework and highlights its significance in the existing literature. It states the research aim and questions.

Chapter 2: Background and Literature Review

This chapter presents background information on energy system modelling and reviews the relevant literature. It describes the current system, reviews prevailing policies and recent progress. It also introduces key definitions related to system modelling and presents the state-of-the-art simulation model (MUSE), which underpins the analysis in this thesis.

Chapter 3: A Simulation Model for Qatar

This chapter contextualises the simulation model (MUSE) to the case of Qatar energy system, encompassing the full value chain from supply through conversion to demand. It evaluates the model behaviour under three distinct scenarios for emissions reduction targets. It elucidates outcome results and discussion, and derives policy recommendations.

Chapter 4: Simulation and Optimisation Paradigms

This chapter presents a comparative analysis of the MUSE simulation model and the TIMES optimisation model in the context of Qatar energy system. It highlights areas of convergence and divergence that influence investment mechanisms and system configurations under varying climate goals. This combined outcome of both models provides strategic insights for policymaking, helping to avoid overplanning or underestimating the scale of emissions reduction targets.

Chapter 5: Hydrogen Pathway

This chapter extends the MUSE model for Qatar by incorporating external energy demand drivers. It assumes shifts in international markets and a growing transition toward clean fuels. The analysis evaluates the implications for Qatar existing infrastructure and examines how the country can maintain its position in the global export market under

mounting climate mitigation pressures. In particular, it explores the potential role of hydrogen as part of Qatar energy transition.

Chapter 6: Discussion

This chapter amalgamates results from previous chapters by synthesising the simulated scenarios, the comparative study, and the hydrogen pathway outcomes. It presents a critical evaluation of the trade-offs across the three pillars of the energy trilemma: economy, environment and resilience, thereby generating insights to inform policy making.

Chapter 7: Conclusion

This chapter concludes the thesis by summarising key findings and addressing the research gap. It outlines the limitations of the study and highlights avenues for future research. It is followed by references and appendices.

Chapter 2

Literature Review

Energy system modelling is a significant and modern toolkit for analysing the complex multi-faceted relationship between the energy system and the economy (Pfenninger et al., 2014). It provides analytical insights into system performance within specific policy context (Subramanian et al., 2018). Policy adjustment informed by such modelling can prevent market failures and sustain economic growth (Helm, 2002). Moreover, these policies can be embedded within strategic frameworks that account for the implications of adjustments and scenario planning (Pfenninger et al., 2014). To apply this approach to the research questions set out in Chapter 1, it is first necessary to outline the underpinning modelling definitions that lead to the conceptualisation of the model employed in this study: MUSE, which is developed at the Imperial College London. This section then, sets the context for the energy system of Qatar, highlighting its market dynamics, and associated policy framework.

This chapter therefore provides an overview of the existing body of work on energy system modelling, the broader decarbonisation discourse, and current structure of the energy system of Qatar, thereby establishing a clear context for this research. It explores various approaches in energy system modelling, laying grounds for the analysis applied in subsequent chapters. It also identifies critical gaps in existing literature, particularly on the applicability of energy transition modelling to hydrocarbon-dependent economies.

2.1 Energy systems

Energy systems represent the complex interconnection between the supply of energy and the demand for energy services (IPCC, 2022). Figure 2.1 provides a visual representation of energy systems as reported in the IPCC fifth Assessment Report (2014). On the supply side, the system comprises primary energy extraction, processing, and transporting, while the demand side reflects the end-use service sectors. These two

sides are closely interlinked: any increase in demand must be matched by an increase in supply. When existing technologies are unable to meet this demand, opportunities arise for investment in new technologies. Energy system models play a critical role in assessing such investment opportunities and analysing system behaviour under different objectives, such as economic profitability or environmental targets.

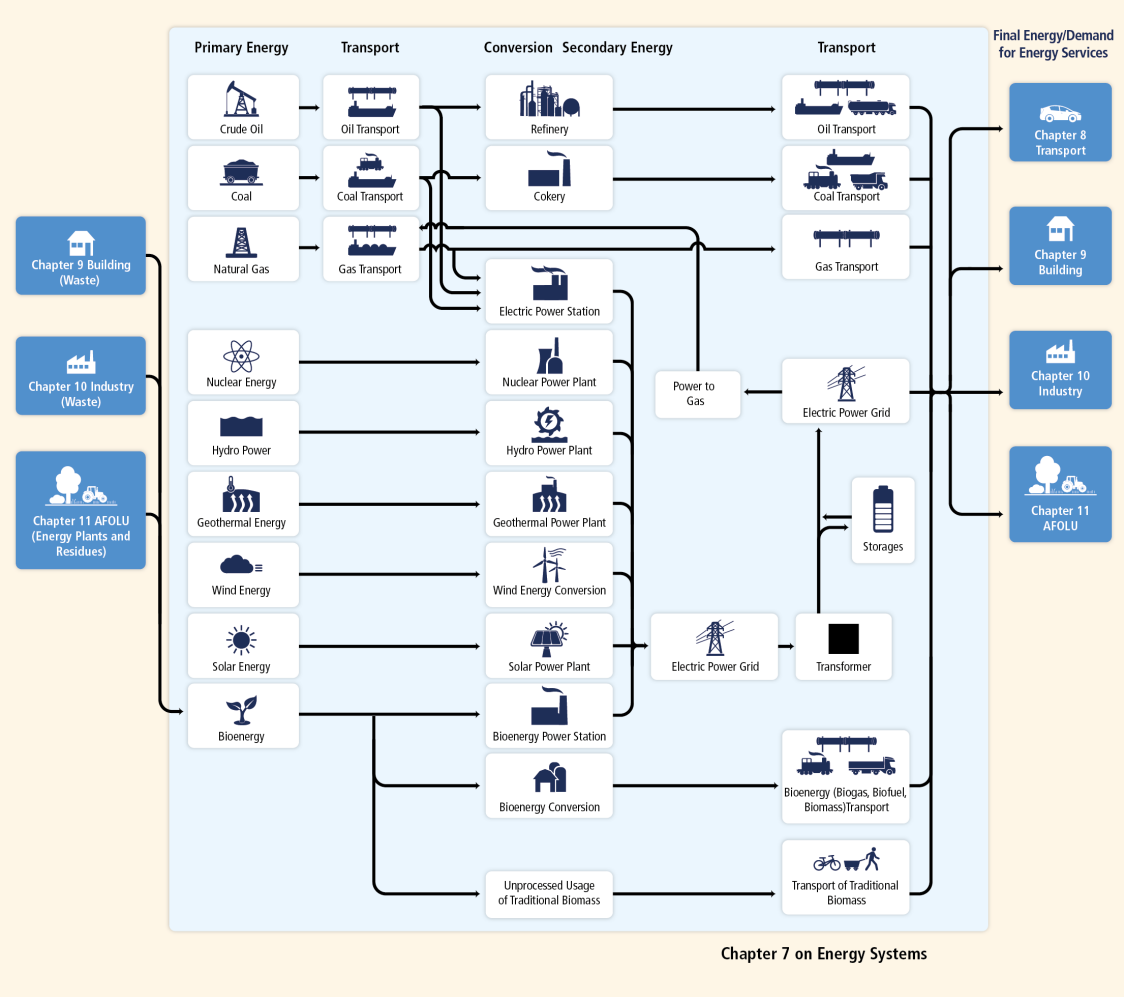


Figure 1: Configuration of integrated energy system illustrating the interconnection between supply and demand and visualising energy flow in the system (IPCC, 2014)

2.1.1 Energy system models

The definition of energy system models is often distinguished from that of energy system frameworks. A model refers to the case-specific representation of an energy system that is analysed using a given modelling framework, incorporating ad hoc attributes and constraints. In contrast, a framework is a general, replicable modelling environment that applies coded mathematical equations to any case study (Prina et al., 2022). For

simplicity and consistency, the following sections will use the term “model” to denote energy system frameworks, while case-specific applications will be referred to as Qatar energy system model.

The primary purpose of modelling energy systems is to develop a structured understanding of the different components of the system and their interconnections, as well as to evaluate the consequences of potential changes, thereby supporting scenario planning and policymaking (Pfenninger et al., 2014). Numerous models have been developed to analyse such changes, which may arise from *economic* shifts driven by technological innovation and adoption; *environmental* pressures stemming from climate mitigation targets; or *resilience* challenges addressed through strategic investments. These three dimensions form the pillars of the “energy trilemma”, which gauges the balance between affordability, environmental sustainability, and energy security within a system (World Energy Council, 2018).

The classification of energy system models varies according to their underlying modelling properties. Pfenninger et al. (2014) classified models according to the modelling paradigm into four groups: system-wide optimisation models, simulation models, electricity system models, and qualitative models. Jebaraj & Iniyan (2006) reviewed models according to their main purpose, including planning and development of integrated systems, analysing supply and demand flows, forecasting future energy consumption, assessing penetration of renewable technologies, optimisation models, neural networks, and emissions mitigation models. Subramanian et al. (2018) proposed a twofold categorisation: the first group is based on the modelling approach, encompassing computational models such as agent-based models, mathematical models, and physical models; and the second group is based on areas of application, particularly process systems engineering and energy economics. Additional categorisations are also available in the broader literature.

2.1.2 Top-Down and Bottom-Up Analytical Approaches

In addition to these classifications, energy system models can also be distinguished by their analytical perspective, most notably through the top-down and bottom-up approaches. Top-down models provide a macro-level, system-wide overview by using aggregated data on energy requirements and prices to assess their impact on supply and demand across economic sectors. However, reliance on generalised data inputs often results in inadequate background detail and insufficient consideration of technology innovation (Subramanian et al., 2018).

In contrast, bottom-up models focus on micro-level system components, incorporating detailed technological and sectoral data to capture the impacts of innovation, efficiency improvements, and policy interventions with greater granularity. These models are significantly data-rich, relying on exogenous demand forecasts aligned with energy supply, alongside extensive datasets on technologies distinctly characterised by their economic and performance properties (Pfenninger et al., 2014; Subramanian et al., 2018). Such a framework enables consistent explanation of technology uptake and robust assessment of potential market penetration. However, this data intensity of bottom-up models can also be regarded as a limitation, given the substantial computational requirements involved. (Subramanian et al., 2018).

2.1.3 Optimisation and Simulation Paradigms

Within the bottom-up approach, two modelling archetypes are highlighted for their relevance in this thesis. The first archetype is the optimisation paradigm, which constitutes a cornerstone of energy system modelling (Pfenninger et al., 2014). This paradigm is widely applied in techno-economic analysis to optimise energy and climate pathways (Manuel et al., 2022). It is mathematically formulated using linear and non-linear programming techniques (Lund et al., 2017), where the optimal solution represents a maximisation or minimisation of a global objective function subject to a set of

constraints (El-Halwagi, 2006). Typically, such optimal solutions are used to assess the economic feasibility of scenarios, such as emissions mitigation targets (Lund et al., 2017).

The second archetype is the simulation paradigm, which employs mathematical techniques similar to those used in optimisation but differ fundamentally in their objectives. Rather than identifying a single optimal solution, simulation models explore the dynamic behaviour of an energy system by generating a range of feasible, often sub-optimal, solutions (Lund et al., 2017; Crow et al., 2018). System performance is evaluated through comparative analysis of existing and prospective configurations, considering both economic and environmental dimensions. This characteristic makes simulation modelling particularly well-suited to backcasting approaches, which assume that a desired future state can be achieved through multiple pathways (Lund et al., 2017).

A key distinction between the two archetypes is rooted in their level of knowledge of future market trends and commodity price fluctuations. Optimisation models stipulate perfect foresight into the future, applying a global objective function to minimise system costs and thereby derive an economically optimal solution (Crow et al., 2018). In contrast, simulation models assume an imperfect foresight, reflecting uncertainty inherent in real-world conditions. This limited knowledge of the future leads to the generation of sub-optimal solutions that capture the diversity of possible system outcomes (Crow et al., 2018).

Both optimisation and simulation models can be applied to assess policy implications within complex systems aimed at mitigation targets, forming part of what is broadly interpreted as integrated assessment approaches.

2.1.4 Integrated Assessment models (IAM)

Integrated assessment models (IAMs) constitute a suite of analytical tools that integrate data and insights from multiple disciplines to evaluate the cost, feasibility, and

implications of alternative energy and climate policy pathways (Subramanian et al., 2018; Giarola et al., 2022, Sachs et al., 2019; Ackerman et al., 2009; Parson & Fisher-Vanden, 1997). These models provide a holistic perspective on climate-mitigation strategies by detailing the trade-offs, synergies, and systemic impacts of potential policy intervention (Giarola et al., 2022).

Despite this integrative strength, IAMs face limitations in accurately capturing the heterogeneity of real-world investment decision-making (Giarola et al., 2022). Arguably, these models often yield excessively rapid transition rates reflecting their reliance on a least-cost objective that neglects behavioural considerations (Ghambir et al., 2019). Furthermore, Ackerman et al. (2009) stressed that IAMs often converge on the optimal solution through the gradual implementation of mitigation policies which can amplify the perceived cost of mitigation while under-representing the leverage of socially driven decisions (Ackerman et al., 2009). Recognising this, Farmer et al. (2015 as cited in Ghambir et al., 2019) emphasised the need to develop new economic models, such as agent-based models, to better represent the heterogeneity of socio-economic systems under climate change targets.

2.1.5 Agent-Based Model (ABM) Theory

Agent-based models (ABM) incorporate the human dimension into energy system modelling. In this approach, agents are entities that influence investment decision-making according to predefined rules (Subramanian et al., 2018). These agents typically represent distinct stakeholder groups or decision-makers, each assigned specific objectives and behavioural attributes that can be quantitatively parametrised using numerical input values, where zero denotes non-applicability (de Marchi & Page, 2014).

The ABM framework enables interaction and competition between agents, which in turn influence technology diffusion, market evolution, and policy response dynamics within the system (Giarola et al., 2022). This makes ABMs particularly valuable for exploring

system behaviour under the non-linear influence of human decision-making and the environmental feedbacks (Lamperti et al., 2019).

Traditional IAM suites often exhibit limited integration of societal influences in representing energy transition pathways (Giarola et al., 2022). To address this shortcoming, the Sustainable Gas Institute at the Imperial College London developed an IAM framework with a built-in ABM component, thereby embedding socio-economic incentives directly into investment decision-making and enhancing the realism of modelled transition.

2.2 ModUlar energy system Simulation Environment (MUSE)

This section introduces a state-of-the-art simulation suite developed at the Imperial College London: the ModUlar energy system Simulation Environment (MUSE). MUSE is an open-source IAM platform integrated with ABM features, enabling investment decisions to be modelled based on consumer-preferred indicators. The source code is available on open access basis for the purpose of development, transparency, and replicability (Imperial College London, 2024). MUSE framework offers notable flexibility in defining levels of heterogeneity and in capturing non-linear dynamics of technology uptake. This represents a novel contribution to the suite of Integrated Assessment Models (Giarola et al., 2022).

2.2.1 MUSE framework

MUSE is a bottom-up, data-rich simulation model designed to capture the dynamics of energy system evolution over time. It enables flexibility in configuring sectoral modules over the full value chain, while incorporating agent-based decision making under user-defined scenarios. This integration accounts for heterogeneity in investment behaviour, reflecting consumer preferences and offering a more realistic depiction of technology penetration into the market. Therefore, MUSE provides a robust platform for investigating uncertain decarbonisation futures and identifying the trade-offs between economic, environmental, and energy-security priorities. (Imperial College London, 2024).

The structure of MUSE, illustrated in Figure 2.2 (Giarola et al., 2022), is organised into three main sets of sectors representing distinct economic activities. The first is the **primary supply sector,** which supplies the primary energy vectors for the energy system such as oil and gas. The second is the **conversion sector,** where primary energy vectors are transformed into secondary energy vectors, including processes such as oil refineries and power plants. The third is the **service demand sector,** which encompasses end-use demand across industry, export, transport, residential, and commercial activities. Each sector is characterised by operational attributes, cost structures, and environmental

impacts. The economic, technical, and environmental flow between the sectors is governed by a central Market Clearing Algorithm (MCA) which is explained in section 2.2.2.



Figure 2: MUSE model structure consists of sectoral modules overarching the full value chain. Adapted for Qatar energy system from Giarola et al. (2022)

The modelling mechanism underpinning MUSE is based on a limited foresight approach. At each timestep, the model converges to partial equilibrium, balancing supply and demand through a microeconomic pricing method. By solving optimisation problem over discrete milestone periods, the model may exaggerate costs and delay investments, thereby reflecting the imperfect knowledge of future market behaviour. (Luh et al., 2020).

Within this structure, sectors are ranked in priority order, with the highest priority given to the service demand sector. MUSE, therefore, first satisfies consumer-side demand, investing in technologies according to agents' preferences. These investment choices

generate *demand* for energy commodities, which are processed by the Market Clearing Algorithm (MCA) and subsequently requested from the *supply* or *conversions sectors*. Investment decisions in the supply and conversion sectors follow a similar process. This process is iterative under the control of the MCA until the model converges to partial equilibrium for the milestone year, after which it advances to the next timestep. (Imperial College London, 2024).

2.2.2 MUSE Market Clearing Algorithm (MCA)

The Market Clearing Algorithm (MCA) serves as the central control node of the MUSE modelling process. It ensures that the simulation operates in line with user-defined configurations. These configurations include the model's spatial and temporal settings and the techno-economic properties of the available options within each sector. The MCA conducts recursive iterations between supply and demand sectors until it reaches a market-clearing commodity price, as illustrated in Figure 2.3. This market clearing equilibrium is recalculated for each time period. Investment decision-making in each period is determined through agent-based analysis of the existing installed capacity and the additional capacity required to meet demand. The final aggregated results of these partial supply-demand equilibria generate updated commodity prices, which are calculated using a user-defined objective function, such as levelised cost of energy (LCOE) or net present value (NPV) or any other cost metric. These updated prices initialise the next execution of the following time period until the end of the simulated timeframe. (Giarola et al., 2022).

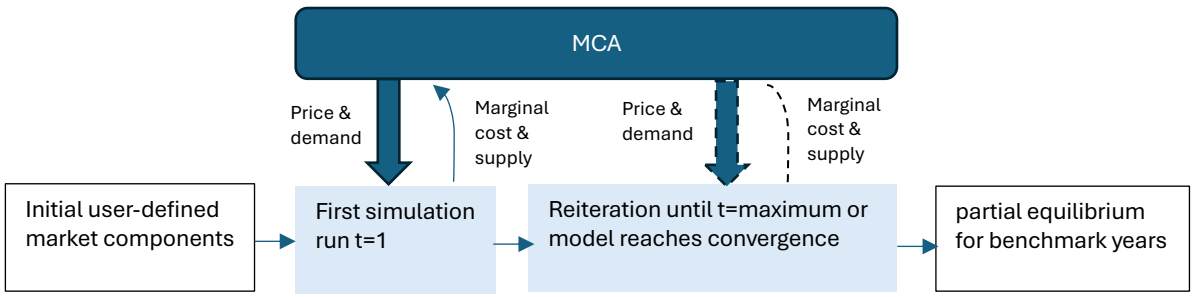


Figure 3: Schematic illustration of the MCA process in MUSE, adapted from Imperial College London (2024)

2.2.3 Agents in MUSE

Investment decisions in MUSE are driven by agents, who determine the type of technologies to invest in, and the level of capacity to dispatch in order to meet demand. Agents may choose to expand the capacity of existing assets, or to replace them with new assets once the installed stock reaches the end of its economic life.

The configuration of agents in MUSE follows a structured sequence of steps. First, the user defines the set of technologies accessible to agents by applying a *search rule, which* may be constrained by factors such as access to capital, market maturity, or environmental attributes. This step reduces the search space by filtering available technologies based on financial limits, *maturity level, or fuel-type preferences*. Second, the user specifies the *objective function* to be optimised, which may involve minimising or maximising a single or multiple decision metrics. Lastly, the *decision method* is configured to establish how agents calculate, prioritise, and rank preferred outcomes when multiple decision objectives are present. These decision objectives can be aggregated, allowing agents to assign priority to certain metrics or give equal weight to all of them. (Giarola et al., 2022, Luh et al., 2020).

In addition, MUSE allows user-defined allocation of demand between agents through the *demand_share* variable. This distinguished between Retrofit Agents, who meet demand by replacing decommissioned assets, and New Agents, who invest to meet newly emerging demand. When enabled, this step allows interaction and asset transfers between at least two pairs of agents. (Imperial College London, 2024). Although this functionality expands the analytical scope for future applications, it is not applied in the context of MUSE for Qatar. Instead, this study uses the *standard_demand* configuration, where a single “new” agent is assigned both decommissioned asset replacement and forecasted new demand, evaluated under a single decision metric. This is elaborated further in Chapter 3.

2.2.4 MUSE Simulation Flow

The simulation process in MUSE in Figure 2.4, as outlined in the official documentation (Imperial College London, 2024), unfolds in two stages. The first stage is **initialisation,** during which the model reads the input files to ensure compliance and detect potential errors. This stage also establishes the baseline market and prepares all the sectors for interaction.

The second stage is the **simulation run**, which is executed as an iterative single-year simulation. Here, agent-based investment decisions drive the system towards convergence, with the option of enforcing a carbon budget as a constraint. Within this framework, the service demand sector is assigned the highest priority, followed by the conversion sector, and finally the primary supply sector.

Once the agent investment step is completed, as described in Section 2.2.3, the aggregation of new and vintage assets determines the required capacity for the corresponding timestep. Production dispatch is then calculated according to a user-defined metric. On this basis, the most cost-effective fuel option is selected. Each supply dispatch is subsequently assigned a weighted average annual LCOE, which generates the updated price set for the following iteration. (Imperial College London, 2024).

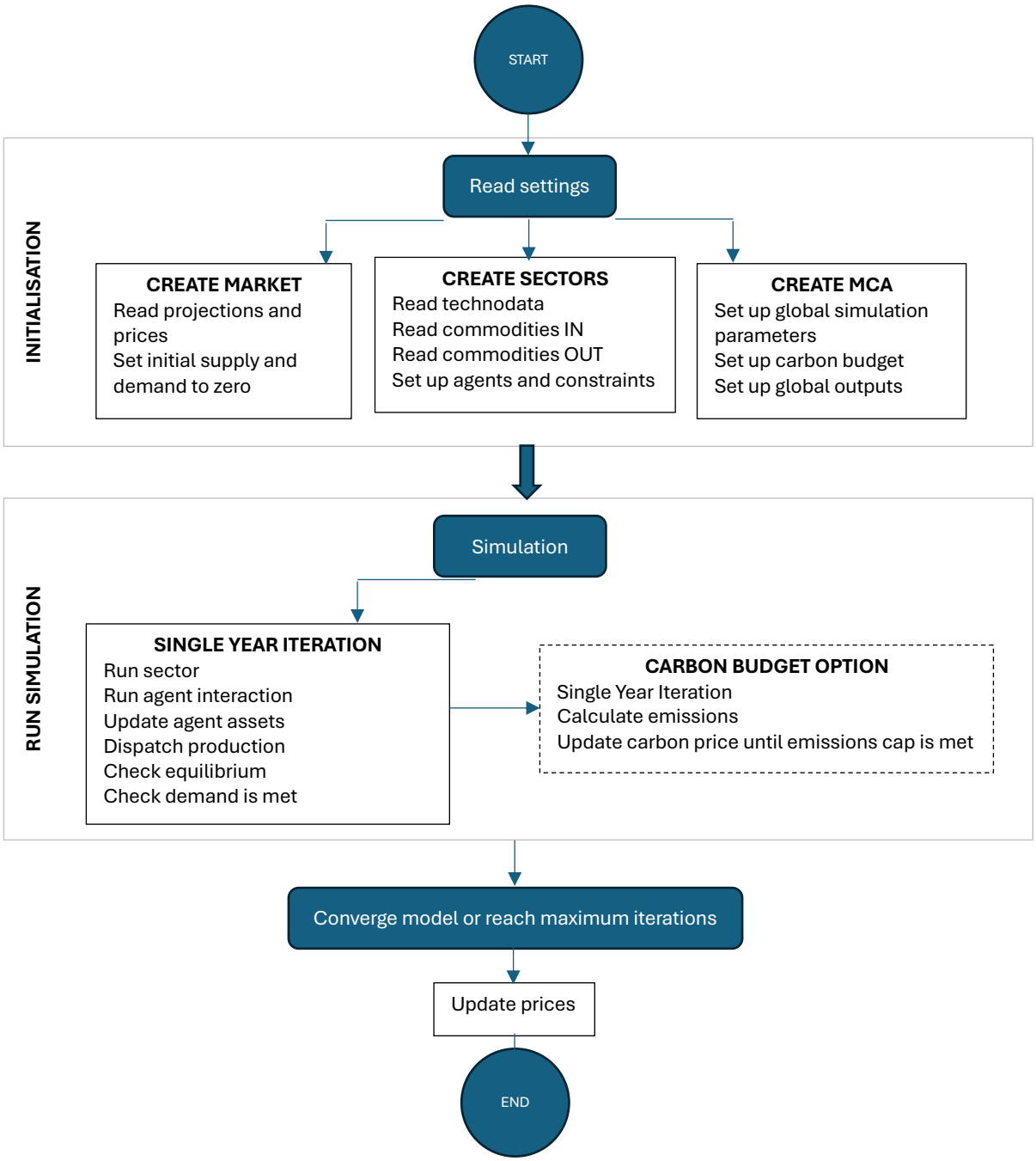


Figure 4: MUSE simulation flow adapted from Imperial College London (2024)

An iteration upper bound ensures that the algorithm terminates even if convergence is not met (Imperial College London, 2024). Such unconverged solutions may result from locked-in initial capacities that cannot be phased out prematurely, very stringent carbon budgets that cannot be met with the available technologies, or constraints on technology scalability. They may also occasionally indicate human errors such as mistakes in data

input, unit conversion, or model setup. The updated release of MUSE can generate error messages to identify these generic issues (Imperial College London, 2024).

2.2.5 Applications of MUSE in the Literature

Since the release of its earliest version, several studies have applied and expanded the MUSE framework across a range of contexts. Crow et al. (2018) evaluated the economics of investment in gas fields by analysing simulated gas supply curves over 28 regions. Garcia Kerdan et al. (2019a) investigated future gas demand in Brazil and cost-efficient imports infrastructure using the MUSE platform coupled with GINO optimisation tool, while Garcia Kerdan et al. (2019b) applied MUSE to explore decarbonisation pathways in Brazil agricultural sector. Sachs et al. (2019) examined heterogeneity in technology uptake and investment decision-making in the residential sector using multi-agent approach.

Applications have also focused on industrial decarbonisation. Luh et al. (2020) developed an industrial module based on MUSE platform to evaluate different emissions reduction strategies in the iron and steel industry in the USA. Another iron and steel decarbonisation model was designed by Moya et al. (2020) for India to examine agents' behaviour under three different investment decision metrics. Expanding to North America, Huntington et al. (2020) compared power markets in Canada, Mexico and United States by analysing market response to fossil fuel price variations using 17 models including MUSE. In the same context, Brown et al. (2021) assessed these power markets under varying gas price shock configurations, extending the earlier comparative analysis.

Further sectoral applications include Budinis et al. (2020), who modelled decarbonisation pathways of the ammonia industry in China using six agent types to represent diverse investment entities. At the global level, Sognnaes et al. (2021) compared near-term CO_2 mitigation strategies using seven IAMs, including MUSE, while Van De Ven et al. (2023) evaluated the feasibility of announced climate policies following

COP26 in Glasgow using four IAMs. Giarola et al. (2021) also investigated renewable energy storage technologies as potential decarbonisation routes for the North American power sector by using four different models.

In terms of framework development, Giarola et al. (2022) presented the official description of MUSE, followed by a summer course on energy modelling for school students (Giarola et al. 2023). Most recently, Moya et al. (2023) developed the geospatial MUSE-RASA model which assess residential sector transitions towards net-zero, incorporating agent-based analysis at a global scale. Table 2.1 summarises MUSE applications in the literature.

Table 1: Applications of MUSE model in the literature

Topic	Reference
"a dynamic model of global natural gas supply"	Crow et al. (2018)
"modelling cost effective pathways for natural gas infrastructure: a southern Brazil case study"	Garcia Kerdan et al. (2019a)
"a novel energy systems model to explore the role of land use and reforestation in achieving carbon mitigation"	Garcia Kerdan et al. (2019b)
"an agent-based model for energy investment decisions in residential sector"	Sachs et al. (2019)
"Long-term development if the industrial sector – case study about electrification, fuel switching, and CCS in the USA"	Luh et al. (2020)
"agent-based scenarios comparison for assessing fuel-switching investment in long-term energy transitions of the India's industry sector"	Moya et al. (2020)
"key findings from the core North American scenarios in the EMF34 intermodel comparison"	Huntington et al. (2020)
"An agent-based modelling approach to simulate the investment decision of industrial enterprises"	Budinis et al. (2020)
"North American energy system responses to natural gas price shocks"	Brown et al. (2021)
"multi-model analysis of long-term emissions and warming"	Sognnaes et al. (2021)
"the role of energy storage in the uptake of renewable energy: A model comparison approach"	Giarola et al. (2021)
"MUSE: An open-source agent-based integrated assessment model"	Giarola et al. (2022)
"multimodal analysis of post Glasgow climate targets"	Van De Ven et al. (2023)
"sustainability education capacity building using muse "	Giarola et al. (2023)
"MUSE-RASA captures human dimension in climate-energy-economic models via global geoAI-ML agent datasets"	Moya et al. (2023)

2.2.6 MUSE within the simulation modelling suite

Within the domain of simulation-based energy system models, several well-established frameworks exist; notably NEMS and PRIMES. The National Energy Modelling System (NEMS) was developed in the United States to address the limitations of earlier models and to better meet the requirements of modern market analysis. It is maintained by the Energy Information Administration (EIA) and the U.S. Department of Energy to serve as the analytical backbone of the Annual Energy Outlook (EIA NEMS, 2019). In Europe, the Price-Induced Market Equilibrium System (PRIMES) is employed to inform European energy regulations (Pfenninger et al., 2014).

NEMS, PRIMES, and MUSE all share a modular structure which consists of supply, conversion, and demand submodules. This modularity enables flexibility but also increases the complexity of both inputs and outputs (Pfenninger et al., 2014). Despite this common architecture, the three models differ significantly in their economic dimension. NEMS incorporates a macroeconomic module, while PRIMES integrates detailed microeconomic attributes into its modelling framework (EIA NEMS, 2019; E3 Modelling, 2018). MUSE, on the other hand, requires techno-economic data across all system technologies, increasing the granularity of sectoral representation (Giarola et al., 2022).

All three models solve for equilibrium through iterative processes, yet the integration mechanism varies. NEMS employs a central integration module which conducts the coordination between the different sectors; exchanges fuel prices and energy demands; and solves linear and non-linear mathematical optimisation problems (Gabriel et al., 2001). PRIMES similarly utilises a central integration module, but decision-making is agent-driven, with investments determined on a microeconomic basis (E3 Modelling, 2018). By contrast, MUSE introduces a novel design feature by explicitly incorporating the human dimension into investment decisions. Agents in MUSE make choices based on techno-economic criteria and investment preferences, capturing behavioural heterogeneity across regional, temporal, technological, and social layers (Giarola et al.,

2022). This approach provides a more realistic representation of market dynamics and distinguishes MUSE from earlier modelling frameworks.

2.2.7 MUSE application in the thesis

The simulation framework of MUSE is tailored to the context of Qatar in a dedicated MUSE-QA version. It encompasses the full value chain of the energy system of Qatar starting with upstream hydrocarbon operations and extending through downstream conversion processes to meet both domestic and international demands for energy commodities.

MUSE-QA investigates the intricate relationship between supply and demand in Qatar energy system, with a particular focus on capital investment decisions as the key driver of system evolution. This will assess Qatar energy system economic performance and environmental implications of alternative pathways. The ultimate objective is to identify and inform transition strategies that balance economic resilience with emissions mitigation, thereby charting a feasible and sustainable policy discourse towards a low-carbon future.

2.3 Qatar Energy Profile

Qatar's early and relatively marginal participation as a nascent and small member of the OPEC and OAPEC, combined with its very small population and limited access to data, initially trivialised its significance in research-based studies. Despite this, one of the earliest documented works that recognised and evaluated Qatar's latent economic and political potential was authored by El Mallakh in 1979 (El Mallakh, 2014). The country's economic influence expanded considerably following its first LNG export voyage to Japan in 1997 (QatarEnergy LNG, 2007), marking the beginning of its emergence as a global energy powerhouse.

With the subsequent rise in demand for Qatari oil and gas, the nation's environmental footprint has also grown markedly. Confronted with intensifying global pressures for climate change mitigation, Qatar has also exhibited awareness of its environmental responsibilities and initiated plans aimed at reducing its impact. This section sets the stage to understand the structure of Qatar energy system, its inherent intricacies and global significance, as well as the country's long-term vision and emissions mitigation outlooks.

2.3.1 Qatar Economic Profile and Global Market Position

Qatar vast reserves of natural gas form the bedrock of the accelerated boom in its economy and the consequent industrialisation and urbanisation. The country's principal resource, the North Field, constitutes the world's largest non-associated natural gas field. Today, Qatar has a natural gas liquefaction capacity of 77 million tons per annum (QatarEnergy LNG, 2024b). Liquefied natural gas (LNG) exports, in addition to refined petroleum products, account for around 37% of the national GDP (International Trade Administration, 2024), while export revenues accrue to more than 50% of total government income (Government of Singapore, 2024).

Second to the hydrocarbon sector, Qatar's industrial sector contributes approximately 15% to the national economic (Trading Economics, 2024a). This sector is largely tied to the energy sector where two-thirds of its output comprising chemicals and petrochemicals (Trading Economics, 2024a). In 2022, Qatar recorded fertiliser exports valued at USD 3.4 billion, strengthening its economic ties with key destinations across North and South America as well as Asia (OEC, 2022). However, this unremitting industrial activity propelled a world score of the highest emissions per capita in 2022 (Statista, 2023).

2.3.2 Qatar Emissions Profile

The Emissions Database for Global Atmospheric Research (EDGAR) compiles extensive global dataset on global emissions that are consistent with the IPCC methodologies and aligned within the UNFCCC reporting framework (EDGAR, 2023). Drawing on this source, Table 2.2 presents Qatar's total emissions (EDGAR, 2023) and the associated CO_2 intensity per unit of GDP over the period 1990-2022. Emissions data for 2010 is obtained from World Bank (2023).

Table 2: Qatar emissions data

	1990	2000	2005	2010	2015	2020	2021	2022	2022% (% of world total)
Total emissions ($MtCO_2$)	17.0	31.8	43.6	60.9	98.9	102.0	106.6	102.6	0.3
CO_2 per capita emissions (tCO_2eq/capita)	35.8	53.6	50.4	35.5	38.9	39.9	36.5	37.5	35.5
CO_2 per GDP emissions (tCO_2eq/1k$)	0.60	0.62	0.57	0.5	0.39	0.40	0.41	0.43	0.4

The year 1990 represents a pivotal stage in Qatar's national development, occurring nearly two decades of political independence from the British Protectorate in the Gulf

region. It marked the nationalisation of the oil sector and the consolidation of a modern governmental and economic framework. This period was characterised by rapid urbanisation, a population hike to approximately half a million, and a one of the highest per-capita income levels worldwide (Al-Malki, 1994). The demographic composition and population growth dynamics are discussed further in Chapter 3.

During the early years of industrial development, electricity and desalinated water were primarily supplied through Ras Abu Aboud Power Station, later supplemented by Ras Abu Fontas-A plant, which had a design capacity of 497 MW (Kahramaa, 2024a; Power Technology, 2024a). The commissioning of these facilities reflected the country's growing energy demand in line with rapid urban expansion and industrialisation.

A major turning point occurred in 1997, when Qatar exported its first LNG shipment to Japan, marking its emergence as a key global energy supplier (Ibrahim & Harrigan, 2012). The subsequent expansion of LNG liquefaction and export infrastructure significantly accelerated the nation's industrial output and energy consumption. As illustrated in Figure 2.5, this industrial and export growth led to a sharp increase in national emissions, with total emissions roughly doubling by the turn of the millennium.

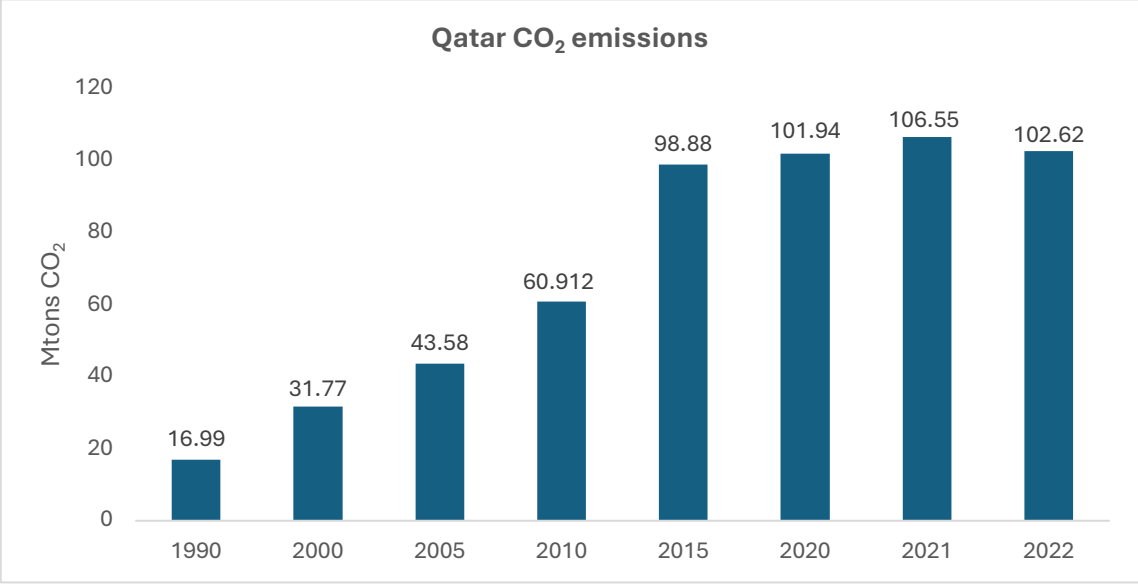


Figure 5: Qatar total emissions trajectory from 1990 to 2022, derived from Table 2.2

Economic growth has made significant strides after the millennium, supported by sustained, though arguably high-risk investments in oil and gas technological advancements. A pivotal step was the inauguration of the *world's first commercial scale GTL plant* in partnership with new joint ventures. This has heralded Qatar's burgeoning technological and economic ambitions. (Al-Malki, 1994).

Following Qatar successful bid to host the FIFA World Cup in 2011, the country experienced a period of rapid industrialisation and accelerated urbanisation, which together drove a substantial increase in national emissions, rising by nearly 60% within just four years (IEA World Energy Balances, 2021). By 2015, the industrial landscape has expanded considerably to include the Oryx-GTL and Pearl-GTL plants, with a combined production capacity of approximately 170,000 bpsd (Shell, 2024). In parallel, the country operated fourteen LNG liquefaction trains with a total output capacity of 77 MTPA LNG (QatarEnergy LNG, 2024b), supported by an extensive chemical and petrochemical production base, further detailed in Subsection 3.1.5.1. This industrial activity alone accounted for 59% of Qatar's total emissions in 2015, as illustrated in Figure 2.5, underscoring the dominant role of the industrial and energy-conversion sectors in shaping the nation's emissions profile (IEA World Energy Balances, 2021).

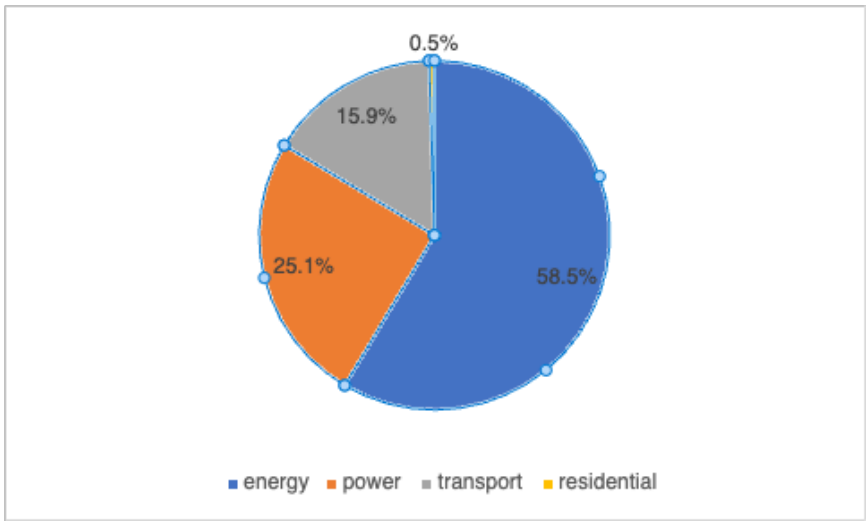


Figure 2.6: Sectoral contribution (%) to total CO_2 emissions in Qatar in 2015, calculated from IEA energy balance dataset for Qatar

In parallel, six new Integrated Water and Power Plants (IWPP) operating on combined-cycle gas turbine (CCGT) were commissioned, delivering approximately 7,500 MW of design capacity alongside ~300 MIGD of thermal seawater desalination. These additions contributed an estimated 20 $MtCO_2$ to national emissions (Kahramaa, 2015). In addition, the transport sector ranked third among emission-intensive sectors, comprising nearly one million vehicles; including private cars, buses, trucks and two wheelers, accounting for an additional 13 $MtCO_2$ (PSA, 2015).

Other sectors, such as the residential sector, contributed only marginally to total emissions, primarily through the use of liquified petroleum gas (LPG) for cooking. The agricultural sector was excluded from this study due to its minimal activity in 2015, when Qatar relied almost entirely on food imports to meet domestic needs. It was not until 2017, when the blockade was enforced on Qatar by the neighbouring countries, during which 40% of Qatar's food imports were disrupted at the southern border, that food security concerns were alarmingly brought into sharp focus (Karanisa et al., 2021). Nevertheless, subsequent initiatives promoting agricultural self-sufficiency and domestic farming expansion fall outside the scope of this thesis.

For the purpose of this research, emissions data are drawn from the IEA energy balance for Qatar. This ensures consistency and reliability in the system-representative data, thereby supporting robust outcome analysis and enhancing credibility of the policy-relevant insights.

2.4 Qatar Policy and Development Strategies

Energy policy and emissions targets gained global momentum after the Paris Agreement in 2016. For Qatar, a hydrocarbon-dependent economy, this represents both a challenge and an opportunity: the country must improve its environmental footprint while safeguarding its economic prosperity. This section outlines environmental improvement plans and energy policy targets for Qatar, providing the foundation for scenario planning, energy system modelling, and policy evaluation in Chapter 3.

2.4.1 World Climate Action

The climate change issue was first addressed in the Earth Summit of the United Nations in Rio De Janeiro in 1992. This was followed by a 5-year review convention which took place in 1997 in Kyoto enforcing emissions caps on developed countries (United Nations Earth Summit+5, 1997, United Nations Climate Action, n.d.). To meet these emissions targets, the protocol suggested three economic strategies: Emissions Trading (ET), Clean Development Mechanism (CDM), and Join Implementation (JI). These strategies launched a new term “Carbon Market” and also opened a window for investment and technology transfer (United Nations Climate Change, n.d.).

After 15 years, the nations reconvened again in Doha, the capital of Qatar, to agree on new mitigation mechanisms for the following period extending to 2020 under the Doha Amendment. This was followed by the Paris Agreement in 2015 which succeeded the Kyoto Protocol and broadened the climate action to include developing countries for a global shared problem (United Nations Climate Action, n.d.). The parties who ratified have set its own climate mitigation plans and released it in Nationally Determined Contributions (NDC).

2.4.2 Qatar Nationally Determined Contribution (NDC)

Qatar ratified at the Paris Agreement in April 2016 and issued its revised Nationally Determined Contribution (NDC) in 2021, committing to reduce its total emissions by 25% of the 2019 baseline level by 2030 under the business-as-usual (BAU) scenario (NDC, 2021). Since the launch of Qatar NDC, mitigation efforts have been evident across the entire energy value chain.

On the upstream side of the energy system, Qatar has already received Kyoto Clean Development Mechanism (CDM) credits for Al-Shaheen Oil Field gas recovery and utilisation project. More recently, it inaugurated the largest carbon capture and storage (CCS) facility in the MENA region, with a 2.2 MTPA CO_2 capture capacity. On the power generation side, Qatar has commissioned its first solar power plant with a capacity of 800 MWp, marking a significant step toward diversifying its energy mix. On the service demand side, *Tarsheed* initiative has been pivotal in promoting public awareness on efficient power and water consumption (Kahramaa, 2013).

Additional measures include improvements in public transportation services through the commissioning of Doha Metro, and setting transport electrification targets (NDC, 2021). These initiatives complement broader urbanisation and sustainability strategies embedded in the Qatar National Vision 2030 (QNV 2030, 2008).

2.4.3 Qatar National Vision (QNV)

Qatar National Vision (QNV) 2030 articulates the principle of balancing economic growth with environmental stewardship. While the country's abundant hydrocarbon reserves have served as the backbone of its prosperity and elevated standards of living, the Vision recognises that these finite resources must be sustained responsibly. Therefore, the QNV emphasises the dual objective of maximising economic benefit while minimising environmental harm. This ambition is framed through industrial strategies that deploy advanced technologies and adopt international benchmarks for environmental

sustainability. Above all, the QNV underscores the necessity of maintaining an equilibrium between *"reserves and production",* to ensure both "*intergenerational equity and long-term resilience".* (GCO, 2008).

2.4.4 Qatar National Development Strategy (NDS-1 & NDS-2 and NDS-3)

Qatar National Vision sets out a long-term blueprint for the way forward for Qatar. It has prompted the formulation of Qatar National Development Strategy (NDS), which translates the overarching vision into concrete policies and actions. A prime priority of both the QNV and the NDS is the sustainability of Qatar economic prosperity, which underpins standards of living, access to education, health services, and other social development needs. To achieve this, the first release, NDS-1 (2011), stressed on three main goals: economic diversification, infrastructure enhancement, and improved efficiency in resource utilisation. (NPC, 2011).

Building on this, the updated release NDS-2 (2018) reinforced the country's "*development planning culture"*, while broadening its scope to strengthen Qatar partnerships within the MENA region and beyond. A key component of the NDS-2 was the economic outlook which addressed the volatility of oil and gas markets. A confluence of factors such as technological innovation in exploration and drilling, the rise of new oil and gas production hubs, and growing advancement in clean energy solutions, was recognised as potential driver of oversupply, lowering energy market prices particularly for LNG in the foreseeable future (NPC, 2018). In response to these risks, Qatar embarked upon diversifying its economy through developing three major economic zones that procure for manufacturing, businesses, and technological innovation (DGJ & Partners, 2024).

The updated NDS-3 (2024) introduced a clearer trajectory for balancing economic and environmental sustainability. It highlighted Qatar's commitment to pursue low-carbon pathways, including carbon capture technology and blue ammonia production (NPC, 2024, QatarEnergy, 2022). These initiatives reflect the country's strategic move to

maintain its role as a leading energy exporter while responding to global climate change imperatives.

Taken together, the QNV, NDS-1, NDS-2, and NDS-3, emphasise the importance of robust policy frameworks in sustaining Qatar economic growth while navigating global market transitions.

2.4.5 Qatar National Environment and Climate Strategy (QNE)

In alignment with the climate mitigation ambitions articulated in the QNV and NDS documents, Qatar has launched the National Environment and Climate Change Strategy (QNE) in 2021. This strategy provides a comprehensive framework structured around three overarching objectives: environmental protection, enhancement of population welfare, and reinforcement of economic resilience (QNE, 2021). It also underscores the country's efforts which include investing in research, innovation, and evidence-based policymaking in achieving sustainable development. This thesis aims to offer an effective contribution to the QNE targets.

Alongside national-level initiatives, Qatar industrial sector has also demonstrated nascent yet significant efforts to support the country's mitigation agenda. Major energy and industrial corporations have begun to embed sustainability into their strategic planning, as evidenced by annual reports that highlight progress in line with the QNV, and the UN Sustainable Development Goals (UN SDG, n.d.).

2.4.6 Sustainability Practices and Long-Term Commitments

This section provides an overview of sustainable practices currently implemented by major key actors in Qatar energy system, while reflecting on their associated environmental impact.

QatarEnergy outlooks represent a central pillar of the country's vision and reflect its commitment to aligning economic growth with environmental responsibility. It asserts on the strategic role of natural gas as a baseload energy source for the global transition due to its reliability, affordability, and relatively cleaner alternative to other fossil fuels (QatarEnergy, 2022). To reduce its emissions footprint, QatarEnergy articulated clear emissions-reduction objectives, including commitment to reduce LNG production line emissions by 35% by 2035, in addition improving operational efficiency in line with the UN SDG 7 and 13. In its 2022 annual report, QatarEnergy exceeded its annual emission abatement target of 35 kt CO2-eq by more than fourfold, demonstrating its capacity to implement effective emissions management strategies.

Qatar Fertiliser Company (QAFCO) is the largest petrochemical company in Qatar and the second largest international supplier of urea (Industries Qatar, 2021). In 2015, the base year used in this thesis, QAFCO produced nearly 6.5% of the world total ammonia production (Statista, 2024). While a considerable amount is consumed internally for urea production, exports amounted to 0.77 Mt ammonia in the same year (Qatar Digital Government, 2024). As a prominent part of QAFCO sustainability agenda, its sustainability report (2022a) identifies the blue ammonia project as a flagship initiative, expected to commence operations before 2030. The project aims to produce 1.2 MTPA of blue ammonia which is an unprecedented scale worldwide; while capturing 1.4 MTPA of CO_2; equivalent to nearly one quarter of QAFCO's current emissions.

Qatar Steel Company leads the steel manufacturing industry in Qatar since 1974, primarily supplying domestic urbanisation and domestic market demands in addition to strategically providing international sales (Industries Qatar, 2023). In its Sustainability Report (2022), it reaffirms its determination in reducing its footprint to present a low-carbon product to the global market through operational efficiency and circular economy. Qatar Steel runs its operations on MIDREX technology which uses natural gas instead of conventional coal, in addition to utilising electric arc furnaces (EAF) which is more energy-efficient than traditional blast furnaces. Hence, Qatar Steel maintains a lower emissions intensity compared to worldwide steel industry average. Looking ahead, Qatar Steel is actively assessing the feasibility of transitioning to hydrogen as a fuel for its

MIDREX operations. This potential shift is incorporated into the modelling framework in this thesis and is examined further in Chapter 3.

Qatar Steel and QAFCO are subsidiaries of the conglomerate **Industries Qatar (IQ)** group which has further investments in other fertilisers and petrochemicals companies in Qatar including QAPCO, QAFAC and their subsidiaries (Industries Qatar Annual Report, 2023). The main energy source across these industries is natural gas; therefore, the main sustainability efforts across all IQ ventures concern four areas of improvement, which are; energy use efficiency by reducing energy intensity and electricity use, emissions reduction by investing in emission reduction technologies, waste management by reporting and storing quantities appropriately and assessing waste recycling, and lastly water management by recycling and investing in Near Zero Liquid Discharge (ZLD) project (Industries Qatar Sustainability Report, 2021). Due to the lack of quantifiable data for several entities under IQ and the absence of clearly articulated sustainability agenda, this level of granularity in modelling inputs is disregarded. Instead, aggregated data from credible sources, such as the IEA energy balance for Qatar, is employed to ensure consistency and reliability in the analysis.

Furthermore, in the power sector, **Qatar Electricity and Water Company (QEWC)** operates electricity generation and water desalination plants in Qatar, while **Qatar General Electricity and Water Corporation (Kahramaa)** manages transmission and distribution of power and water supply and demand, and negotiating new projects with QEWC (Kahramaa, 2024a). To align with the QNV and reduce the environmental footprint of the sector, Kahramaa (2024c) launched Qatar National Renewable Energy Strategy (QNRES), which sets 2030 targets for sustainability and reliability. It proposes increasing the share of renewables in the electricity mix to 13%, while reducing CCGT and OCGT shares to 72% and 3% respectively. Currently, two solar power plants are inaugurated: one with 800 MWp capacity which has been operational since 2022, and another 875 MW project under development by QatarEnergy. These initiatives are projected to reduce CO_2 emissions by 10% while also supporting transport electrification.

The Ministry of Transport has introduced a comprehensive master plan for Qatar transportation sector, extending to 2050 (MOT, 2024). Among its key objectives, the plan sets a target of achieving a 10% penetration of electric vehicles (EV) by 2030, reflecting the country's commitment to sustainable mobility and emissions reduction.

On the air transport side, Qatar Airways (QA), the state-owned national flag carrier aligned its benchmark for environmental sustainability against the International Air Transport Association (IATA) Four Pillar Strategy, which emphasised technological innovation, operational and infrastructure improvements, sustainable aviation fuels (SAF), and compliance with global market-based measures (QA, n.d.). A key for QA target is the integration of 10% sustainable aviation fuel (SAF) by 2030; which is derived from alternative non-petroleum feedstocks and can reduce lifecycle emissions by up to 80% compared to conventional jet fuel (QA, 2023; USDE n.d.). Because SAF is not yet produced in Qatar, jet fuel production remains tied to refinery production, with capacity calibrated to meet growing international aviation demand. The emissions from refining are included in Qatar emissions balance, but international aviation emissions are excluded under existing UNFCCC accounting framework. This arrangement is consistent with IEA emissions reporting and is considered in following chapters.

2.5 Qatar Energy Transition Studies in the Literature

In recent years, there has been a notable increase in research output addressing the energy transition landscape in Qatar and the broader MENA region. This growing academic and policy interest stems from global climate commitment and the implementation of national development visions, which collectively incentivise the exploration of sustainable pathways for hydrocarbon-dependent economies.

Much of the research focuses on energy-system modelling and optimisation. Bohra (2019) develops a multi-sectoral supply-demand optimisation model to evaluate transition pathways; while Al-Ansari (2015) applies life-cycle assessment (LCA) methods to the energy-water-food nexus to assess the environmental implications.

A number of sector-specific studies complement these system-level analyses. Monawwar et al. (2024) examine electricity consumption patterns to identify opportunities for demand management and efficiency improvements. Ali (2023) assesses the feasibility of energy storage technologies for renewable integration, and Alishaq (2024) explores transport sector electrification as a pathway to reduce national emissions.

Parallel efforts have examined circular carbon economy (CCE) strategies, focusing on carbon capture, utilisation, and storage (CCUS) applications. Ghiat et al. (2022) utilise a mixed integer linear programming (MILP) model to optimise carbon utilisation pathways, while Al-Yaeeshi et al. (2020) and Al-Mohannadi et al. (2020) propose techno-economic and network-integration frameworks to connect CO2 sources and sinks within Qatar's industrial clusters. Sawaly et al. (2024) have extended this research to the LNF sector, evaluating opportunities for emission reduction across the liquefaction process chain.

A summary of key literature addressing to Qatar's energy transition and related environmental research is presented in Table 2.3.

Table 2.3: Summary of research papers on Qatar energy transition in the literature

Topic	Reference	Category
Decarbonization pathway for Qatar: A sectoral approach	Al-Noaimi et al. (2025)	System-wide
Pathways to decarbonisation and economic diversification in Qatar	Contestabile et al. (2025)	System-wide
Analysis of GHG per capita and influencing factors, and the way forward towards transition for countries with major emissions	Filonchyk (2024)	score
Optimisation model to explore environmental solutions for LNG production in Qatar using CO2/LNG metric through circular carbon economy and carbon tax	Sawaly et al. (2024)	Upstream
A system perspective on the sustainable development of Qatar	Contestabile (2023)	System-wide
Optimisation and eviro-economic assessment of solar-cooling systems towards sustainable development: A case study of Qatar	Ismaen et al. (2023)	Residential
Mixed Integer Non-linear Program model to assess carbon integration network and the uptake of renewables to inform policy making in Qatar	Al-Mohannadi et al. (2020)	Upstream
Multi-scale optimisation model to explore carbon capture and utilisation technologies in Qatar	Ghiat et al. (2022)	Upstream
Multi-period optimisation model for techno-economic assessment of carbon networks in Qatar using a number of techno-economic indicators like NPV and IRR	Al-Yaeeshi et al. (2020)	Upstream
Urban growth model for transportation demand in regard to the metro system in Qatar	AlKhereibi et al. (2021)	Transport
Assessing the energy-food-water nexus of Qatar using indicators such as security and resilience to inform policy making	Namany et al. (2021)	EFW nexus
Analysis of the electricity consumption pattern in Qatar to inform policy making at the demand side management	Monawwar et al. (2024)	Power
Optimisation model to assess economic feasibility of energy storage technologies for renewable energy in Qatar	Ali (2023)	Power
Optimisation model for Qatar energy transition over the full supply, conversion, and demand sectors	Bohra and Shah (2019)	System-wide
Life cycle analysis model of the Energy, Water and Food nexus, Qatar as a case study	Al-Ansari et al. (2016)	System-wide
Modelling impact of sustainability policies in Qatar using agent-based approach and life cycle analysis	Attallah et al. (2014)	Construction

2.6 Broader Transition Context

Qatar's energy transition must be understood within the broader context of the Gulf Cooperation Council (GCC) countries, which share comparable socio-economic, environmental, and cultural characteristics, as well as similar hydrocarbon endowments. The economies of the region remain heavily reliant on oil and gas exports, yet all states are now under mounting pressure to diversify and decarbonise in alignment with global climate commitments.

Currently, the GCC countries are implementing distinct, yet converging, strategies for achieving low-carbon transitions. Their Nationally Determined Contributions (NDC) vary in ambition and structure: Qatar targets a 25% reduction in emissions by 2030, Oman 21% by 2030, Saudi Arabia 278 MTCO2 annual reduction by 2030, the UAE 47% by 2035 , Kuwait 7.4% by 2035, while Bahrain has yet to formalise an NDC target (UNFCCC Qatar, 2021; UNFCCC KSA, 2021; UNFCCC UAE, 2024; UNFCCC Kuwait, 2022; UNFCCC Oman, 2023). These commitments are complemented by long-term carbon-neutrality pledges, by 2050 for the UAE and Oman, and by 2060 for Saudi Arabia, Kuwait and Bahrain (Climate Action Tracker, 2024; EA, 2022). Across the region, shared mitigation strategies centre on improving energy efficiency, expanding renewable energy generation, deploying carbon capture and storage (CCS), and promoting electrification.

Within the regional research landscape, Qatar features prominently in comparative studies examining energy system transitions across OAPEC and GCC member states. For instance, Baidas (2024) develops a policy evaluation study to measure national progress toward environmental sustainability using Circular Carbon Economy Index (CCEI). Broader analyses by Sanfilippo et al. (2024), Qanas & Sawyer (2024), Alnafrah & Mouselli (2024) collectively assess regional transition challenges and opportunities.

Additionally, all of the GCC states have stablished research and institutional frameworks to support evidence-based transition planning. Saudi Arabia leads through the King Abdullah Petroleum Studies and Research Center (KAPSARC, 2025), which develops decarbonisation roadmaps, CCS pathways, and hydrogen-economy scenarios. The UAE,

through Masdar (2025) and its broader national strategies, has positioned itself as a regional hub for renewable energy innovation. Qatar, meanwhile, advances sustainability research through the Qatar Environment and Energy Research Institute (QEERI, 2025) which spans its sustainability studies spectrum to include transition road-mapping, renewable-energy technologies, carbon removal technologies, and air and water quality management. Complementary applied research is also conducted at the Qatar Science and Technology Park (QSTP), where the solar test facility supports efficiency impartments and cost reduction studies (Masterson, 2012).

2.7 Hydrogen Economy Pathway

Qatar's fossil fuel-based economic structure faces the dual challenge of safeguarding its economic resilience, which is vulnerable to export price volatility, while responding to progressively heightened environmental criteria for fossil-based exports (Mendez and Contestabile, 2025). A hydrogen economy offers a strategic diversification opportunity with natural gas serving as a significant enabler for future hydrogen market (Japan Agency for Natural Resources & Energy, 2014). However, the viability of this pathway hinges on the deployment of cost-competitive carbon capture technologies to maintain the economic attractiveness of steam methane reforming (SMR) (Chapman et al., 2019).

This reliance would inevitably centralise natural gas supply from major gas reserves worldwide, including Qatar; while simultaneously accelerating the need for large-scale carbon sequestration hubs (Hydrogen Council, 2021). Yet, the transition to blue hydrogen alone would not resolve existing risks. It would perpetuate import dependencies, remain exposed to natural gas price volatility (IRENA Hydrogen, 2022), and still emit nearly double the carbon dioxide compared to green hydrogen pathways (Hydrogen Council, 2021). Despite these limitations, a combination of both pathways is economically more implementable solution in the near-to-medium term (BNEF, 2024; Hydrogen Council, 2021).

The economics of hydrogen become more favourable at a narrowed price gap between hydrogen and fossil fuels; assumingly at crude oil prices over ~100$/barrel (Ball and Weitschell, 2009). This means that crude oil price would need to multiply by twofold compared to the base-year average of 52 $/barrel Brent benchmark (EIA Today in Energy, 2016). In principle, fuel switching from fossil fuels to hydrogen is likely to impose an initial cost premium. However, this is expected to be progressively offset by the introduction of carbon taxation, higher hydrocarbon prices, falling renewable energy costs, economies of scale in addition to operational efficiency improvement (EPRS, 2020; IRENA Hydrogen, 2022).

2.7.1 Hydrogen Value Chain

The burgeoning effort in transitioning to hydrogen is prominently driven by energy policy imperatives aimed at enhancing energy security and reducing emissions. However, similar to electricity, hydrogen is not an energy source but an energy carrier, and its role in the energy transition is fundamentally bound to its production route. (Ball & Wietschell, 2009).

Hydrogen production through the thermal steam methane reforming process (SMR) is already a mature and established technology in Qatar, currently supplying 1.20 MTPA of grey hydrogen to petroleum refineries, chemical and petrochemical industries, and steel plants, with an associated carbon footprint of ~12 $MtCO_2$ per annum (Earthna, 2025). This production route, characterised by uncapped emissions of 9.3 $kgCO_2/kgH_2$, remains cost-competitive with a production cost of 1.5 €/kg H_2, however, integrating carbon capture facilities raises this cost to 2 €/kg H_2; to produce blue hydrogen (EPRS Erbach & Jensen, 2021). Such a pathway is particularly relevant for Qatar, as capturing the total CO_2 emissions from existing industrial hydrogen production would offset nearly one-third of the reductions required to meet the footprint target under the NDC scenario discussed in Chapter 3.

Another variation of SMR is Autothermal Reformation (ATR) process, which offers higher efficiency and produces a more concentrated CO_2 stream that can be captured at a relatively lower cost than SMR (IEA, 2025). Electrolysis, on the other hand, is the process that utilises renewable electricity to split water into oxygen and hydrogen. The resulting "green hydrogen" is currently more expensive, with a production cost of ~5.51.5€/kg H_2 (EPRS Erbach & Jensen, 2021). Other emerging processes, such as natural gas pyrolysis (Oni et al., 2022) and thermolysis of water (Faye et al., 2022), are excluded from this study due to limited efficiency (Li et al., 2024) and low Technology Readiness Levels (TRL) (Ozcan et al., 2023).

Hydrogen transport and storage account for the majority of its delivered cost, with production contributing only ~15%, compared to 35% for transportation and 50% for

storage (McKlveen & Roy, 2024). Transportation distance has the highest effect on the cost (Ball & Wietschell, 2009). Hydrogen can be transported through adapted gas distribution networks, depending on its physical state. Notably, liquified hydrogen (LH_2), as an analogue to liquified natural gas (LNG), has already been successfully shipped from Australia to Japan in the world's first Suiso Frontier vessel (Kawasaki, 2024). However, arguably, the International Chamber of Shipping (ICS) estimates that ~300 such vessels would be required to meet Europe's 2030 hydrogen demand target (Hydrogen Insight Martin, 2024).

For long-haul maritime transport, hydrogen storage and delivery are expected to focus on two main vectors: liquified hydrogen (LH_2) and ammonia (NH_3). Both options are compatible with proposed "hydrogen-ready" LNG import terminals, as recently announced by the German utilities RWE and Uniper (Lambertz, 2022; Radowitz, 2022). These pathways are considered the most viable for large-scale, cross-border hydrogen trade and are examined further in Chapter 5.

2.7.2 Global Hydrogen Demand

The hydrogen council projects a global expanded use for hydrogen by 2050, especially in the transport and industrial sectors, spurring demand up to 660MT in a Net Zero scenario (Hydrogen Council McKinsey & Company, 2021). Hydrogen for transport has already been deployed in China in the world's third largest market for fuel cell electric vehicles. This large demand is met by local grey hydrogen supply (IRENA Hydrogen, 2021). In a Net Zero future, however, grey hydrogen is expected to be gradually phased out and replaced by an estimated 38% expansion in electrolysis capacity (BNEF, 2024). Under these conditions, blue and green hydrogen demand in China is projected to account for one-third of global demand (Hydrogen Council McKinsey & Company, 2021).

Given that China is currently the largest importer of Qatari LNG (GIIGNL, 2023), Figure 2.6, this relationship established a strategic foundation for continued energy trade.

Should hydrogen gradually displace natural gas, China emerges as a highly attractive long-term export market for Qatar.

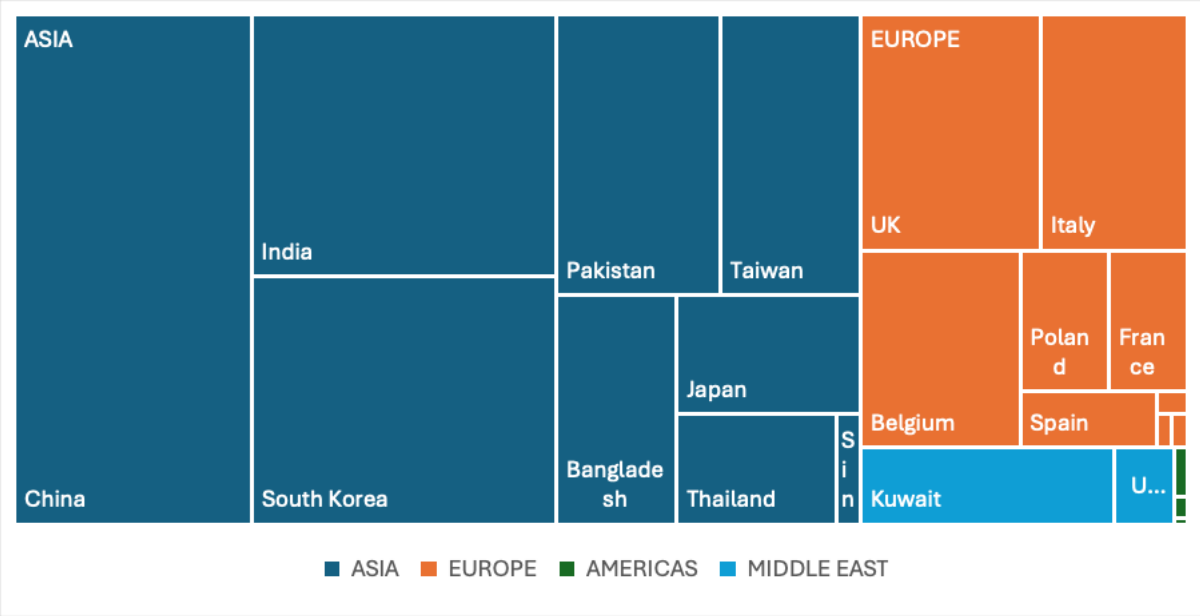


Figure 6: Qatari LNG importers in 2022, showing large market concentration in Asia.

India, the second largest LNG importer in Asia, recently extended its supply agreement with Qatar 20-years beyond the original 2028 expiry (QatarEnergy news, 2024). Domestically, India aims to double the share of natural gas in its fuel mix by 2030 (Offshore Technology, 2024). However, under its extended Net Zero target for 2070, India also plans a gradual shift towards domestically produced green hydrogen as a means to reduce import dependency (Government of India Ministry of New and Renewable Energy, 2023).

South Korea has positioned itself as a frontrunner in the global hydrogen transition (Milweski, 2023), inaugurating its first blue hydrogen facility in 2023 with a production capacity of 1 ton H_2/day, targeted at decarbonising its public transportation (Collins, 2023). Similarly, Japan successfully imported liquified hydrogen from Australia in 2022 under the Hydrogen Energy Supply Chain (HESC) project, reflecting its strategy to hedge against limited domestic supply (Toshibayashi & Kutty, 2024); while simultaneously seeking to expand its role in exporting hydrogen technology advancements worldwide

(METI, 2023). By 2050, combined hydrogen demand in South Korea and Japan is projected to reach 33 Mt, much of which will be supplied from imports (Hydrogen Insight Martin, 2024). This underscores a strong potential export opportunity for Qatari LNG and blue hydrogen, which is assessed in Chapter 5.

Europe, incentivised by the switchover from Russian energy imports (Tatarenko et al., 2023), has become a central actor in the hydrogen transition. The European Green Deal charts a pathway to achieve 55% emissions reduction by 2030, complemented by the European Clean Hydrogen Alliance, which bolsters the rollout of clean hydrogen projects (European Commission, 2023; European Commission, 2021).

A leader in this switchover is Germany, who owns ~50% of Europe's electrolysis capacity (Power Engineering, 2021). It has rolled out decarbonisation projects of the steel industry like tkH2Steel, which will consume 140 kt of green hydrogen abating 3.5 $MtCO_2$ annually (BMWK, 2023). Similarly, the United Kingdom targets of 10 GW of low-carbon hydrogen within its energy mix by 2030 of which 4 GW to be CCS-derived (Department for Energy Security & Net Zero, 2023; The Oxford Institute for Energy Studies, 2024).

At COP28, the EU announced a 2030 target of 20 Mt of renewable hydrogen, with 10 Mt sourced domestically and another 10 Mt imported (The Hydrogen Europe Quarterly, 2023). To meet this domestic target, it is estimated that an 18% increase in 2021 power production levels is required coupled with a significant scale-up of electrolyser capacity (ERCST Marcu et al., 2024). However, progress remains limited, and the European Court of Auditors (2024) has criticised the target as politically driven and overly ambitious (ERCST Marcu et al., 2024). The turmoil is further uneased by the implications of inflation and high discount rates, stranding the profitability of the economy of scale (Martin(b), 2024).

Therefore, amongst the different colours of hydrogen, blue hydrogen emerges as an economically attractive option, at nearly half the cost of green hydrogen (Martin(b), 2024). This positions Qatar as a potential supplier, especially as Europe's projected

hydrogen demand by 2030 is comparable to the LNG volumes exported by Qatar to Europe in 2022.

2.7.3 Readiness to import hydrogen

Perhaps the most critical challenge in realising a hydrogen economy lies in the establishment of a dedicated market for hydrogen. A functioning market would, in turn, drive technological development, infrastructure expansion, and regulatory improvements. This must be accompanied by efforts to reduce the *levelised cost of hydrogen production and delivery* (Rasul et al., 2022). Importantly, the pace and success of market creation are highly contingent on policy initiatives and clearly defined targets, as demonstrated in Chapter 5.

On the technical side, the transition from LNG to LH2 poses substantial challenges. Hydrogen liquefaction requires more than three times the energy consumed in LNG liquefaction (Sameul & Fakhry, 2023). It also requires cryogenic temperatures, leading to inevitable boil-off losses induced by the substantial temperature differential between the LH_2 storage tanks and the ambient conditions (Ratnakar et al., 2021). Furthermore, LH_2 has a substantially lower energy density than LNG, which necessitates more than double the shipment volume to deliver an equivalent energy content (Martin(c), 2024).

As an alternative, hydrogen can be transported as ammonia (NH_3). The virtue of this method is that it benefits from existing infrastructure and market familiarity; as Qatar is already a major global exporter of ammonia and has announced future plans for blue ammonia production as discussed in Section 2.4.6. Moreover, ammonia can be shipped at an efficiency of 90% compared to 84% for LH_2 (Chatterjee et al., 2021). However, reconversion back to hydrogen at the point of use incurs significant efficiency losses, reaching up to 80% of the initial energy input (Martin(c), 2024). In fact, the installation of ammonia cracking facilities at destination ports introduces additional cost factors, despite the economic feasibility of repurposing LNG terminals for ammonia handling (Fraunhofer, 2022).

Nevertheless, both LH_2 and NH_3 face limitations as fuels compared to LNG, with uncertainties surrounding the long-term size and stability of demand markets (Fraunhofer, 2022). Technical challenges including the repurposing of LNG infrastructure, regasification at receiving terminals, and distribution to hydrogen fuelling stations are beyond the scope of this study. Instead, this research assumes a progressively more prepared market by mid-century and focuses on production technologies as the primary driver of hydrogen integration.

2.7.4 Qatar hydrogen strategy and readiness to export hydrogen

As non-renewable hydrogen exhibits a potential accelerator of the energy transition, it has drawn particular attention from oil- and gas- exporting states in the Gulf Cooperation Council (GCC). The United Arab Emirates and Oman have already established national hydrogen strategies (MoEI, 2023; MEM, 2022), while Qatar has not yet formalised one. Nevertheless, the State has articulated its hydrogen ambitions through large-scale blue ammonia production initiative (Hydrogen Insight, 2024) Investment in blue ammonia harnesses the State's natural gas endowment and mature infrastructure, offering an attractive pathway to low-carbon energy production through integrated carbon mitigation measures (Okonkwo et al., 2021).

The anticipated ramp up of blue hydrogen demand across emerging hydrogen economies could serve as a strategic outlet for increased demand for natural gas, potentially supporting the stability of LNG export market (Al-Kuwari & Schonfisch, 2021). Beyond direct export of LNG for blue hydrogen production abroad, another investment avenue lies in repurposing domestic LNG infrastructure for low-carbon hydrogen production. This approach positions blue hydrogen as a transitional substitute for LNG in energy-importing economies (Hjeij et al., 2022). The uncertainty surrounding hydrogen impact on Qatar energy system, and its role in shaping export trajectories, provides the rationale for the modelling analysis developed in this chapter.

2.7.5 Relevant studies

The hydrogen pathway represents more than just a decarbonisation strategy; it also provides a potential mechanism to circumvent emerging trade regulations, such as the European Union's Carbon Border Adjustment Mechanism (CBAM). CBAM imposes a carbon price on imported goods based on their embedded emissions (European Commission, 2025). Although LNG is currently not included within its scope, however, it is likely to be enacted in the future as the EU seeks to level market competitiveness by offsetting cost disparities between its producers and exporters from jurisdictions without carbon pricing (Fundacion Empresa & Clima, 2023). In light of to such uncertainties and market risks, recent studies have increasingly explored both the domestic deployment of hydrogen to decarbonise hard-to-abate industries and its role in international trade as a clean energy commodity (Mendez & Contestabile, 2025; Earthna, 2025). Furthermore, research has been extended to assess and propose a hydrogen framework for production and export in Qatar (Hjeij et al., 2022; Okonkwo et al., 2022), underscoring the country's emerging potential to leverage its natural gas resources and infrastructure in transitioning toward a low-carbon hydrogen economy,

2.8 Research Gap and Contribution

While numerous regional and global studies have emerged to evaluate energy transitions, persistent gaps remain in Qatar-specific system modelling, scenario integration, and cross-sectoral decarbonisation analysis. Existing research largely focuses on optimisation models or ad hoc, sector-specific frameworks that prioritises cost-minimisation objectives. However, these approaches overlook the behavioural, temporal and technological diversity that characterises real-world system evolution. Consequently, no study has yet developed an integrated simulation framework that captures the dynamic interactions across the entire energy value chain. Chapter 1 addresses this gap through the development of the MUSE-QA simulation model, which integrates Qatar's supply, conversion, and demand sectors to evaluate their interactions, and long-term evolution under alternative decarbonisation scenarios.

A second knowledge gap concerns the absence of comparative frameworks that synthesise simulation and optimisation paradigms within Qatar's unique hydrocarbon-based economy. Without such comparative studies, policy design risks being guided by narrow optimisation outcomes or unrealistic emission-reduction ambitions. Chapter 2 responds to this need by benchmarking MUSE-QA outcomes against the optimisation-based QT-TIMES model. This comparison identifies complementarities between the two approaches and extracts policy-relevant insights that bridge the gap between global optimisation paradigms and market-behavioural dynamics.

Finally, there is a clear need for evidence-based modelling tools that link national transition pathways to global climate objectives, particularly under growing international pressure to diversify away from fossil fuels towards clean alternatives such as hydrogen. While recent studies, such as Mendez & Contestabile (2025) and Okonkwo et al. (2021), have explored market uncertainties and strategic options, none have yet incorporated Qatar’s full energy system dynamics to assess how national decarbonisation interacts with international mitigation goals. Chapter 3 fills this gap by analysing hydrogen production pathways, market competitiveness, and infrastructure implications, thereby situating Qatar within the emerging global clean-energy export landscape.

Collectively, these research components provide a comprehensive, multi-layered framework that advances both methodological and policy understanding of Qatar’s energy transition. By integrating simulation, optimisation, and future-fuel foresight, this thesis generates novel, policy-relevant insights that support the design of adaptive strategies for achieving sustainability goals while safeguarding national economic resilience.

2.9 Chapter Summary

This chapter sets the grounds for the context of Qatar energy system. It illustrates Qatar energy and economic portfolio and its role in the global market. It showcases that Qatar, as an early Paris Agreement signatory, is willing to reduce its carbon footprint. This is

evident in the nation climate action plans and the local energy industries contributions. This thesis will assess Qatar energy system economic and environmental performance using energy system modelling and will evaluate its policies in the next chapters.

Chapter 3

A Simulation model for Qatar Energy System

This chapter addresses a critical gap in the knowledge base of Qatar energy system by developing a simulation model to analyse its structure and delve into its intricacies. The focus is on modelling decarbonisation pathways under specific emissions reduction targets, providing insights into system configuration and transition strategies. The simulation will be complemented by a sensitivity analysis to assess the impact of exogenous attributes on the model outcomes. This chapter forms the basis for the subsequent chapters.

3.1 MUSE-QA

This section tailors MUSE platform to the context of Qatar energy system. It establishes the baseline configuration for the reference year, reflecting the system's intricacies and distinctive characteristics, thereafter, projects the system evolution toward mid-century under three distinct emissions scenarios.

This project utilises MUSE-OS version 1.5.2, written in Python, operated on macOS Terminal using TOML files, and visualised in Jupyter Notebook using Ai generated codes, Origin and Microsoft Excel platforms. The source code is available on open-access basis via the Energy Systems Modelling Lab's Github repository: (https://github.com/EnergySystemsModellingLab/MUSE_OS.git)

3.1.1 Model settings and framework

MUSE-QA is configured as a single-region model with 2015 as the base year. This year is selected because it represents a typical period for Qatar, supported by a complete dataset for both the national energy balance and emissions balance in the IEA database.

Unlike subsequent years, 2015 was unaffected by the political blockade imposed in 2017, the industrial disruptions of the COVID-19 pandemic, or the accelerated preparations for hosting the 2022 FIFA World Cup. Moreover, it provides a benchmark year prior to Qatar's ratification of the Paris Agreement in 2016, making it a suitable starting point for long-term projections.

The simulation timeframe spans from 2015 to 2050, divided into 5-year intervals. Each model year consists of two representative days (a weekday and a weekend) across two seasons (summer and winter). Each day is further divided into four diurnal timeslices: morning, afternoon, evening and night; yielding a total of 16 uniformly *distributed* timeslices per year. Table 3.1 summarises these settings.

Table 3.1: Global settings for MUSE-QA model

Settings	Definition
Simulation periods	2015-2050
Temporal steps	5-year step
Timeslice	2 seasons, 2 representative days per season, 4 diurnal timeslices
Sectors	Industry, export, residential, water desalination, service, transport, power, oil and gas processing, upstream supply of oil and gas
Regions	Qatar - single region model
Data interpolation	different demand projection scenarios
Tolerance on commodity demand	0.1% deviation between iterations
Number of iterations	100
CO2 budget	different scenarios
Budget method	bisection

The model sectors are illustrated in Figure 3.1, which depicts the Reference Energy System (RES) of the model. The RES, originally developed for the TIMES model for Qatar (QT-TIMES), visually represents the complex network of technologies and commodities

flows in the base year (IEA-ETSAP, 2005). For this study, the RES has been adapted from QT-TIMES model to align with the MUSE-QA framework.

The structure of the RES comprises three main components:

1. **Supply sector (UPSTREAM):** This includes extraction technologies for the primary energy vectors which are natural gas, natural gas liquids (NGL), and crude oil.
2. **Conversion sectors (GTL-REFINERIES and POWER):**
    - *GTL-REFINERIES* represents oil and gas processing facilities, encompassing oil refineries, gas-to-liquid (GTL) plants, and liquefaction plants for LNG. It also incorporates hydrogen production technologies, notably steam methane reforming (SMR), alongside other low-emission options.
    - *POWER* represents electricity generation capacity, primarily gas-fired plants, supplemented by renewables. It also produces heat in Combined Heat and Power (CHP) plants for use in water desalination plants located at the demand side of the model.
3. **Demand sectors:** These encompass service demand categories, including:
    - *WATERDESAL* for desalinated water demand,
    - *INDUSTRY* for fuel and feedstock consumption in industrial processes,
    - *EXPORT* for external demand of both primary energy and processed petroleum commodities,
    - *TRANSPORT* for fuel use across modes of transportation,
    - *RESIDENTIAL* for domestic energy use,
    - *SERVICE* for commercial energy use.

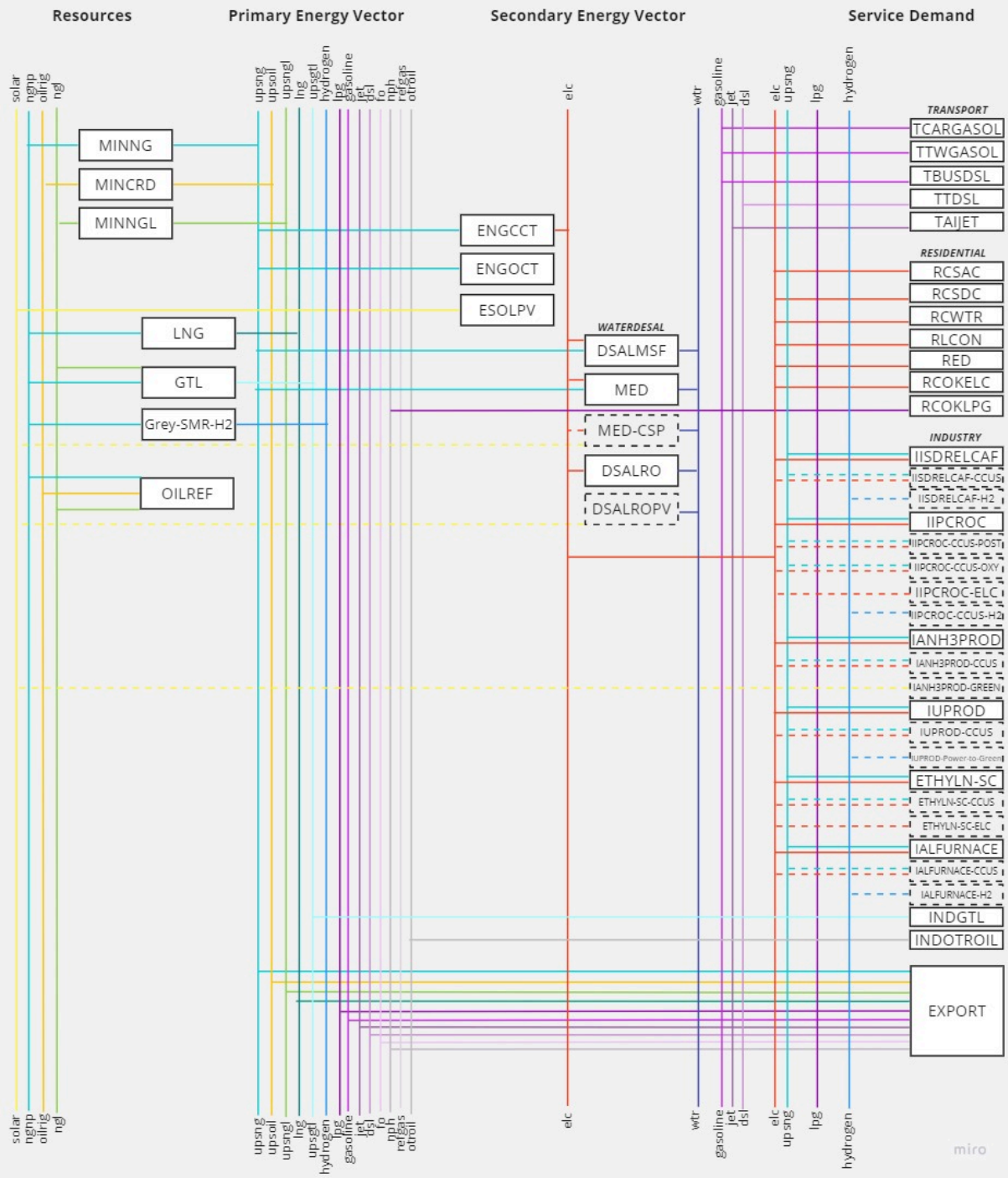


Figure 3.1: MUSE-QA Reference Energy System, adapted from QT-TIMES RES

MUSE also incorporates a global trade feature which enables energy imports and exports, and interregional exchanges. In the case of MUSE-QA, however, this function has been disabled, as the Qatar energy trade is predominantly export-oriented. Furthermore, regional electricity interconnectors, such as the Gulf Cooperation Council

Interconnection Authority (GCCIA) grid, does not represent a stable or continuous demand line, as it is primarily activated during emergency outages (GCCIA, 2020).

3.1.2 Agents Settings

In agent-based modelling (ABM), the selection of agents must reflect a realistic representation of the system decision-making powers and their interactions within a defined framework (Singh, 2024). Contextual relevance is key, as different types of agents are suited for specific study purposes. For example, in studies of social transformation dynamics, the principal actors would be families and communities, whereas in studies of market behaviour dynamics, the critical actors are consumers and suppliers (Singh, 2024).

The literature reports various approaches to agent selection within the context. In a study by Mohandes et al., (2019), agents were identified as households differentiated by ownership types to the diffusion of residential solar systems. Atallah et al. (2014) analysed the construction sector designating developers, consultants, and contractors as the primary agents to simulate rate of adoption of sustainability practices. Meza et al. (2021) studied global LNG market under volatile dynamics, defining agents as LNG exporters including Qatar, LNG importers, ships, shipments, and contracts. In each of these studies, agents were assigned attributes that reflect their influence on decision-making processes. *These attributes serve as proxies for the economic, social, and technical drivers shaping energy-related* investments.

In the context of Qatar energy system, the government of Qatar retains ownership of natural resources and full authority over its utilisation, ensuring that resource wealth is leveraged for national benefit (Al-Malki, 1994). This strategy was effectively implemented through international partnerships and joint ventures, facilitating both knowledge and technology transfer (QatarEnergy JVs & Partners, 2023). Despite these collaborations, the state-backed National Oil Company (NOC), QatarEnergy, consistently retains a majority stake in all ventures. For instance, QatarEnergy's shareholding in the LNG sector ranges

from 63% to 100% (QatarEnergy LNG, 2024), in the North Field expansion project stands at 75% (TotalEnergies, 2022), and in the upstream and downstream segments typically ranges between 51% to 70% (QatarEnergy Annual Review, 2022). Such substantial shareholding ensures custodianship over national resources while providing strategic leverage in investment and policy decision (Al-Fattah, 2013).

In MUSE-QA, agents represent the decision-making entities of investors and consumers, designed to reflect real-world investment preferences (Imperial College London, 2024). Their behaviour is governed by a set of configurable rules, as outlined in Section 2.2.3. For this study, the *search rule* is defined as unconstrained, enabling agents to select freely among available technologies to meet demand. The *decision metric* (objective function) is set to the levelized cost of energy (LCOE), which will be discussed in detail in section 3.1.3. The agent type is specified as *New*, allowing for investment in both replacement of decommissioned assets and capacity expansion to meet emerging demand (Imperial College London MUSE, 2024). Table 3.2 summarises the configuration of the agent settings applied in this model.

Table 3.2. Basis of scenario design and agent characterisation

Scenario	Agent	Objective Function	Carbon Price	Carbon Budget
BAU	A1	LCOE	unconstrained	unconstrained
NDC	A1	LCOE	EU ETSA	25% emissions reduction by 2030 due BAU
NZ50	A1	LCOE	EU ETSA	zero emissions by 2050

3.1.3 The Decision Metric: LCOE

The levelised cost of energy (LCOE) is a widely used economic metric for ranking cost-effectiveness of energy technologies within a system (Sung & Jung, 2019). It is frequently employed by governments to inform policy decisions and evaluate decarbonisation pathways (Aldresey-Williams & Rubert, 2019). Several modelling studies have utilised this metric in comparative analysis between carbon-based and renewable technologies. Aldresey-Williams & Rubert (2019) used a Monte-Carlo simulation model to explore a

spectrum of energy LCOE based on different interest and inflation rates. Another Monte-Carlo model used by Tran & Smith (2018) to compare technologies in the power mix in the United States.

In MUSE-QA, the LCOE is adopted as the principal driver of investment decisions. Given the centrality of oil and gas to Qatar economy, minimising energy costs to meet domestic demand while safeguarding export revenues is of paramount importance.

This objective is not confined to the supply sector alone but extends across the full energy system, encompassing conversion and end-use consumption. The reliance on LCOE as the overarching objective is justified by the linear structure of Qatar energy system, in which a centralised key actor, the government and its representatives, plays a dominant role in investment decision. Furthermore, the influence of this objective extends to consumer behaviour, particularly under the current regime of heavily subsidised energy prices for citizens.

From a modelling perspective, adopting LCOE as the central optimisation criterion also ensures computational tractability and *reduces computational burden*, thereby allowing efficient execution of multiple simulation runs in MUSE. Conceptually, LCOE gauges the total cost of a technology over its lifetime relative to the total energy produced (CFI, 2024). As shown in Equation 3.1, the LCOE formula incorporates the capital costs of development, fixed and variable operation and maintenance (O&M), and fuel costs (Royal Academy of Engineering, 2014).

Equation 3.1

$$LCOE = \frac{\text{Total Lifetime Cost}}{\text{Total Lifetime Energy Production}}$$

This equation can be tailored to the context of analysis by including or excluding specific data inputs (Tran & Smith, 2018). Accordingly, equation 1 can be adjusted in terms of the Net Present Value (NPV). The NPV is calculated by subtracting the revenues from the total project cost over its lifetime (Homer Energy as cited in Imperial College London, 2024).

For LCOE calculations, NPV is typically set to zero, so that the Internal Rate of Return (IRR) equals the interest rate. Hence the LCOE equation can be rewritten as the energy price at which project revenues are sufficient to cover costs while achieving IRR (Aldresey-Williams & Rubert, 2019). This definition of LCOE is consistent with that reported by the UK Department for Business, Energy & Industrial Strategy (BEIS, 2016), and is mathematically expressed in Equation 3.2 (Aldresey-Williams & Rubert, 2019). This formula is also known as the "discounting method" (Filimonova et al, 2022).

Equation 3.2

$$LCOE = \frac{\text{NPV of total costs}}{\text{NPV of electricity generation}} = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}}$$

Here, the time period starts at *t=1* and ends at *n* years, the numerator represents the total costs, and the denominator represents the energy generated in period *t,* all discounted at rate *d*.

Another version of the LCOE formula is generated by the US National Renewable Energy Laboratory (NREL, 2018), which accounts for the capital cost adjusted at a capital recovery factor (CRF). The CRF is a ratio used to annualise cost of capital based over the project lifetime, based on a given interest rate (NREL, 2018). In this approach, expressed in Equation 3.3, the LCOE represents "the minimum price at which energy must be sold for an energy project to break even" (NREL, 2018):

Equation 3.3

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i is the interest rate and n is the number of years to recover the capital cost. On this basis, the NREL LCOE formula is also referred to as the "annuitizing method" and is expressed in Equation 3.4 (Filimonova et al., 2022):

Equation 3.4

$$LCOE = \frac{\text{(overnight capital cost x capital recovery factor)} + \text{fixed O\&M cost}}{\text{(8760 x capacity factor)}} + (fuel\ cost\ x\ heat\ rate) + variable\ O\&M\ cost$$

Both the BEIS and NREL formulations can yeild comparable outputs and remain viable if the input parameters are largely simplified, for example, in the case of a single wind turbine (Aldresey-Williams & Rubert, 2019). In general, the $LCOE_{BEIS}$ generates a present energy value at which the IRR equals the interest rate, making it particularly sensitive to variations in interest rates. By constrast, $LCOE_{NREL}$ generates a minimum energy price required to cover project costs. While it accounts for costs on annual basis, it does not capture cost variability nor the present value of investments. (Aldresey-Williams & Rubert, 2019).

Within the MUSE source code, the LCOE calculation is based on the NREL (2018) version (Imperial College London, 2024). This aligns with the structure of MUSE input framework, which is designed to incorporate year-on-year costs. Thus, the formula can be further adjusted to reflect MUSE-specific parameters as follows in Equation 3.5. The unit is expressed in million U.S. dollars per unit of energy, specific to the relevant sector.

Equation 3.5

$$LCOE = \frac{\mathrm{C} \circ + \mathrm{f} + \mathrm{e} + \mathcal{m} + \mathrm{FV}}{\mathrm{p}}$$

where,

C_0 installed capacity costs = capital costs x capacity (m$/PJ)

f fuel costs = total fuel consumed x consumption rate x fuel price (m$/PJ)

e environmental costs = emissions price (m$/kt$CO_2$) x emissions rate x production (m$/PJ)

$\mathcal{m}$ material costs=production x feedstock price x feedstock consumption rate (m$/PJ)

FV fixed and variable costs = (fixed costs + variable costs) per unit capacity (m$/PJ)

p production = capacity x fixed outputs x utilisation factor (m$/PJ)

In MUSE, the adaptation of the LCOE formula to incorporate environmental impacts is already precedented in the literature. Villone (2019) proposed modifying the conventional LCOE formula to include for the cost of avoiding emissions, while Lazard

(2024) integrated carbon pricing in its LCOE analysis. Such adjustments reflect a growing recognition that environmental externalities should be internalised in techno-economic assessments.

Nonetheless, the LCOE is not without its limitations. Its most notable weakness is that it does not account for utilisation rates (EIA, 2022) which can lead to overestimating the competitiveness of intermittent renewables relative to dispatchable technologies (Joskow, 2011). It is also highly sensitive to financial parameters such as interest rates (BEIS, 2016), which can distort cost and revenue projections under high-rate scenarios (Sung & Jung, 2019). Moreover, the LCOE framework generaly overlooks costs associated with *transmission and distribution* (Kabeyi & Olanrewaju, 2023) as well as costs related to *replacement or degradation* (NREL, 2018).

Realistically, the LCOE alone is not the only economic metric that levers investment decisions, rather, a combination of more complicated economic tools is required to yield a comprehensive analysis that accounts for risks and uncertainties (Thomson & Harrison, 2015). However, with that in mind, the LCOE remains a valuable metric for assessing the economic merit of competing technologies. Its relevance is well established in the literature, including applications such as the Wind Energy Report by the Royal Academy of Engineering (2014). Therefore, in this thesis, the use of LCOE represents a practical tool contributing to the economic evaluation tools for Qatar energy studies and opens a window for future research to expand upon its economic scope to better inform national policy.

3.1.4 The Investment Mechanism in MUSE

As elucidated in Section 2.2.2, the MCA resolves partial equilibrium through a commodity pricing mechanism that balances supply and demand sectors, with the overarching objective of minimising system costs. These prices are calculated endogenously as the *weighted average levelised cost of commodity production* after the first year. The initial year is referred to as the *current year* of investment, the end year in

this timestep is referred to as the *investment year*, while the end year of the simulation horizon is referred to as the forecast year, as illustrated in Figure 3.2. For parameters with unavailable future values, the model applies linear extrapolation.

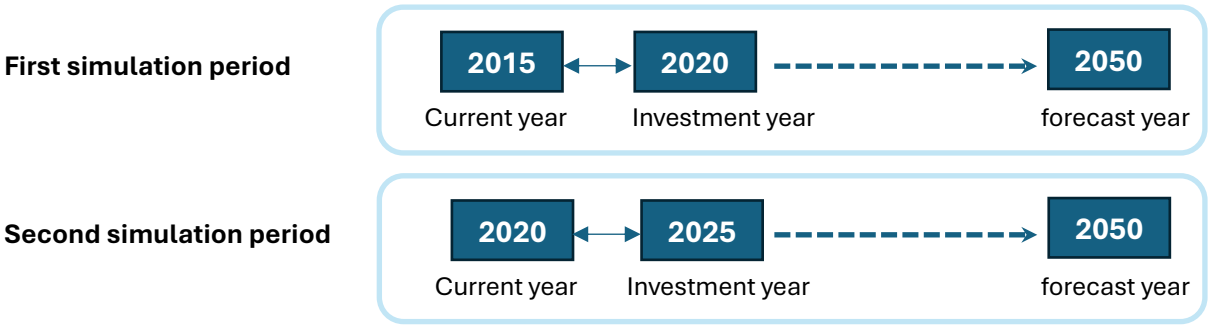


Figure 3.2: Schematic diagram illustrating years of investment at every simulated timestep for MUSE-QA until it reaches the forecast year at the end of the modelling horizon.

3.1.5 Data parametrisation

In MUSE-QA, data are sourced primarily from the IEA energy balance for Qatar and cross-checked with national and international datasets. Input data are structured into three main sets.

First, the **techno-economic set** describes both the technical and economic characteristics of the technologies set, including capital and operating costs. These costs are benchmarked to the 2015 base year and are extrapolated flat-forward to 2050, with the exceptions for variable renewable energy (VRE) technologies and hydrogen, where cost variations are anticipated. Technology naming convention as used in MUSE-QA is listed in Appendix A.

Discounting is applied at user-defined interest rate to reflect the time value of money (Subramanian et al, 2018). For this model, a benchmark rate of 4.5% is used, reflecting a 5-year of historically stable rate of interest in Qatar, despite fluctuations during the COVID-19 downturn and subsequent recovery. Particularly, in 2020 the rate was fixed at 2.5% which was affected by the plunge in international oil prices induced by the COVID-

19 pandemic and the turbulent economic relations between Saudi Arabia and Russia (Trading Economics, 2024; QCB, 2020). Furthermore, in 2023 the rate hiked up to 6.25% which is attributable to the Federal Reserve (Fed) rate hike which is enforced to control post-pandemic inflation (Trading Economics, 2024; QCB, 2022). Despite these fluctuations, the value averages itself to 4.65% over the period from 2015 to present. The discount rate value assigned for MUSE-QA is intended to incentivise economic growth following Qatar Central Bank (QCB) initiative of low interest rate strategy (QCB, 2015).

Next, the **commodity set** identifies system-wide commodities, categorised as energy or environmental, along with attributes such as emission factors, heat rates, and units. This global commodities index is available in **Appendix B**.

Lastly, the **technical set** captures the energy balance in the model through installed capacity profiles, decommissioning schedules, fuel consumption rates, and emissions factors. This is summarised in Table 3.3. It is also possible to assign exogenous constraints on the model which include technology uptake limits by imposing restriction on capacity growth, or power production limits by specifying the temporal utilisation factor per time slice or environmental limits by enforcing a carbon budget.

Table 3.3: Type of exogenous attributes required for MUSE

Area	Parameter
Economy	System cost (capex, fixed and variable)
Environment	CO_2 emission factor
Primary Energy Supply	Installed, decommissioning, expansion of supply capacity
Conversion	Installed capacities and renewable potentials
Service Demand	Growth or supressed service demands limitation

3.1.5.1 Initial Capacity

As part of the technical set, the simulation begins by verifying the stock availability of each technology across all sectors, which extends over the supply, conversion, and demand sides of the system. For every sector, a distinct capacity input file is defined reflecting initial installed stock.

Supply Sector: UPSTREAM

On the supply side, the UPSTREAM sector supplies the system with natural gas, natural gas liquids, and crude oil. Figure 3.3 illustrates the primary energy stock from producing oil and gas fields in 2015 (Pipeline Magazine, 2002; Offshore Technology, 2015; Ugal, 2022; EIA, 2023; Aljazeera, 2018). Beyond the base year, the model extends these capacities aligned with its reported economic life (Offshore Technology, 2024).

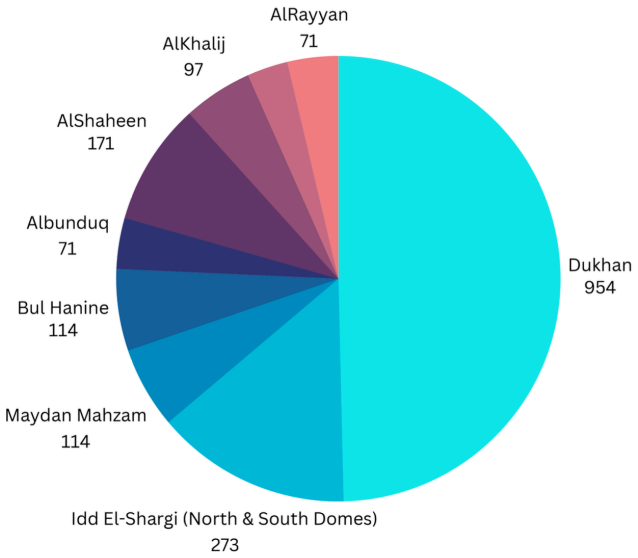


Figure 3.3: Reported oil and gas production capacities in 2015 expressed in (PJ), with the exception of the North Field which is a non-associated gas field

Exceptionally, the North Field service life is estimated to exceed 100 years (Abi-Aad, 1998), which implies that its current production capacity could be sustained well beyond 2050 under favourable cost conditions. However, MUSE does not yet support the enforcement of early retirement or shut down of assets, as is the case in other modelling

frameworks such as TIMES, as elaborated in Chapter 4. Instead, MUSE triggers investment only when supply shortages occur.

To circumvent this limitation, oil and gas fields are assigned a generic retirement profile of 25 years, consistent with the typical lifespan of oil and gas fields which ranges typically between 15-30 years (TotalEnergies, 2015). This retirement constraint ensures that the base-year stock diminishes progressively before 2050 as shown in Table 3.4, thereby enabling the model to allocate new investments earlier in the simulation.

In contrast, all alternative technologies in this sector; particularly those coupled with Carbon Capture and Storage (CCS) and Direct Air Capture (DAC), are assumed to have zero initial capacity. This modelling arrangement ensures that technology in the supply sector is driven by lowest LCOE, allowing MUSE to optimally allocate investment pathways.

Table 3.4: Capacity profile (PJ) for the primary energy vectors. *MINNG* denotes the stock of natural gas and natural gas liquids from associated and non-associated gas fields, while *MINCRD* represents the stock of crude oil from oil fields in Qatar. Base year stock is aligned with the IEA energy balance.

Process Name	Region	Unit	2015	2020	2025	2030	2035	2040	2045	2050
MINNG	QA	PJ/y	8142	7828	7347	7045	6063	5023	0	0
MINCRD	QA	PJ/y	1368	463	335	335	306	0	0	0

Conversion Sector: GTLREFINERIES

This sector groups oil and gas processing technologies, which are gas liquefaction, oil refining, and GTL plants. It also includes potential future investments in hydrogen production technologies, such as steam methane reforming (SMR) and electrolysis.

In 2015, Qatar had two operational oil refineries: the QP Refinery in Mesaieed Industrial City and the Laffan Refinery in Ras Laffan Industrial City. The QP Refinery processes up to 137 kbpsd of crude oil and condensate sourced from Dukhan and North fields. Refined

products are primarily supplied to the domestic market, with surplus allocated for export (QP, 2015). Laffan Refinery 1 (LR1), commissioned in 2009, has a processing capacity of 146 kbpsd. This was complemented in 2016 by Laffan Refinery 2 (LR2), which added another 146 kbpsd to national refining capacity (QP, 2018). Together, these three refineries are classified as large-scale facilities, with potential lifetime of up to 57 years (Lei et al., 2021). Consequently, a significant share of refining capacity will remain beyond 2050. Again, because MUSE does not allow enforced shutdowns, new refinery investments cannot be triggered. Therefore, to enable investment windows in the model, a typical 20-year service life is assigned to refineries in MUSE-QA, reflecting standard assumptions about equipment maintenance and replacement (Kozhemyatov & Bulauka, 2019).

Furthermore, Gas-to-Liquid (GTL) facilities include Oryx GTL and Pearl GTL, commissioned in 2007 and 2011, respectively. Combined, these plants have a capacity of 172 kbpsd of high-quality liquid hydrocarbons (Shell GTL, 2024; QatarEnergy GTL, 2023). Although both plants are technically capable of operating until 2040, they are also assigned a 20-year decommissioning profile in MUSE-QA, consistent with the refineries, to allow reinvestment opportunities towards the end of the timeframe. Initial capacity in this conversion sector is illustrated in Table 3.5.

Table 3.5: Initial capacity profile for oil and gas processing sector in MUSE-QA. Data for 2015 is extracted from the IEA balance and is reduced over a decommissioning profile that corresponds to each asset retirement year

Process Name	Region	Unit	2015	2020	2025	2030	2035	2040	2045	2050
OILREF	QA	PJ/y	526	526	526	222	0	0	0	0
GTL	QA	PJ/y	858	858	858	566	0	0	0	0
UPSLNG	QA	PJ/y	4454	4454	4454	3522	2716	452	0	0

Petroleum products from both refineries and GTL plants include LPG, gasoline, jet fuel, diesel, fuel oil, and naphtha. The IEA energy balance indicates that nearly three-quarters

of this production is exported. Figure 3.4 shows production routes against export. This emphasises the central role of global markets in driving local industrial activity. This concept forms the basis of the study in Chapter 5.

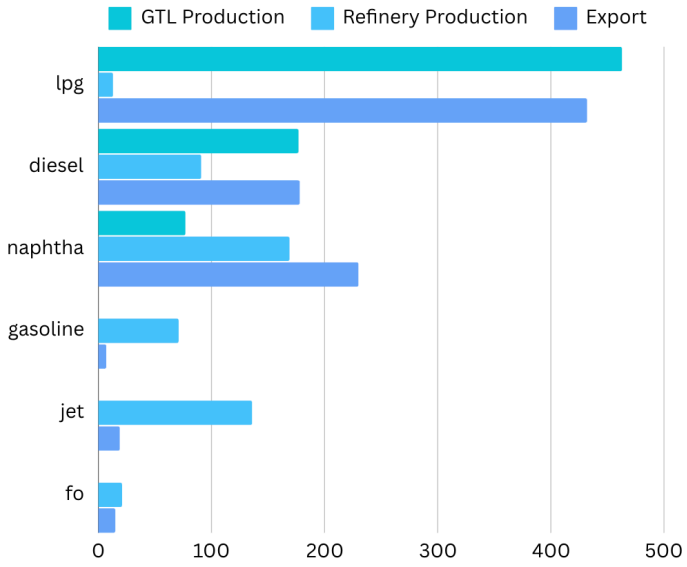


Figure 3.4: Commodities output from the gas processing sector in MUSE-QA illustrating different production routes and comparing produced stocks to exported quantities in (PJ). Data extracted from IEA energy balance for 2015

Moreover, natural gas liquefaction is also represented within this conversion sector. In 2015, Qatar's liquefaction capacity consisted of 14 trains, with a total capacity of 77.5 MTPA, as shown in Table 3.6 (QP, 2018). These plants liquefy North Field gas and export LNG through Ras Laffan Port. Operations are managed by QatarEnergy LNG, a recent merger of Qatargas and RasGas (QatarEnergy LNG 2024).

Table 3.6: LNG plants in Qatar

Liquefaction Plant	Train	Commercial start year	Production capacity (PJ)
Qatargas 1	Train 1, 2, 3	1984	571.7
Qatargas 2	Train 4, 5	2009	445.9
Qatargas 3	Train 6	2010	445.9
Qatargas 4	Train 7	2011	445.9
RasGas I	Train 1, 2	1999	377.3
RasGas II	Train 3	2004	268.7
	Train 4	2005	268.7
	Train 5	2006	268.7
RasGas III	Train 6	2009	445.9
	Train 7	2010	445.9

Conversion Sector: POWER

The power sector in Qatar has evolved significantly since its first diesel-fired power station in Mushaireb in 1953, which had an installed capacity of just 2 GWh (Kahramaa History, 2021; Al-Malki, 1994). Rapid urbanisation and the adoption of air conditioners and refrigerators quickly escalated electricity demand, prompting infrastructure upgrades (Al-Malki, 1994). In 1963, the Ras Abu Aboud steam turbine was inaugurated, followed by Ras Abu Fontas gas turbine power plant in 1977, which supplied 80% of the country's electricity needs (Al-Malki, 1994, Kahramaa History, 2021).

By 2015, Qatar had eight operational power plants, listed in Table 3.7, producing a combined ~38.9 TWh of electricity (Kahramaa, 2015; Power Technology, 2024). This output aligns with the ~140 PJ of electricity consumption reported in the IEA balance for the base year. The initial stock in the POWER sector reflects combined peak load capacity, with retirement profiles of 20 years for open-cycle gas turbines (OCGT) and 25-year for combined-cycle gas turbines (CCGT) as illustrated in Figure 3.5 (ETSAP Gas-Fired Power, 2010).

Table 3.7: Power plants in Qatar

Power Plant	Production Start Year	Capacity (MW)	Technology	Type
Ras Abu Fontas A	1980	497	CCGT	Cogen
Ras Abu Fontas B	1995	609	CCGT	Cogen
Ras Abu Fontas B1	2002	376.5	Gas turbine	Electricity
Ras Abu Fontas B2	2007	567	CCGT	Cogen
Ras Laffan A	2004	756	CCGT	Cogen
Ras Laffan B	2006	1025	CCGT	Cogen
Ras Laffan C	2011	2730	CCGT	Cogen
Mesaieed Power Station	2009	2010	CCGT	Electricity
Um Al Houl Power (UHP)	2018	2520	CCGT	Electricity
Al Kharsaah Solar	2022	800	Solar	Solar

Beyond the base year, a major addition includes Al Khasrsaah Solar Power Plant, which is inaugurated in 2022 with 800 MW capacity, representing Qatar's first large-scale renewable project and it is designed to meet 10% of domestic peak load while avoiding *~26 Mtons* CO_2 (TotalEnergies, 2022). Transmission and distribution networks remain outside the scope of this study.

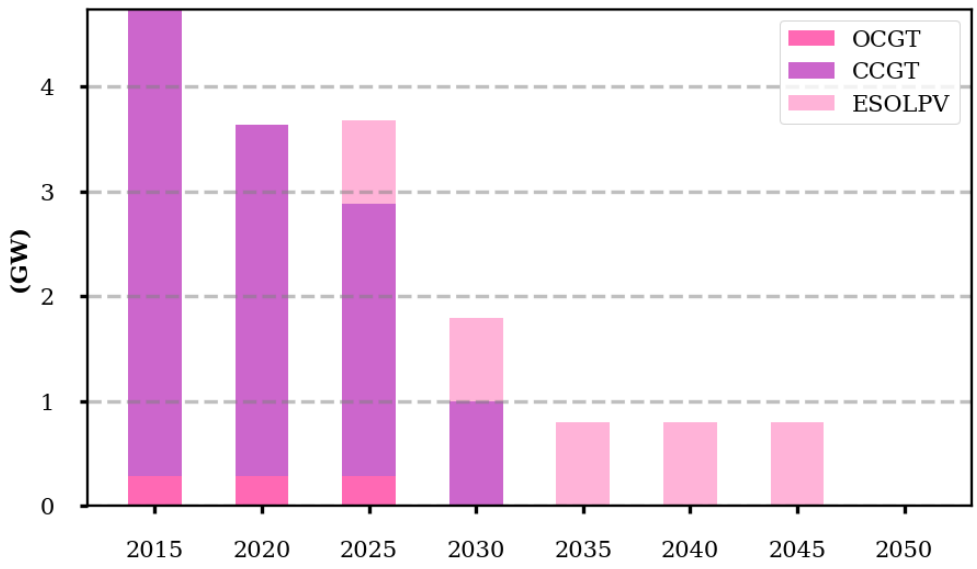


Figure 3.5: Initial power production capacity at a decommissioning profile

Demand Sector: WATERDESAL

The first modern desalination plant in Qatar, Ras Abu Aboud, came on stream in 1964 distilling water through flash evaporation process (Al-Malki, 1994; Kahramaa History, 2021). By 2015, Kahramaa reported seven Multistage Flash (MSF) desalination plants, one Multi-effect Evaporation (MED) plant, and two Reverse Osmosis plants (RO), as shown in Table 3.8 (Kahramaa Annual Report, 2020).

Table 3.8: Seawater desalination plants in Qatar

IWPP	Operator	Start Year	Plant Type	Capacity (MIGD)
RAF A1	QEWC	1981	MSF	44.31
RAF A2	QEWC	2015	MSF	35.14
RAF A3	QEWC	2016	SWRO	35.14
RAF B	QEWC	2002	MSF	33
RAF B2	QEWC	2008	MSF	29.14
Ras Laffan A	Ras Laffan Power	2004	MSF	40
Ras Laffan B	QPower	2008	MSF	60
Ras Laffan C	Ras Girtas Power	2010	MED	63
Umm Al Houl Power (UHP)	Umm Al Houl Power Company	2018*	MSF + SWRO	136.5

In MUSE-QA, these plants represent the initial capacity stock for meeting water demand in 2015. Consistent with the modelling approach for the supply and conversion sectors, capacity is reduced over time to a 25-years plant retirement profile as depicted in Figure 3.6 (Raluy et al., 2006).

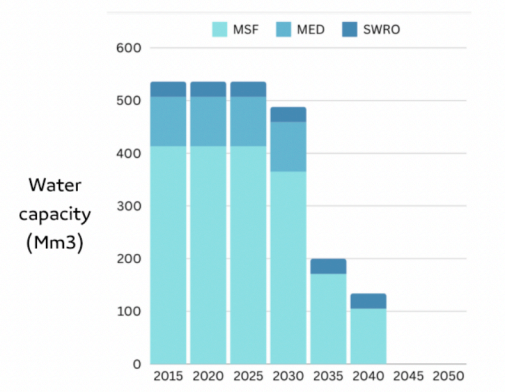


Figure 3.6: Initial capacity of desalinated water (Mm^3) through different technologies as per the base year stock

Demand Sector: EXPORT

In the IEA balance for the base year, the majority of primary energy production in Qatar is allocated for export. Approximately three-quarters of extracted natural gas is exported as LNG, with an additional fixed annual export of 730 bscf supplied to the United Arab Emirates through the Dolphin (Dolphin, 2015). Crude oil exports account for 88% of crude oil production. Natural gas liquids exports comprise half of the extracted stock as the remainder is consumed domestically in refineries and GTL plants. Similarly, most refined products are directed to international market, with domestic demand representing only 28% of total refining output.

In MUSE-QA, the petroleum export stock for the base year is presented in Table 3.9 (IEA World Energy Balance, 2021) This defines the availability of export supply at the start of the simulation. Export volumes are subsequently driven by external demand, as elaborated in Section 3.1.5.1.

Table 3.9: Petroleum commodities exports in 2015 (IEA balance)

Export commodity	(PJ)
LNG	3849.60
Pipeline gas	766.50
Crude oil	1209.70
NGL	1051.30
LPG	432.30
Gasoline	7.30
Jet fuel	18.50
diesel	178.40
Naphtha	229.70
Fuel oil	15.30

Demand: INDUSTRY

After exports, the remaining ~25% of extracted natural gas is directed to downstream operations and used across various industries as both fuel and feedstock. The most energy-intensive industrial sectors in Qatar include iron and steel, chemicals and petrochemicals, and minerals production. For the base year, the initial capacity is represented by the 2015 production stock measured in million tons (MT). These values are compiled from industry annual reports and cross-checked against statistics published by the Planning and Statistics Authority (PSA), and are summarised in Table 3.10.

Table 3.10: Initial industrial stock in the base year 2015 for MUSE-QA expressed in (MT)

Industrial Commodity	Initial Stock (Million Tons)	Reference
Iron and steel	2.71	Qatar Steel (2022)
Minerals: Portland cement	21.84	QNCC (2024)
Chemicals: Ammonia	3.72	QAFCO (2022)
Chemicals: Urea	5.69	QAFCO (2022)
Petrochemicals: Ethylene	1.22	Industries Qatar (2021)
Other industries	1	IEA World Energy Balance (2021)

Demand Sector: TRANSPORT

In the IEA energy balance for 2015, transport fuels are classified as gasoline and diesel. To reconcile with the IEA fuel consumption data, vehicle categories from PSA records were streamlined into four main groups: private cars and two-wheelers which consume gasoline, and trucks and buses which consume diesel (Chapter VIIII Transport, 2015).

The initial transport capacity in MUSE-QA is expressed as the travelled kilometres of each vehicle type in 2015, derived from FAHES data (Alishaq & Mehlig, 2024). Vehicle stock is then assigned a lifetime profile, with decommissioning based on the standard operating limits as elucidated in Table 3.11.

Table 3.11: Initial transport stock in the base year 2015 for MUSE-QA expressed in (MVKT)

Process Name	Region	Unit	2015	2020	2025	2030	2035	2040	2045	2050
cars	QA	Mvkt/y	13947	9205	0	0	0	0	0	0
Two-wheelers	QA	Mvkt/y	195	129	64	0	0	0	0	0
bus	QA	Mvkt/y	3757	2480	1240	0	0	0	0	0
Heavy duty trucks	QA	Mvkt/y	1489	983	491	0	0	0	0	0

Demand Sector: RESIDENTIAL

Energy use in Qatar's residential sector is mainly supplied by electricity, with LPG still used for conventional cooking appliances. However, official statistics providing a detailed breakdown of household electricity consumption by end-use are not publicly available.

One indicative source is a report published in *The Peninsula* newspaper (Ataullah, 2021), which offered rough estimates of household energy use patterns. Based on these estimates, the aggregated electricity consumption from the IEA energy balance was distributed across different household end-uses. Predictably, air conditioning accounts for the largest share of domestic electricity consumption, reflecting the country's climatic conditions and high cooling demand. Table 3.12 summarises this domestic energy consumption distribution.

Table 3.12: Distribution of electricity use in a typical Qatari household.

Residential service demand	Electricity use (%)	Initial Capacity based on electricity use (PJ)
Space cooling	70	38.15
Space heating	1	0.54
Water cooling	3	1.64
Water heating	2	1.09
Lighting	20	10.90
Appliances	4	2.18
cooking	0	0

Demand Sector: SERVICE

Energy use in the commercial sector is almost entirely electricity-based, primarily for space cooling and appliances. In 2015, part of the cooling demand in commercial buildings was met through district cooling, which reached a peak load of 288,660 TR (Kahramaa Annual Report, 2016). Table 3.13 presents the district cooling capacity in 2015 (Kahraama, 2017). The initial capacity for this sector is represented by an aggregated figure, which is taken from the IEA energy balance and is then split according to TIMES-QT estimations.

Table 3.13: District cooling (DC) capacity in 2015

Number of DC	Cooling capacity (TR)	Facility status
23	665,650	operational
42	879,138	Under construction
16	407,800	Under design

3.1.5.2 Sectoral Demands Forecast

Service demand represents the principal driver that specifies and draws energy commodities from the supply and conversion sectors. In MUSE, demand can be generated endogenously through regression models linking GDP PPP and population growth curves (Imperial College London, 2024). Alternatively, users can define a demand profile directly. For MUSE-QA, the latter approach is adopted to better reflect real-world conditions and specify a deterministic demand profile. The demand profile is balanced for the base year 2015.

In many applications, population growth serves as a proxy for service demand projections. This is intended to capture lifestyle modernisation associated with rising GDP. For this study, population growth is taken from the United Nations database for *World Population Prospects* and is projected over medium variant index (UN data, 2022). This projection is verified against other prospects such as World Bank (2022) and World Population Review (2022), and is also consistent with Qatar national population reports

(Permanent Population Committee Qatar, 2024). Table 3.14 summarises the population growth outlook applied in MUSE-QA (UN data, 2022).

It is observed that there is a dip in the total population between 2020 and 2050 reflecting unprecedented decline that occurred in 2021 reducing population growth by -2.61% (macrotrends, 2024). This downturn is linked to COVID-19 impact, including exodus of expatriates followed school closures (Qatar Tribune, 2021) and borders closures (PWC, 2021), in addition to 13.7% COVID induced deaths (PSA Births & Deaths, 2021). Incremental increases, which were as low as 0.26%, were observed in the years following COVID-19 (macrotrends, 2024).

Table 3.14: Qatar population growth forecast based on the United Nations medium variant projection factor

	2015	2020	2025	2030	2035	2040	2045	2050	2100
Population growth (thousand)	2,414.6	2,760.4	2,757.2	2,855.3	2,962.2	3,088.2	3,225.5	3,358.5	4,379.3

Each demand sector in MUSE-QA is assigned a calibrated demand profile for 2015 and projected forward to 2050. These projections are derived from distinct growth indices relevant to each sector, ensuring that the forecast reflects sector-specific drivers rather than a uniform assumption across the system.

Demand Trajectory for Desalinated Water in Sector: WATERDESAL

Annual demand of desalinated seawater beyond the base year is calculated using Equation 3.6, which multiplies average per capita water consumption *x*, by projected population growth p_{t+2}. The average per capita consumption is derived from a five-year period between t_{-2}=2015 and t_{-1}=2020, n=2, and is verified against historical production and census data (Kahrama, 2021). Table 3.15 depicts water demand forecast.

Equation 3.6

$$Annual\_WTR\_Dem_t = \frac{x_{t-2} + x_{t-1}}{n} \times p_t$$

A similar forecast method is applied in Bohra & Shah (2019) for their optimisation model of Qatar, with the difference that they proposed high and low bounds of 200-300 m^3/capita/year. In contrast, the MUSE-QA model assigns an average value of 236 m^3/capita/year, which better reflects observed patterns. Historical records show only modest variation, ranging 216 m^3/capita in 2016 to to 246 m^3/capita in 2020 (Kahraama, 2021). Setting an upper value of 300 m^3/capita appears overstated, particularly in light of ongoing consumption awareness; and risks biasing the model towards unnecessary investments.

Table 3.15: Water demand forecast based on population growth expressed in (Mm^3)

	2015	2020	2025	2030	2035	2040	2045	2050
Water demand (Mm3)	535.40	691.49	651.03	674.19	699.44	729.17	761.62	793.00

Demand Trajectory for Industrial Commodities in Sector: INDUSTRY

Iron and Steel

Qatar Steel, the country's first iron and steel company in Qatar, is also the first in the MENA region to deploy direct reduction-electric arc furnace technology using natural gas (MIDREX, 2022; Atsushi et al., 2022). Commercial production began in 1978 and reached 1 Mt of steel within just three years (Qatar Steel history, 2024). The plant consists of a DRI/HBI Midrex Module, an electric arc furnace (EAF), ladle refining furnace (LRF), rolling mills and other auxiliaries (Qatar Steel brochure, 2022).

Annual reports published by the company provide data from 2010 to 2020, which are used in this study to establish historical production trends. As shown in Table 3.16, steel output fluctuated over this period, reflecting phases of accelerated urbanisation and infrastructure expansion (Midrex, 2021). Notably, steel production surged in response to major construction projects announced in preparation for the FIFA World Cup 2022, before slowing as those projects neared completion. A pronounced drop in production in 2020 is attributed to the economic disruption caused by the COVID-19 pandemic.

Table 3.16: Historical data for Qatar steel production with calculated growth rate

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Steel production (Mt)	2.16	2.23	2.42	2.39	2.64	2.71	2.58	2.63	2.63	2.49	0.78
Growth rate (%)		2	4	-1	5	1	-2	1	0	-3	-52

To project post-2020 demand in MUSE-QA, population growth is indexed as a proxy for continued urbanisation-driven demand. Table 3.16 presents this forecast, which enables the model to capture incremental investment opportunities in line with gradually increasing steel demand.

Cement

Qatar National Cement Company (QNCC), established in 1969, is the country's first national cement manufacturer, developed in response to the booming urbanisation and construction needs (Al-Malki, 1994). The company operates using a Semi-Dry Process. It has undergone several expansions reaching a production capacity of 14,500 TPA (QNCC timeline, 2024).

Historical cement production data, shown in Table 3.17, reveal a clear correlation between cement output, urbanisation trends, and population growth (PSA, 2020). Accordingly, future demand in MUSE-QA is projected in line with population growth profile as depicted in Table 3.19.

Table 3.17: Historical data for Qatar cement production

	2013	2014	2015	2016	2017	2018	2019	2020
Cement production (Mt)	5.17	9.18	21.84	25.37	24.10	21.89	28.62	24.27

Chemicals and Petrochemicals

Qatar Fertiliser Company (QAFCO), established in 1973, has expanded its operations over the years to reach a production capacity of 3.8 MTPA ammonia and 5.6 MTPA urea

(QAFCO, 2024). Ammonia production is conducted through the Haber-Bosch process, where natural gas serves both as a feedstock for hydrogen production via Steam Methane Reformers (SMR), and as a fuel for heat generation. The carbon dioxide released during ammonia production is recycled as a feedstock for urea synthesis (QAFCO sustainability report, 2013).

Furthermore, Qatar Petrochemicals Company (QAPCO) came on stream in 1981, cracking ethane feedstock into ethylene at a capacity of 800 ktpa, and transforming it into low density polyethylene (LDPE) with a total capacity of 700 ktpa across three LDPE plants (QAPCO integrated report, 2015).

In MUSE-QA, future demand for fertilisers and petrochemicals, illustrated in table 3.19, is indexed to population growth. This approach reflects the link between fertiliser consumption and agricultural productivity, as well as the role of petrochemicals in construction and broader industrial applications.

Other industrial products

The category "Other industrial products" in the IEA balance refers to an aggregate of industrial activities with unclear breakdown, yet it accounts for fuel consumption and associated emissions in the system (IEA World Energy Balances, 2023). In the IEA energy balance for 2015, this category reported a fuel consumption of 20.28 PJ of "other oil products" and electricity consumption of 42.79 PJ.

To incorporate this into MUSE-QA, a dedicated demand line is assigned to reflect this consumption, along with corresponding emissions, thereby preserving the integrity of the energy balance of the model. For modelling purposes, an indicative demand of 1Mt is used to denote the 20.28 PJ of fuel consumed. Table 3.18 depicts historical consumption of this category as recorded in the IEA balance.

Table 3.18: Historical consumption data for the fuel: "other oil products" in the IEA balance, that is consumed within a general "other industrial product" technology.

	2015	2016	2017	2018	2019	2020
Other oil products (PJ)	20.3	29.6	21.1	37.6	18.8	34.8

A trend analysis of this data shows a compound annual growth rate value (CAGR) of 2.76%, which is applied as a proxy for projecting future demand. This ensures consistency with observed historical patterns while allowing the model to generate realistic forecasts. Table 3.19 collates demand trajectories for industrial commodities within the MUSE-QA framework.

Table 3.19: Industrial commodities demand forecast

	2015	2020	2025	2030	2035	2040	2045	2050	Reference for base year demand
Steel (Mt)	2.7	0.8	2.5	2.6	2.6	2.6	2.6	2.6	MIDREX (2020)
Cement (Mt)	21.8	24.2	24.7	25.0	25.2	25.4	25.6	25.7	PSA(2020)
Ammonia (Mt)	3.72	3.8	3.86	3.91	3.95	3.98	4.00	4.03	QAFCO (2019)
Urea (Mt)	5.69	5.8	5.89	5.97	6.03	6.07	6.11	6.14	QAFCO (2019)
Ethylene (Mt)	1.22	1.35	1.37	1.39	1.40	1.41	1.42	1.43	PSA
Other industrial products (Mt)	1.00	1.15	1.31	1.50	1.72	1.97	2.26	2.59	IEA balance

Demand Trajectory for Energy Export Commodities in Sector: EXPORT

In MUSE-QA, export commodities consist primarily of LNG and petroleum products. International projections of global demand for energy products anticipate a turbulent market due to rising environmental and climate policy considerations. However, such dynamics are not explicitly incorporated into the baseline scenario of this study, but it is discussed in Chapter 5. Instead, the baseline assumes a business-as-usual trajectory, with continuous demand for energy commodities at a fixed rate. This is consistent with the assumption that Qatar energy system will continue to operate at maximum technical capacity, achieving optimal economic returns without being constrained by environmental obligations. This assumption also frames decarbonisation primarily around domestic emissions reduction objectives, without accounting for uncertainties

in future energy export demand. This export forecast strategy is also aligned with QT-TIMES model as elaborated in Chapter 4.

Table 3.20 presents the export demand projection in MUSE-QA. A significant increase is observed in 2030, when LNG exports rise by approximately 85%. This increase corresponds to QatarEnergy capacity expansion plans under the North Field Expansion (NFE) project, which will increase the country's LNG production capacity from 77 mtpa to 142 mtpa by 2030 (Reuters Mills and El Dahan 2024; QatarEnergy, 2020).

It should be noted that while LNG constitutes the largest share of Qatar export portfolio, natural gas liquids (NGL) also form an important component. NGL is separated from raw natural gas during processing and exported alongside refined petroleum products (Miller, 2022). Their treatment in MUSE-QA follows the same assumption as other export commodities.

Table 3.20 Demand projection for energy export commodities expressed in (PJ)

Export Commodity (PJ)	2015	2020	2025	2030	2035	2040	2045	2050
NG interconnector	766.5	766.5	766.5	766.5	766.5	766.5	766.5	766.5
Crude oil	1209.7	1209.7	1209.7	1209.7	1209.7	1209.7	1209.7	1209.7
NGL	1051.3	1051.3	1206.2	2231.5	2231.5	2231.5	2231.5	2231.5
LPG	432.5	432.5	432.5	432.5	432.5	432.5	432.5	432.5
Gasoline	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
Jet	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
Diesel	178.4	178.4	178.4	178.4	178.4	178.4	178.4	178.4
Fuel oil	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Naphtha	229.7	229.7	229.7	229.7	229.7	229.7	229.7	229.7
LNG	3849.6	3767	4435	8204.8	8204.8	8204.8	8204.8	8204.8

Demand Trajectory for Transport in Sector: TRANSPORT

A breakdown of different types of transportation modes and their associated stock is extracted from PSA datasets (PSA Transport and Telecommunication, 2016). In MUSE-QA, transport modes are collated in groups based on fuel type. According to the IEA balance, two fuel types dominate Qatar's transport sector: gasoline and diesel.

Gasoline is primarily consumed in light-duty vehicles, namely passenger cars and two-wheelers. In 2015, the passenger car fleet consisted of approximately 1.2 million vehicles, corresponding to a saturation level of ~506 cars per 1000 people, detailed in Appendix C. This indicates that nearly half of the population in Qatar owned a car in that year. Historical data shows a 6% increase in car ownership between 2015 and 2019 (PSA, 2020). The rate is expected to grow linearly with population growth. Two-wheelers accounted for only 1% of the light-duty vehicle fleet. Both fleets combined, consumed 64 PJ gasoline in 2015, resulting in an estimated ~2000 $ktCO_2$ of emissions (IEA World Energy Balance, 2021).

Furthermore, diesel is consumed mainly by buses and heavy-duty trucks. In 2015, the fleet consisted of ~2,700 buses and ~39,000 trucks (PSA environment statistics, 2020). Their combined diesel consumption was 113 PJ (IEA World Energy Balance, 2021). Due to the higher carbon intensity of diesel, associated emissions were approximately fourfold higher than those from light-duty gasoline vehicles. Table 3.21 provides a disaggregated breakdown of road transport mode and its corresponding stock in the base year, as reported in PSA Transport and Communications Statistics (2016).

Table 3.21: Initial capacity of different road transport modes in Qatar in the base year

Transportation type	Stock (total number of vehicles)	Average travelled distance (km)	Capacity (kvkt)
Private cars	1,233,147	26,549	13946.99
Two-wheelers	13,169	30,397	195.36
Buses	2,345	53,003	3766.91
Trucks	34,273	72,227	1489.25
Aeroplane * (bn-pass-miles/y)			43.02

In MUSE-QA, transport service demand is defined in terms of the distance travelled by vehicles, expressed as vehicle-kilometres-travelled (VKT). This is calculated by multiplying the vehicle stock in a given year by the average annual distance travelled per vehicle (AADT) as expressed in Equation 3.7. The AADT is derived from FAHES inspection data; which is obtained from the Ministry of Interior to support transport and energy studies including MUSE-QA, QT-TIMES-QT, and Alishaq & Mehlig (2024).

Equation 3.7

$$vehicle\ km\ travelled = annual\ average\ traveled\ distance \times \frac{vehicles\ stock\ per\ 1000\ people}{population}$$

In the literature, transport service demand projection has been approached using a variety of methods. Giarola et al. (2023) extrapolated historical data for passenger car demand by correlating historical evolution with socio-economic drivers such as population growth and GDP. Similarly, Alishaq & Mehlig (2024) utilised Qatar-specific demographic and economic data to inform future technology diffusion rates under a range of assumptions and scenarios.

For this study, a projection strategy was harmonised with QT-TIMES to ensure methodological consistency and comparability in the analysis presented in Chapter 4. Transport service demand in MUSE-QA was estimated by evaluating the relationship

between vehicle ownership and income per capita. This approach follows Anderson & Larsen (2007), who applied a Gompertz curve, expressed in Equation 3.8, to describe the non-linear diffusion of private vehicles with rising income, a method also adopted in other transport demand studies (Alishaq, 2024). GDP per capita values were acquired from United Nations datasets, and vehicle saturation levels, which is the number of vehicles per capita, was calculated for the base year and then extended to 2050. These saturation levels informed the projected vehicle stock, which was subsequently converted into vehicle-kilometres-travelled (VKT) using Equation 3.8. The resulting transport demand projections are reported in Table 3.22.

Equation 3.8

$$C_t = \gamma e^{\alpha e^{\beta . GDP_t}}$$

Similar approach is applied to public transport (i.e. buses), and two-wheelers (motorcycles). Both modes exhibit significantly lower saturation levels compared to private cars, resulting in smaller demand growth trajectories. A key difference lies in the proxy variable where private vehicle demand is projected using GDP per capita to reflect affordability and standard of lifestyle; whereas public transport demand is linked to total GDP as an indicator of national economic evolution. Under the same approach for both MUSE-QA and QT-TIMES, small discrepancies arise due to variations in data sources and estimation approaches; however, overall trends remain consistent across both models.

Moreover, air transport represented by Qatar Airways, the national carrier, has experienced rapid expansion in passenger and cargo services, supported by extensive global networks and international travel routes, and facilitated by Hamad International Airport hub capacity. Historical passenger data, acquired from PSA Transport and Communication (2021), reveal a compound annual growth rate (CAGR) of 4.5% for the years 2015-2019, consistent with ICAO global growth projections (UN ICAO, 2024). Detailed calculations are available in Appendix C. The following years experienced a drastically sharp plunge in air service demand due to the COVID-19 pandemic.

Air passenger demand in MUSE-QA is modelled following the approach of Bohra & Shah (2019), who correlated jet fuel demand to passenger-kilometres and freight transport. In this study, passenger-kilometres are estimated by combining reported departures with route frequencies and distances from the Doha hub to major international hubs as expressed in Equation 3.9. The total passenger kilometre is then converted to billion-passenger-miles for data handling convenience.

Equation 3.9

$$passenger\_kilometres = total\ passengers_n \times \frac{flight\ frequency_d}{\Sigma frequency} \times distance_d$$

Cargo demand is calculated separately from passenger demand and is expressed in terms of ton-kilometres. Approximately 10% of total cargo is transported on dedicated freighters, while the majority is carried on passenger aircraft. This assumption is consistent the composition of the Qatar Airways fleet, which in 2016 included 16 dedicated freighters compared to a total fleet of 180 aircrafts (Qatar Airways, 2016).

In MUSE-QA, cargo demand projection is calculated using the same methodology as for passenger demand. Key international destinations are selected to represent high-frequency hubs, and cargo tonnage is multiplied by the corresponding route distance to yield ton-kilometres. The resulting demand projection is thus consistent across passenger and cargo transport while recognising their distinct operational profiles.

The Qatar Airways Sustainability Report (2015-2016) further supports this approach, as air service demand is commonly expressed through indices such as passenger weight per kilometre, cargo weight per kilometre, and revenue tonne-kilometres (Qatar Airways, 2016). In QT- TIMES, air service demand is also defined using passenger-kilometres, a convention that has been adopted in MUSE-QA for comparability.

Table 3.22: Transport service demand forecast based on Gompertz curve assumptions and aligned with QT-TIMES transport data projections

	unit	2015	2020	2025	2030	2035	2040	2045	2050
car	mvkt	13.95	39.09	45.83	50.58	53.91	56.86	59.70	62.30
bus	mvkt	3.76	3.46	3.97	4.35	4.62	4.87	5.11	5.33
trucks	mvkt	1.49	1.41	1.73	1.94	2.08	2.20	2.32	2.42
motorcycles	mvkt	0.19	0.21	0.26	0.29	0.31	0.33	0.35	0.36
Aviation-passengers	Bn-pass-miles	43.02	53.61	66.82	83.27	103.78	129.33	161.18	200.87
Aviation-cargo	Bn-tons-miles	4.30	5.36	6.68	8.33	10.38	12.93	16.12	20.09

Demand Trajectory for Domestic Service Demand in Sector: RESIDENTIAL

Energy demand in the residential sector is exclusive to electricity consumption with the exception of LPG for cooking. This fuel demand is represented in the model by an indicative value of 1 PJ, consistent with the IEA balance for household fuel use. Domestic energy service demands are projected forward by extrapolating with forecasted population growth as illustrated in Table 3.23.

The dominant energy demand end-use in households is space cooling, which represents the largest share of electricity consumption. Estimating this demand is assumed based on floorspace projections. Average residential floorspace per person in Qatar is not explicitly reported in the literature, therefore, it is inferred from the distribution of household types. Table 3.23 presents the percentage breakdown of dwelling types in Qatar from the PSA Census (2015), which provides the basis for estimating per capita floorspace and, in turn, forecasting space cooling demand.

Table 3.23: Percentage distribution of household types in 2015

	Villa/palace	apartment	Arabic/popular/ elderly house	Part of unit /building	other	Total number
distribution of household types (%)	40.5	42.9	7.2	4.75	4.7	201,432
Equivalent numbers	81,580	86,414	14,503	9,467	9,467	
Distribution of household members (%)	51.7	32.7	9.5	3.5	2.6	955,769
Equivalent numbers	949,133	312,536	90,798	33,452	24,850	

For the purpose of this study, only villas and apartments are considered when estimating residential cooling demand. Other housing types, such as Arabic/popular/elderly houses, are excluded as they are declining at an annual rate of -9% and are therefore not expected to contribute significantly in the long term. Similarly, “other” housing types listed in the census, such as tents, kiosks, or vacant spaces, are retained for consistency, but assumed to have negligible energy use (PSA Census, 2015).

Household occupancy rates in villas and apartments are presented in Table 3.24 (PSA Census, 2015). The census reports that households of six members or fewer generally reside in apartments, while those of seven members or more typically live in villas (PSA Census, 2015). Villa and apartment sizes are not standardised, as they vary across municipalities, residential developments, and high-end compounds. This variation is also reflected in the price per square meter between upscale urban areas and suburban districts (Saakin, 2024).

Table 3.24: Number of households based on occupancy type

Household family size (member/unit)	**1 - 3**	**4 - 6**	**7 - 9**	**10+**
Number of households by family size (thousand)	93	65	23	21

To approximate average apartment size, data were sampled from two major residential developments. In Msheireb Downtown Doha, a newly developed smart and sustainable urban project, a typical two-bedroom apartment average size is 162 m^2 (Msheireb Properties, 2024). By comparison, an equivalent two-bedroom apartment in The Pearl, which is a luxury waterfront development, average size is 135 m^2 (The Pearl Gates, 2024). Given their comparable market value, an average apartment size of 150 m^2 for a typical four-person household is assumed, corresponding to 37.5 m^2 per capita.

This estimate is consistent with international benchmarks. It is slightly larger than the average per capita floorspace in London which is 32.8 m^2/capita (Breach & Sells, 2019) and is about 1.5 times larger than the average in Saudi Arabia which is 24 m^2/capita (Krarti, 2019). The larger per capita floorspace in Qatar is attribute to the country’s small population and land availability.

Accordingly, the average floor area per person is applied as a proxy for cooling demand, scaled with population growth. This approach yields the residential cooling demand forecast presented Table 3.25.

Table 3.25: Domestic energy demand forecast for MUSE-QA. Cooking represents an indicative demand value that can be met by conventional LPG fuel or replaced by electricity at future years.

Residential service demand (PJ)	2015	2020	2025	2030	2035	2040	2045	2050
Space cooling	38.15	49.12	46.31	47.96	49.75	51.87	54.18	56.41
Space heating	0.54	0.70	0.66	0.69	0.71	0.74	0.77	0.81
Water cooling	1.63	2.11	1.98	2.06	2.13	2.22	2.32	2.42
Water heating	1.09	1.40	1.32	1.37	1.42	1.48	1.55	1.61
Lighting	10.90	14.03	13.23	13.70	14.22	14.82	15.48	16.12
Appliances	2.18	2.81	2.65	2.74	2.84	2.96	3.10	3.22
Cooking*	1.00	1.14	1.14	1.18	1.23	1.28	1.34	1.39

Demand Trajectory for Commercial Energy Service Demand in Sector: SERVICE

The projection of energy demand in the commercial and service sector is derived using a conservative assumption of slow GDP growth, as reported by the International Monetary Fund (IMF). This approach is adopted to mitigate the risk of overestimating electricity demand in the sector, particularly given the high uncertainty associated with future economic and service-sector expansion.

The resulting demand forecast is shown in Table 3.26, which outlines the projected electricity consumption trajectory for commercial and service activities over the modelling horizon.

Table 3.26: Service sector energy demand forecast for MUSE-QA. Base year stock represents electricity consumption in the commercial and service sector as per the IEA balance

Commercial service demand (PJ)	2015	2020	2025	2030	2035	2040	2045	2050
Space cooling	10.49	10.72	10.97	11.22	11.47	11.74	12.00	12.28
Appliances	12.06	12.33	12.61	12.90	13.20	13.50	13.80	14.12

3.1.5.3 Sectoral Technologies: Operational and Environmental Attributes

As outlined in Section 3.1.5, technologies in MUSE-QA are characterised by initial capacity as well as operational, environmental, and economic attributes. Each sector is equipped with a user-defined portfolio of technologies that consume fuel and emit carbon dioxide to generate an output commodity.

This relationship is represented as the rate at which *X* units of fuel enter a process to produce *Y* units of output commodity, while simultaneously emitting *Z* $ktCO_2$ from fuel combustion. These input-output flows and emissions are calibrated against the IEA World Energy Balance database to ensure internal consistency and data reliability.

This section elaborates on the technical parameters assigned to technologies within each sector in MUSE-QA, covering their operational behaviour, environmental impact, and economic performance.

UPSTREAM Supply Sector

Two primary extraction technologies are identified in this sector. *MINNG* represents associated and non-associated gas fields, yielding natural gas and natural gas liquids (NGL). *MINCRD* represents crude oil extraction from oil fields.

According to the IEA balance, a portion of the extracted natural gas is consumed as fuel during the extraction process itself. Therefore, the upstream supply side accounts for the total quantities of extracted natural gas, crude oil, and NGL, in addition to the share of natural gas used internally as fuel. This combined total constitutes the initial stock of "resources" entering the system (PJ_{in}), as illustrated in Figure 3.7.

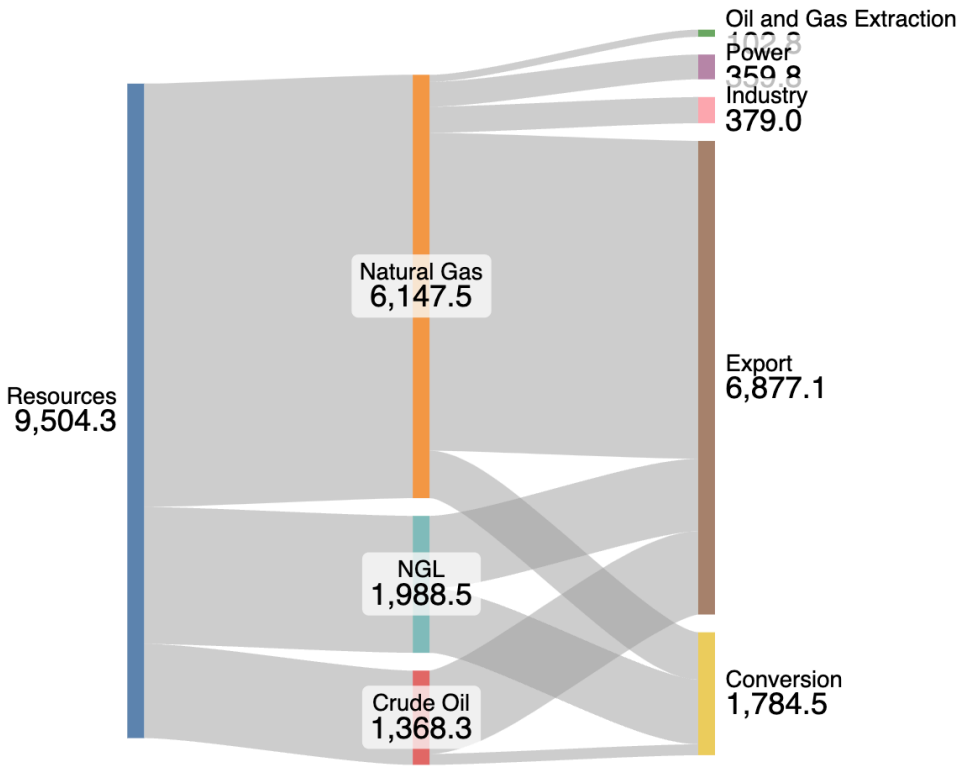


Figure 3.7: Primary energy balance (PJ) at the supply sector and fuel distribution across conversion and demand sectors as per IEA energy balance sheet

The fuel-to-output ratio is calculated as the total commodity of "resources" to the total output energy commodities, using Equation 3.10.

Equation 3.10

$$fuel_{in}/\ primary\ energy_{out} = \frac{fuel_{ng} + \sum stock_{ng,ngl,oil}}{\sum stock_{ng,ngl,oil}}$$

At the output side of the UPSTREAM sector, the extracted energy commodities are expressed as ratio of unit production to unit fuel consumption (PJ_{out}/PJ_{in}). For each primary energy commodity, the output-to-fuel ratio is calculated as the reciprocal of Equation 3.10.

The associated environmental output is calculated as *ktCO₂ per PJ* of fuel consumed to produce one unit of output commodity, as expressed in Equation 3.11. This varies across energy commodities according to its specific emissions factors, which are acquired from the IPCC Emissions Factors Database (Greenhouse Gas Protocol, 2024) and listed in Appendix D. Multiplying this factor by the total output stock (PJ) yields the total emissions of each technology in a given year. This method is used to verify the emissions balance in the base year against the IEA balance.

Equation 3.11

$$fuel_{CCS} = \frac{fuel_{input}}{output\ commodity} x[specific\ fuel\ emissions\ factor]$$

In addition to conventional extraction technologies, an extended set of options is included to represent future low-carbon investments. These comprise carbon capture and storage (CCS) units and direct air capture (DAC) systems. Both technologies require additional fuel inputs to operate. According to ETSAP (CO2 Capture and Storage, 2010), 6.2 GJ of natural gas is required to capture 1 ton of CO_2. This value (*PJ/ktCO₂*) is parametrised in Equation 3.12. for all CCS units in MUSE-QA, under the assumption of a 90% capture efficiency (IEA Carbon capture, 2024).

Equation 3.12

$$fuel_{CCS} = \frac{fuel_{initial}}{output\ commodity} + \left[output\ ktCO2\ \times 90\% \times \frac{6.2}{1000}\right]$$

Similarly, additional fuel is required to operate DAC units, which capture the remaining 10% of emissions that are not abated by CCS. This requirement is calculated on top of the CCS fuel input and is formalised in Equation 3.13.

Equation 3.13

$$fuel_{DAC} = \frac{fuel_{initial}}{output\ commodity} + \left[output\ ktCO2\ \times 10\% \times \frac{6.2}{1000}\right]$$

GTL-REFINERIES Conversion Sector

Technologies in this sector receive the primary energy commodities from the supply sector as feedstock and process it in refineries, liquefaction plants, and GTL plants to produce petroleum products. As illustrated in Figure 3.8, natural gas serves both as a feedstock and as a fuel input, with its combustion representing the primary source of emissions in this sector. Crude oil and NGL are used predominantly as feedstocks in refineries and GTL plants, while natural gas is the principal feedstock for LNG liquefaction trains.

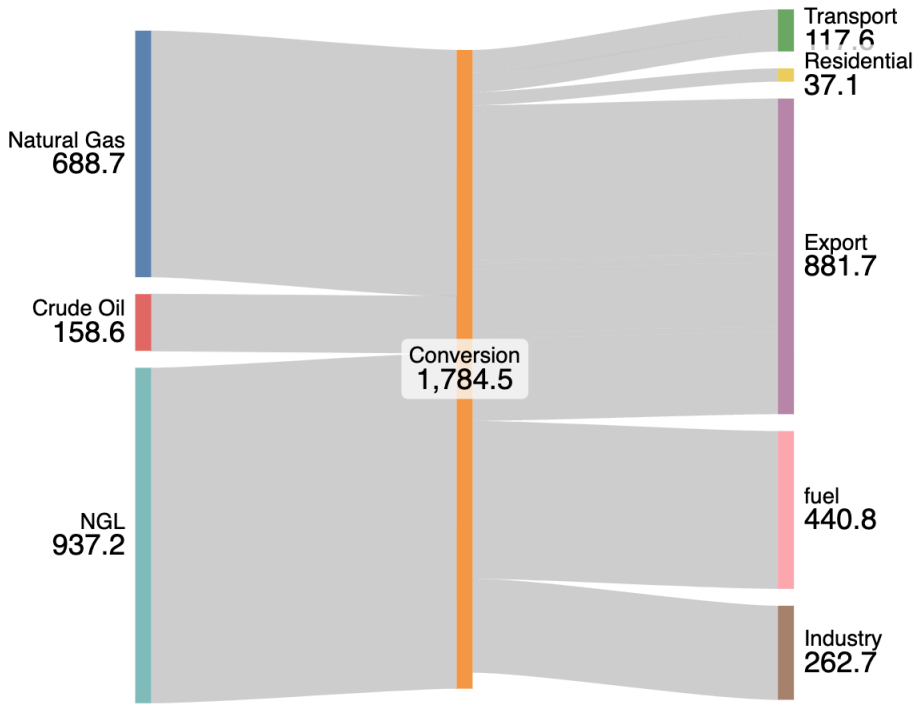


Figure 3.8: Fuel balance (PJ) at the conversion sector for oil and gas processing as per IEA balance, showing primary energy flow into conversion, thereafter into distinct energy service demand sectors.

In the liquefaction process, the fuel-to-output ratio reflects the share of natural gas consumed during liquefaction, and that converted into liquid gas (LNG), as expressed in equation 3.14.

Equation 3.14

$$fuel_{in} \,/\, LNG_{out} = \frac{LNG_{fuel} + LNG_{stock}}{LNG_{stock}}$$

In the refining process, three primary inputs are considered: natural gas, crude oil, and NGL. These are converted into LPG, diesel, naphtha, gasoline, jet fuel, fuel oil, refinery gas, and other oil products. Similarly, in the GTL process, the input ratios consist of natural gas and NGL, which yield LPG, diesel, naphtha, and ethylene.

In this sector, the integration of low- and zero-emission technologies is limited to CCS and DAC. The technical characterisation of this route follows the same calculation method considered for the supply sector in Section 3.1.5.3. In addition, future hydrogen production technologies such as SMR and electrolysis are also included in this sector. Relevant technical data are drawn from the literature and adapted to the MUSE framework.

POWER Conversion Sector

The base-year technology stock for electricity generation consists of six combined cycle gas turbines (CCGT) and one open-cycle gas turbine (OCGT). According to the IEA balance, nearly 23% of total domestic natural gas supply in 2015 was consumed in power generation plants, contributing by 25% to total system emissions.

Figure 3.9 illustrates fuel consumption in two main power generation categories defined by the IEA. One category is termed “main activity producer” which primarily generates electricity for sale, while the other category is termed “autoproducer” which generates electricity for use within the plant (IEA documentation, 2023). In MUSE-QA, these categories are translated into OCGT and CCGT technologies respectively. In addition to electricity, CCGT plants also generate heat for further use in the desalination plants denoting combined heat and power plants (CHP).

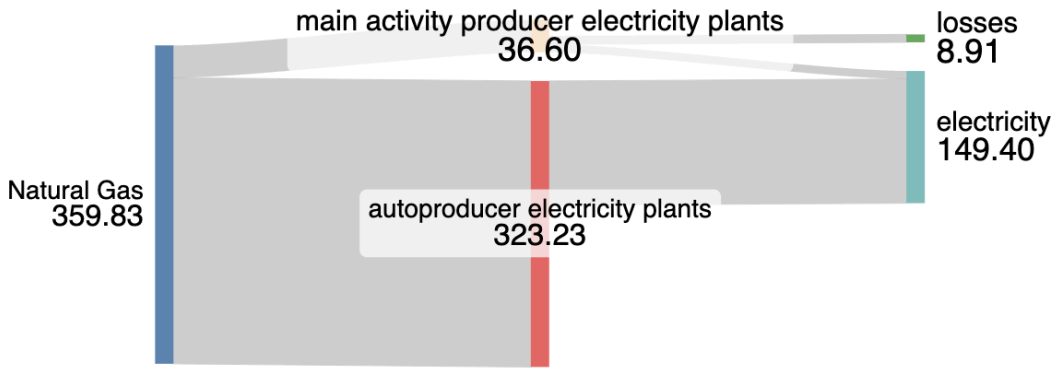


Figure 3.9: Fuel balance (PJ) at the conversion (power) sector as per the IEA balance

Combined cycle turbines (CCGT) are more thermally efficient and less polluting than open cycle gas turbines (OCGT). This is because waste heat is recovered in a *heat recovery steam generator (HRSG)*, which enables additional steam generation and increases electricity output (IEA ETSAP Gas fired power, 2010). By contrast, OCGT loses a significant share of heat, resulting in much lower efficiency. The preference for CCGT in Qatar is evident from the dominance of such assets in the national power mix. Accordingly, in MUSE-QA, the decarbonisation of thermal power processes is represented exclusively through CCGT route by incorporating CCS and DAC.

Another decarbonisation option in the power sector is the deployment of renewable power. Since variable renewable energy (VRE) is subject to intermittency, its integration into MUSE-QA is modelled through the temporal capacity utilisation factor (CUF). The CUF parameter gauges the ratio of total daily electricity generation in a year to the system maximum nominal capacity (Kumar et al., 2020). For MUSE-QA, CUF estimates are derived from the Renewables Ninja (2023) database. Solar potential is assessed for areas with high irradiance and land availability, using two representative days in summer and winter, each divided into 16 timeslices, in line with QT-TIMES conventions. Mean CUF values are then assigned to the corresponding diurnal timeslices, reflecting daily solar variations; peaking in the afternoon and falling to zero at night. To enhance reliability, storage coupling is introduced to smooth the power supply curve (Sayed et al., 2023), modelled with increased costs and improved diurnal CUF. Solar power CUF calculations is shown in Appendix E.

In addition to solar, wind power is also assessed for both onshore and offshore installations. Wind potential data are sourced from Renewables Ninja (2023) database. Onshore sites are selected from the most wind-prone areas away from dense urban development, while offshore sites are selected at 20 km from shore, consistent with typical siting distances (Diaz & Guades Soares, 2020). Although turbine foundation limits are generally set at water depths of ≤30 m (Diaz & Guades Soares, 2020), contour maps of the Arabian Gulf show that Qatar shoreline is already bordered by 20 m deep waters (Al-Barwani & Purnama, 2011), deeper zones extend well beyond the turbine-to-shore distance limitations.

Nevertheless, Qatar National Renewable Energy Strategy (QNRES, 2024), highlights Kahramaa strategic preference for solar energy over wind, reflecting Qatar high solar resource potential and established expertise in solar technology deployment. This preference is evident through the commissioning of the country's first large-scale renewable project, Al Kharsaah Solar Power Plant, which comes online in 2022 with a generation capacity of 800 MWp. The project is designed to meet 10% of peak domestic electricity demand (TotalEnergies, 2022). In MUSE-QA, this capacity is introduced after the base year, with "solar" as a fuel input with no direct tailpipe emissions. Life cycle emissions are excluded from the scope of this study.

WATER DESALINATION Demand Sector

Water desalination in Qatar has traditionally been dominated by thermal processes, where heat from Independent Water and Power Plants (IWPP) is used to desalinate seawater. An alternative route is membrane-based desalination, which relies on electricity to mechanically pressurise and pump seawater through filtering membrane (IEA ETSAP water desalination, 2013). Thermal desalination is strongly influenced by fuel prices, capacity availability, and economies of scale (IEA ETSAP water desalination, 2013); whereas membrane desalination is advantaged by higher energy efficiency and modularity (Sayed et al., 2023).

Firstly, thermal desalination process in MUSE-QA is illustrated linearly in Figure 3.10. The input energy vector, which is natural gas, is thrusted into power generation turbines to produce electricity and heat. These outputs are subsequently used as 'fuel' in the desalination unit. Emissions are allocated at the power production sector, where the combustion of natural gas occurs.

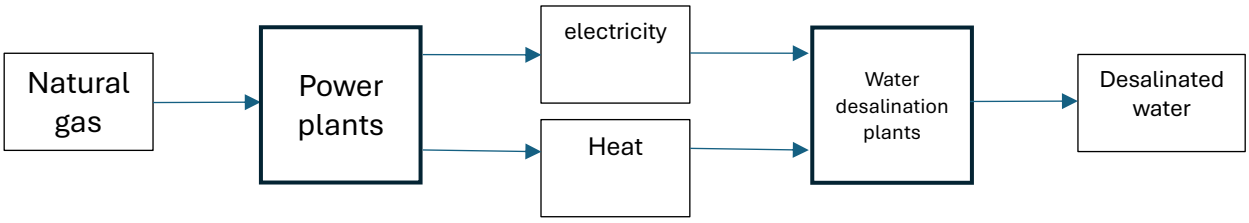


Figure 3.10**:** Schematic diagram of thermal water desalination process in MUSE-QA

Furthermore, membrane desalination process in MUSE-QA is represented by seawater reverse osmosis (SWRO); which consumes electricity as its primary energy input. Consequently, tailpipe emissions are allocated to the power production sector. Indirect emissions remain outside the scope of this study.

In the IEA balance, specific electricity and heat requirements for desalination in IWPP are not explicitly reported. Instead, the balance indicates an aggregated value of 9.529 PJ under the category 'own use in electricity, CHP, and heat plants'. To address this, technology-specific energy consumption rates for desalination processes were extracted, and verified, from ETSAP Water Desalination (2013) and NCBI (2023) references. Appendix E lists ranges for energy requirements for different desalination routes.

INDUSTRY Demand Sector

In the IEA energy balance, the main industrial segments are iron and steel, chemicals and petrochemicals, minerals, and 'other industries'. The balance reports an aggregated energy consumption values for each of these segments. Disaggregating the energy value was necessary to calibrate input-to-output attributes and forecast demand projections.

This was achieved by reconciling IEA values with granular data from local references and PSA databases.

Iron and Steel Production

First, steel manufacturing in Qatar was founded on MIDREX NG™ technology, which employs natural gas in the direct-reduction and electric-furnace route (DRI-EAF). This route reduces CO_2 by nearly 50% compared to traditional blast furnace steelmaking, making it one of the cleanest near-term options for emissions reduction (MIDREX H_2 webpage, 2024).

In the direct reduction process, depicted in Figure 3.11, natural gas is reformed onsite to produce a syngas mixture of hydrogen and carbon monoxide, which acts as both the fuel and the reductant. This mixture is then fed into a thermally controlled shaft furnace, where it separates oxygen from iron ore to produce direct reduced iron (DRI). The hot DRI is then processed into crude steel either by mixing with scrap steel and melting in an Electric Arc Furnace (EAF), or through direct briquetting (MIDREX, 2024). Qatar Steel main products are hot briquetted iron (HBI) and cold direct reduced iron (CDRI) (Qatar Steel, 2022).

In MUSE-QA, this 'traditional' route is represented as *IISDRELCAF*. Its fuel-to-output ratio (PJ/Mt steel) is calibrated against the IEA balance, and the environmental attribute is determined by multiplying this ratio by the emissions factor of natural gas.

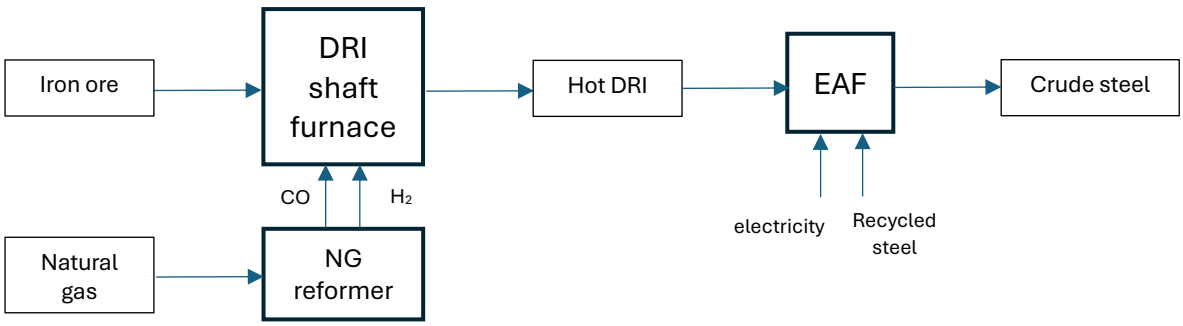


Figure 3.11: Schematic process flow of steel manufacturing through MIDREX NG DRI-EAF route as the standing technology in Qatar Steel without carbon capture

The MIDREX NG configuration, which already consumes large amounts of hydrogen, can further substitute 30% of the reductant natural gas with hydrogen input. Only minor equipment adjustments are required for this substitution. This allows the configuration to remain efficient until hydrogen economies become more favourable (Astoria et al., 2022). In MUSE-QA, this future route is termed *IISDRELCAF-100H$_2$*. The hydrogen fuel-to-output ratio is derived from EPRS (2020), which estimates that 50 kg H_2 per ton of steel is required, alongside 700 kWh/t steel for the EAF (Gray, 2023).

Alternatively, MIDREX NG can be coupled with carbon capture unit at two key points: the reformer fuel gas, which can abate ~0.65 tCO_2/ton DRI, and at the reformer flue gas, which can abate ~0.5 tCO_2/ton DRI (MIDREX NG, 2022). Combined, these measures enable a reduction of nearly 85% of total CO_2 emissions. This route is termed *IISDRELCAF-CCS* in MUSE-QA. The additional energy requirements for capture are incorporated in the input attributes by using the IEA indicative value, consistent with the approach adopted for the UPSTREAM sector.

Cement Production

Second, cement production is widely recognised as a hard-to-abate sector due to its inherent process emissions released during calcination. Figure 3.12 illustrates the overall cement process. At the calcination stage, calcium carbonate is chemically decomposed in a rotary kiln into calcium oxide (clinker), and carbon dioxide. Approximately, 58% of total emissions arise directly from this chemical reaction, 37% from fuel combustion, and the remainder from indirect electricity use (Bosoaga et al., 2009). In MUSE-QA, this process is represented as *IIPCPROD*, which consumes natural gas fuel calibrated against IEA balance data for minerals industry. Fuel combustion emissions are calculated by multiplying the fuel-to-cement ratio by the emissions factor of natural gas.

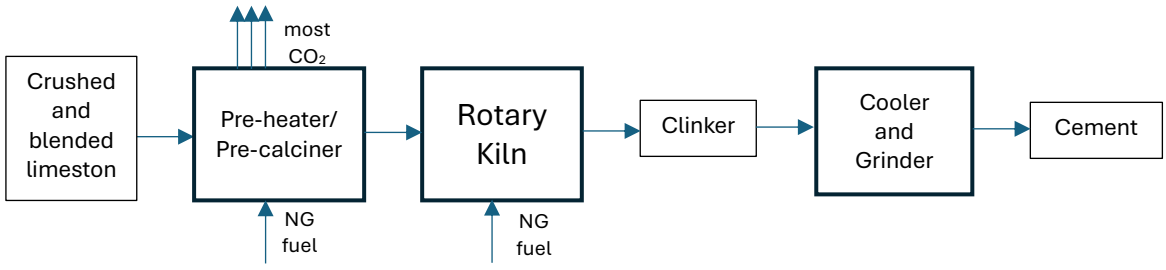


Figure 3.12: Schematic process of cement manufacturing

Decarbonising the cement industry presents significant challenges due to the dominance of process emissions. Possible mitigation solutions are generally limited to three approaches: (i) energy efficiency improvements, achieved through equipment upgrades (IEA cement, 2023; Bosoaga et al, 2009); (ii) fuel switching to low-carbon alternatives such as biomass and hydrogen (UK Concrete mpa 2020); and (iii) reduction of clinker blend ratio by incorporating supplementary cementitious materials like calcined clay- and magnesium-based cements (IEA cement, 2023; Barbhuiya et al,. 2024).

These approaches remain at varying stages of technological maturity, and their large-scale deployment is still under development (Barbhuiya et al., 2024). This creates a critical area for ongoing research to optimise their technoeconomic feasibility and ensure financial viability. This challenge is further compounded by the highly localised nature of cement production, which relies on the abundance of domestic limestone feedstock (Gordon, 2023).

Again, a prominent overarching solution for industrial emissions abatement is carbon capture and storage (CCS). The Global Cement and Concrete Association estimates that CCS could abate up to 1370 Mt CO_2; equivalent to nearly one-third of the total emissions reduction potential from all other measures combined (GCCA, 2022). CCS can be implemented in different configurations, including pre-combustion, oxy-combustion, and post-combustion capture. The latter is particularly relevant to cement production, as it enables the capture of CO_2 from flue gas streams emitted during both process and fuel combustion stages.

An unprecedented industrial-scale roll-out of this technology is scheduled to come on stream in 2024 at Brevik in Norway, where Heidleberg Cement Norcem facility will integrate a post-combustion CCS unit that is capable of abating approximately 50% of total plant emissions (Heidleberg Materials, 2024). This route is termed *IIPCPROD-CCS-post* in MUSE-QA, calibrated to reflect the abatement potential of post-combustion capture applied to the cement sector.

This capture approach can be retrofitted relatively easily to existing plants (Barbhuiya et al., 2024). The main challenge; however, resides in the purity of the flue gas stream and the additional energy burden that influences the energy efficiency of the process (ETSAP Cement, 2010; Barbhuiya et al., 2024; Bosoaga et al., 2009).

On the other hand, pre-combustion capture process separates CO_2 in the fuel reforming stage, enabling the use of hydrogen-rich gas as a combustion fuel. Despite its high capture efficiency, this route represents limited applicability in cement production, as it primarily addresses fuel-related emissions but not the dominant process emissions from calcination (IEA Greenhouse Gas R&D Programme, 2008). Combined with its poor technical adaptability to existing plants (Barbhuiya et al., 2024), pre-combustion capture is relegated within MUSE-QA.

Alternatively, oxy-combustion is a process which replaces air with pure oxygen during fuel burning, which emits a CO_2-rich flue gas (Bosoaga et al., 2009). This route is represented in MUSE-QA as *IIPCPROD-CCS-oxy*. Modelling attributes including fuel input for cement production with integrated CCS and the resulting emissions are calibrated using the IEA-ETSAP Technology Brief for Cement Production (2010).

Moreover, fuel switching in the cement industry is another decarbonisation option, where natural gas is replaced with hydrogen. This is modelled in MUSE-QA as *IIPCPROD-H2*.

Chemicals Production

Third, chemicals manufacturing in Qatar represents the country's second largest industrial capacity in the Gulf region and the fourth worldwide, heavily weighted towards fertilizers production which amounts to more than half of the total chemicals output (GPCA, 2022; QAFCO Sustainability Report, 2015). This segment is highly energy-intensive and is responsible for over 60% of fuel consumption and associated emissions reported under 'manufacturing' in the IEA balance for the base year of this project.

Ammonia Production

Ammonia is a primary chemical commodity produced through the Haber-Bosch process, illustrated in Figure 3.13, which relies on natural gas both as a feedstock for steam reforming to generate hydrogen, and as a process fuel for heating (QAFCO Sustainability Report, 2013). In Qatar, approximately 84% of the ammonia output is directed for urea production, with the remaining share allocated for export. The ratio of natural gas fuel input (PJ) to ammonia output (Mt) is derived from the IRENA benchmark rate of 29 GJ/ton of ammonia and subsequently calibrated against values reported for the chemicals industry in the IEA energy balance (IRENA & Ammonia Energy Association, 2022).

At the reforming stage, a substantial volume of carbon dioxide is generated, which is subsequently recycled into the urea synthesis plant to react with liquid ammonia for urea formation (QAFCO Sustainability Report, 2015). This makes the steam reforming stage the primary emissions hotspot within ammonia production. Accordingly, emissions mitigation can be achieved either through the integration of carbon capture technology or by substituting natural gas-based hydrogen with electrolytic hydrogen (IEA Chemicals, 2024; IRENA and Ammonia Energy, 2022). Within MUSE-QA, these decarbonisation routes are represented as IANH3PROD-CCS and IANH3PROD-Green, respectively.

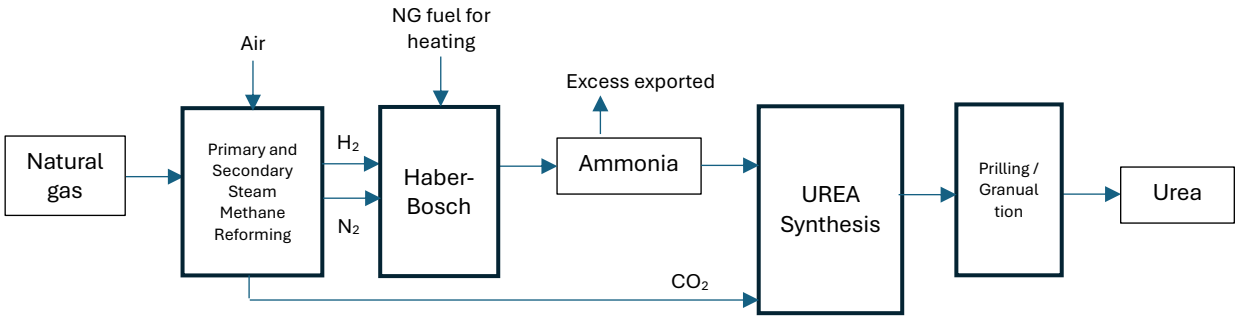


Figure 3.13: Schematic process flow of ammonia and urea production

In the case of green ammonia, the substitution of natural gas with hydrogen introduces several important considerations. These include higher production costs compared to conventional routes (IRENA and Ammonia Energy Association, 2022), the distinct

physiochemical properties of hydrogen that necessitate modifications in process design (Koestner, 2021), and enhanced safety requirements associated with hydrogen handling (Salgari, 2024). For the purpose of this modelling exercise, the technoeconomic parameters provide the key inputs that underpin the simulation. Two attributes are particularly important: the fuel-to-output ratio and the capital investment cost. To specify the hydrogen fuel input replacing natural gas, the heating value of hydrogen is compared on a volumetric basis with that of natural gas for fixed equipment size. Although hydrogen possesses a higher gravimetric energy density than natural gas, approximately three times the volumetric amount of hydrogen is required to deliver an equivalent energy output (Koestner, 2021). In MUSE-QA, this relationship is reflected by tripling the hydrogen input for green ammonia production route to achieve the same output as in the natural gas-based process.

Emissions circularity between ammonia and urea plants is not explicitly captured in MUSE due to the linearity of the modelling framework. However, in practice, nearly 60% of the carbon dioxide generated during steam reforming is recycled into the urea synthesis stage (Det Norske Veritas, 1987). In this study, this recycling loop is approximated by deducting the quantity of CO_2 fed into urea production from the total emissions, ensuring that only net atmospheric emissions are accounted for. The emission factors are calibrated against the IEA emissions balance to avoid misinterpretation. For example, IRENA (2022) reports a benchmark of ~0.75 tCO2 per ton of urea produced under renewable ammonia pathways. Conventional ammonia production, by contrast, typically requires ~29 GJ of natural gas per ton of ammonia and emits between 1.9-2.6 tCO2 per ton of ammonia, depending on the process configuration and efficiency (McKinsey, 2021; IRENA Renewable Ammonia, 2022).

High Value Chemicals (HVC) Production

Fourth, a major share of Qatar's petrochemical sector is derived from the processing of ethane into ethylene, which serves as the fundamental building block for a variety of downstream products. Ethylene is further processed into polyethylene at QAPCO, low density polyethylene at Qatofin, and caustic soda, ethylene di-chloride (EDC), and vinyl chloride monomer (VCM) at QVC (QAPCO integrated report, 2015). Additional derivatives

such as high- and medium-density polyethylene, (HDPE, MDPE), normal alfa olefins (NAO), and 1-Hexene are produced at QChem facilities (QChem sustainability report, 2015).

The largest ethylene cracker in Qatar is operated by RLOC, with a capacity of 1.3 MTPA, serving as the main supplier for the downstream petrochemical complexes (QChem, 2015). Other significant crackers include QAPCO at 800 KTPA capacity and QChem I at 500 KTPA (QAPCO, 2015; Knott, 2020). The petrochemical value chain begins with ethane feedstock derived from oil and gas processing, which is cracked into ethylene before being distributed to the various petrochemical plants (QAPCO, 2017).

In MUSE-QA, this process, illustrated in Figure 3.14, is represented in two stages: First the supply stage, where gas-to-liquid (GTL) plants convert natural gas into syngas and subsequently into ethane, and second the industrial supply stage, where ethane is procured as feedstock for petrochemical facilities. Ethane is then cracked into ethylene, which is almost entirely consumed in downstream processes, with only surplus quantities available for external sales (Industries Qatar, 2023). Accordingly, the production pathway is represented as PETRO-ETH-CRACKER in the model. Associated emissions are allocated to the gas processing stage, since the ethane cracking process itself does not generate direct emissions, only the combustion of natural gas used as process fuel contributes. Decarbonisation options are incorporated through the addition of carbon capture and storage (CCS) and direct air capture (DAC) utilities, represented as PETRO-ETH-CRACKER-CCS, and PETRO-ETH-CRACKER-DAC, respectively. For calibration purposes, the model assumes an ethane-to-ethylene conversion efficiency of ~78%, consistent. With standard industrial practice.

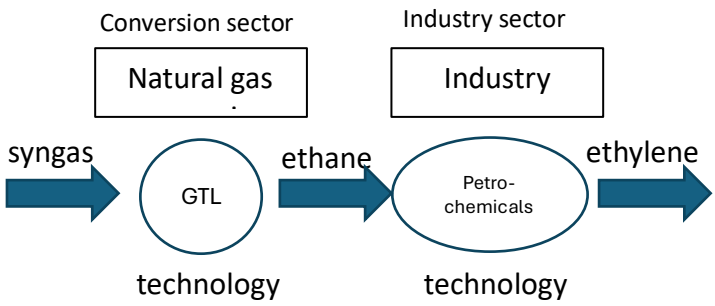


Figure 3.14: Schematic diagram for energy value chain for petrochemicals production in MUSE-QA

Methanol Production

Methanol represents another key segment of Qatar's chemical industry that reached 0.87 Mt in 2015 (PSA Qatar in Figures, 2017). In Qatar, methanol is produced at QAFAC through natural gas steam reforming, as illustrated in Figure 3.15 (Methanol Institute, n.d.). Within this process, a portion of the natural gas is consumed as a fuel for heating, while the remainder serves as feedstock for synthesis.

Decarbonisation options for this pathway are twofold. First, the fuel component of natural gas can be substituted with renewable electricity, thereby eliminating associated combustion emissions. Alternatively, the process can retain natural gas as feedstock while replacing conventional hydrogen with electrolytic hydrogen for methanol synthesis. This approach effectively couples natural gas reforming with renewable hydrogen inputs, offering a hybrid decarbonisation route (IRENA and Methanol Institute, 2021).

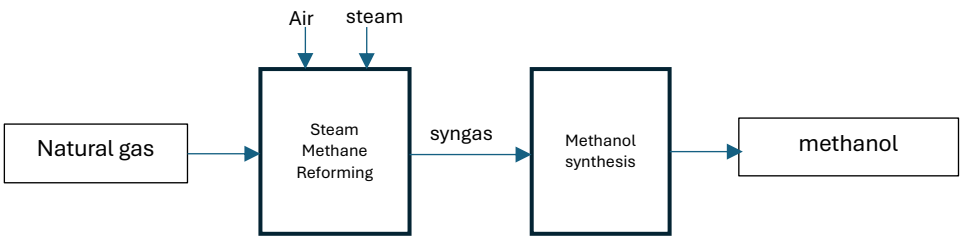


Figure 3.15: Schematic process flow of methanol production

Industry Not Elsewhere Specified

In MUSE-QA, an additional industrial route is introduced to reconcile the IEA balance category *"industry not elsewhere specified"* (IEA World Energy Balances, 2023). This category accounts for industrial activities that are not explicitly covered under the International Standard Industrial Classification of All Economic Activities (ISIC) but nonetheless consume *"other oil products"*. Within the model, this pathway is represented as IOTRLTH and is equipped with a decarbonisation option through the integration of carbon capture.

The energy inputs for this route include both *"other oil products"* and electricity, consistent with the IEA balance. When carbon capture facilities are introduced,

additional natural gas fuel is incorporated into the fuel mix to support the capture process. This ensures that the emissions profile of this industrial category is appropriately reflected in the model while aligning with the broader decarbonisation framework of MUSE-QA.

TRANSPORT Demand Sector

Transport service demand in MUSE-QA is represented in terms of vehicle-kilometres-travelled (VKT) and is allocated across the technologies listed in Appendix C consistent with the categorisation of transport modes described earlier. The ratio of fuel consumption (PJ) to transport service demand (kVKT) is derived from vehicle fuel economy estimates, based on data from the IEA World Energy Balance and the WOQOD annual report (2015).

For gasoline vehicles, WOQOD reports total sales of gasoline in 2015 that are approximately 10 PJ higher than the IEA value. Fuel economy of passenger cars differs slightly between the two datasets, with WOQOD estimating 6.03 km/L and IEA estimating 7.01 km/L. Both figures fall within the efficiency range for sedans and SUVs as reported by the U.S. Department of Energy *Fuel Economy Guide* (2015). Given the relatively minor role of two-wheelers in Qatar, fuel consumption for this category is assumed to be negligible, 0.2 PJ, consistent with QT-TIMES assumptions in Chapter 4. The associated emissions are calculated by multiplying these fuel use rates with the gasoline emissions factor. Detailed calculations are available in Appendix C.

The second fuel type is diesel and is allocated to buses and trucks. WOQOD sales of diesel in 2015 were ~25% lower than the IEA-reported figure. Converting both values to fuel economy indicates 1.8 km/L for WOQOD and 1.5 km/L for IEA. Since the difference between the two values is relatively small, the IEA estimate is adopted as a representative ballpark figure. This choice is further supported by international benchmarks, which report an average consumption of ~25 L/100km for diesel buses (Ivkovic et al., 2017), and 25-35 L/100km for heavy-duty diesel trucks (Class Trucks, 2023). Within MUSE-QA, no direct competition is modelled between transport modes sharing the same fuel; instead, investment dynamics are governed by relative economic and environmental

performance. Emissions are estimated by multiplying fuel consumption rates (kvkt/PJ) by the diesel emissions factor ($ktCO_2/PJ$).

In 2015, emissions from the road transport sector accounted for ~10.9% of the total emissions in Qatar, making it the fourth largest contributor after oil and gas and heavy industries ((Ritchie & Rosado, n.d.; PSA, 2020). Recognising this, the Third National Development Strategy (NDS-3) emphasises the need to decarbonise the transport sector, calling for policies to incentivise rapid electrification and public transport use (PSA, 2024).

In MUSE-QA, transport decarbonisation is represented through two pathways: vehicle electrification and fuel switching. Electrification occurs when rising demand exceeds existing capacity, allowing new investments to replace conventional vehicles, consistent with the mechanism explained in section 3.1.5.3. This aligns with Qatar National Renewable Strategy (QNRES, 2024), which targets 10% road electrification by 2030. Technical properties of EVs are based on specifications from Tesla (2024) and Sustainable Bus (2023). Fuel-switching is modelled for trucks, with hydrogen consumption assumed at ~0.08 kgH2/km (Drawer et al., 2024).

Beyond road transport, air transport is a major consumer of jet fuel. In 2015, the IEA balance reports aviation bunkers of 53.92 PJ, which are disaggregated into passenger and cargo air services based on ratios of jet fuel-to-passenger kilometres (unit: bn-pass-miles) and jet fuel-to-ton kilometres (unit: bn-ton-miles), respectively. Air freighters are assumed to represent ~10% of the fleet, consuming a corresponding share of the fuel. Importantly, emissions from international aviation are excluded from Qatar's national balance, in line with Article 13 of the Paris Agreement, which requires such emissions to be reported separately and not as part of the national balances, liberating this route from mitigation commitments (UN Climate Change, 2024).

Overall, the transport sector modelling highlights that demand is primarily driven by fossil fuel combustion, as noted by Al-Alawi et al. (2021), with emissions trajectories strongly shaped by the extent of electrification and hydrogen uptake in the future.

RESIDENTIAL Demand Sector

The residential sector in MUSE-QA is primarily powered by electricity, with the exception of liquid petroleum gas (LPG) used in traditional cooking appliances. This constitutes the only source of emissions in the sector, and it can be readily mitigated through electrification of cooking technologies.

A key challenge in modelling this sector lies in representing the rate of energy use across a diverse set of household appliances and utilities. To address this, each domestic technology is assigned an indicative energy usage rate of 1, which represents baseline consumption equivalent to 100% electricity use. More efficient alternatives are assigned proportionally lower energy usage rate. For example, LED lighting is modelled with a lower energy usage rate compared to incandescent bulbs, reflecting its higher efficiency. This relative scaling allows the model to capture efficiency improvements while maintaining consistency in overall threshold energy service provision.

SERVICE and COMMERCIAL Demand Sector

The service and commercial sector in MUSE-QA is represented as a fully electrified sector. While it does not directly contribute to fuel-related emissions, its electricity demand imposes a significant burden on the power sector, thereby influencing technology investment decisions in electricity generation. The fuel-to-output ratio for this sector is derived from the aggregated electricity consumption of 22.54 PJ reported in the IEA World Energy Balance for commercial and public services. As detailed consumption breakdowns are not available in the literature, the sector is assumed to consume electricity primarily for space cooling and for appliances.

Consistent with the residential sector, space cooling is assumed to dominate electricity use. In Qatar, a substantial share of commercial cooling demand is met by district cooling utilities. District cooling systems are up to 50% less energy-intensive compared to conventional air conditioning technologies (Hayes, 2010). Consequently, this technology route is assigned a lower fuel-to-output ratio to reflect its relative efficiency advantage.

EXPORT Demand Sector

The export sector in MUSE-QA represents the demand pipeline for output commodities originating from both the oil and gas supply sector and the oil and gas processing sector. The technologies included in this sector are configured to represent specific export commodities, such as LNG, gasoline, and diesel, but are not assigned technical, economic, or environmental characteristics. This design choice ensures that the sector remains demand-driven, isolating it from endogenous technoeconomic or environmental dynamics, and allowing the model to capture export quantities without bias from internal cost of emissions parameters.

3.1.5.3 Sectoral Technologies Techno-economic Parameters

Following the operational and environmental characterisation of technologies in Section 3.1.5.2, their economic attributes are parametrised in MUSE-QA using a set of cost indices.

The **capital cost (CAPEX)** is calculated endogenously using Equation 3.15 (Imperial College London, 2024):

Equation 3.15

$$CAPEX = cap\,par \times (Capacity)^{cap\,exp}$$

Here, the variable cap_par represents the modeller's input for the capital cost of producing one unit of output commodity over one year. This variable is further calculated endogenously to reflect economies of scale where the price drops as the capacity expands using Equation 3.16, where *CapRef* denotes the "the *reference size for the cost estimate decided by the modeller*"(Imperial College London MUSE 1.1.0, 2024).

Equation 3.16

$$cap\_par = (\frac{CAPEXref}{CapRef})^{cap\_exp}$$

In MUSE-QA, the scaling parameter *cap_exp* is set to 1, ensuring that technology scaling is driven by production. Rather than exogenously imposed multipliers.

The **fixed cost (FOM)** is calculated using Equation 3.17, where the fixed cost of the production of one unit of output commodity over one year (*fix_par*) is multiplied by capacity at an exponential value (*fix_exp*), set to 1 to ensure costs scale proportionally with capacity rather than unreferenced growth assumptions:

Equation 3.17

$$FOM = fix\_par * (Capacity)^{fix\_exp}$$

Similarly, the **variable cost (VAREX)** is determined through Equation 3.18, in which the variable cost of the production of one unit of output commodity over one year (*var_par*) is multiplied by capacity at an exponential factor (*var_exp*), also set equal to 1:

Equation 3.18

$$VAREX = var\_par * (Capacity)^{var\_exp}$$

This confined set of cost parameters govern investment decisions under the imperfect foresight paradigm of MUSE-QA. The foresight window is defined as five years, meaning that agents have knowledge of technology costs, demand, and price expectations only within this period. Beyond this horizon, future forecasts for plant lifetimes, demand trajectories, and energy prices are derived using a *flat-forward extension* of present values, assuming constant prices over the operational lifetime of each technology (Imperial College London, 2024). Endogenous supply-demand interactions subsequently adjust commodity prices at each iteration of the simulation.

The following subsections provide technology-specific economic attributes for each MUSE-QA sectors, informed by literature benchmarks or derived estimations. Carbon

capture technologies, for example, are parametrised using IEA cost ranges, as summarised in Table 3.27 (Beylin-Stern & Berghout, 2021; IEA Direct Air Capture, 2022).

Table 3.27: Cost estimation for different carbon capture technologies

Technology	Cost (USD/ t CO_2)	Area of application
CCUS	15 – 25	Natural gas processing industries
CCUS	40 – 120	Industrial manufacturing and power production
DAC	125 - 335	Large scale plant

It is important to emphasise that these values correspond to typical facilities and are not adjusted for regional cost factors or additional cost multipliers (EIA, 2022). As such, they may risk under- or overestimating actual investment costs for technologies either mature or under development. Nonetheless, these references provide indicative benchmarks for economic evaluation and can be further refined as more context-specific data becomes available.

Supply Sector: UPSTREAM

The Qatar National Renewable Energy Strategy highlights that natural gas can be effectively extracted from fields at substantially low costs (Kahramaa, 2024). However, detailed production cost data is not readily accessible. Therefore, for MUSE-QA, the cost of extraction of primary energy technologies is parametrised through the variable operation and maintenance cost (*var_par*), which is approximated using the international export price of primary energy commodities, as listed in Table 3.28. This assumption does not reflect the low physical cost of extraction in Qatar, but rather the opportunity cost of diverting hydrocarbons from export markets where they generate revenues. In doing so, the model ensures that domestic consumption of oil and gas is valued equivalently to their export potential, thereby aligning investment decisions with Qatar's resource-exporting economic structure.

The price index for natural gas is based on the Japan/Korea Marker PLATTS (JKMc1) (Investing, 2024), which is a relevant benchmark since Japan accounted for over 25% of

Qatar's LNG imports in 2015, equivalent to approximately 45% of Qatar's spot LNG exports that year (GIIGNL, 2016). To ensure consistency, this value is cross-checked against the UK National Balancing Point (NBP) benchmark (Trading Economics, 2014), with both values showing close alignment as illustrated in Table 3.28. For crude oil extraction, the Brent benchmark price (EIA, 2016) is adopted, which broadly aligns with OECD oil import prices.

Table 3.28: Export price reference for the variable cost attribute (var_par) in MUSE for primary energy extraction technologies

Technology	Price index	Price	Unit	Var_par as the export price ($MUSD_{2015}$/PJ)
MINNG	NBP	42.13	GBP/therm	6.10
	JKMc1	7.35	USD/mmbtu	6.97
MINCRD	OECD	53.80	USD /barrel	8.79
	Brent	52.00	USD /barrel	8.66

Capital cost estimates for carbon removal technologies, including capture and storage (CCS) and direct air capture (DAC), are derived from IEA ETSAP CO2 Capture and Storage (2010), IEA Direct Air Capture (2022), and Baylin-Stern & Berghout (2022). These benchmarks are applied as a cost premium on conventional technologies, with DAC-incorporated options consistently carrying the highest capital intensity. This framing allows the model to distinguish the relative economic viability of CCS versus DAC when integrated into the system.

All primary energy extraction technologies in MUSE-QA are assigned a technical lifetime of 15 years. This value aligns with the typical operating range of 15-30 years reported for oil and gas fields (TotalEnergies, 2015). While Qatar's large reserves can sustain production for over 50 years (TotalEnergies, 2015), well beyond the forecast year, 2050. However; the modelling logic requires asset retirement to trigger reinvestment over the simulation horizon. Thus, a 15-year retirement limit ensures that capacity is cyclically renewed and reflects dynamic investment decisions across the modelling timeframe.

Conversion Sector: GTLEREFINERIES

Capital (*cap_par*) and variable (*var_par*) cost estimates for conventional oil refining and gas-to-liquid (GTL) processes, as well as for carbon removal integration, are derived from QT-TIMES model in combination with published technoeconomic data. Sources include IEA ETSAP Liquid Fuels Production from Coal and Gas (2010), IEA ETSAP Oil Refineries (2010), and IEA Levelised Cost of Hydrogen Maps (2020; 2024). Fixed operation and maintenance costs (*fix_par*) are assumed at 2.5% of capital expenditure, consistent with IEA assumptions in the IEA-ETSAP Technology Briefs (2010) and Global Hydrogen Review: Assumptions Annex (IEA, 2021). This approach is also aligned with the methodology applied across system-wide technologies in the absence of Qatar-specific referenced values. These values provide a consistent technoeconomic baseline while allowing differentiation between conventional and decarbonised processing routes.

For liquified natural gas (LNG), cost parameters are adopted from Zhou et al. (2022), contextualised for Qatari LNG plants, listed in Table 3.29. Qatar's LNG production exhibits some of the lowest global liquefaction costs, in stark contrast to higher-cost projects in Australia and Norway (Zhou et al., 2022). Variable costs are treated consistently with other oil and gas processing technologies in the GTLREFINERIES sector.

Table 3.29: Natural gas liquefaction process costs for Qatar-specific plants

Plant	Capacity (MMtpa)	Liquefaction cost (USD/MMBtu)	FOB cost (MMBtu)
QatarGas II	7.8	1.75	1.96
RasGas I	6.6	1.98	2.20

All oil and gas processing technologies are assigned a technical lifetime of 20 years, representing the lower bound of reported ranges (ENG, 2022; HILTI, 2024). This assumption ensures periodic reinvestment opportunities while recognising MUSE-QA's structural limitation in enforcing premature capacity retirement. A shorter technical life also helps balance the abundance of initial installed capacity within the system.

In addition to conventional processes, hydrogen production technologies are included within this sector. Fossil-based routes include steam methane reforming (SMR) and its decarbonisation variants, SMR-CCS and SMR-DAC. Costs are estimated from IEA Global Hydrogen Review (2021), Spath & Mann (2001), IRENA (2020), and Zhao et al. (2020).

Conversion Sector: POWER

Cost estimates for conventional power generation technologies and their CCS-integrated counterparts are derived from the *EIA Global Energy and Climate model* (2023) and the *EIA Annual Energy Outlook* (2022). The additional cost of coupling with DAC is estimated following the same methodology applied in the upstream and processing sectors. Thermal power plants are assigned a technical lifespan of 15-20 years, consistent with the values reported by EPRI (2019) and Evans (2017).

Given that the technology stock in the power sector includes a substantial share of renewable options, a system-wide cost reduction trajectory is assumed over the modelling horizon. Capital and variable investment costs for renewable technologies are obtained from the National Renewable Energy Laboratory (NREL), and extrapolated according to forecasted cost decline pathways (NREL, 2024). This reflects anticipated reductions in technology costs due to learning effects, innovation, and economies of scale assumptions, thereby incentivising deployment once renewables become market competitive. In line with standard modelling practice, variable operating costs are assumed to be zero for all renewable technologies (EIA GEC, 2022). The operating life of renewables is set at 20 years based on NREL (2013) and Kiger (2016).

Demand Sector: WATERDESAL

The unit cost of water production from both thermal and membrane desalination processes is derived from Alrowais et al. (2022), expressed in million USD per million cubic meters of desalinated water. Fixed operation and maintenance costs are estimated at 2.5% of the capital cost, consistent with the approach applied across other sectors. Variable costs are taken directly from Alrowais et al. (2022). The average operational lifetime of desalination plants is assumed to be 25 years, following Raluy (2006).

Demand Sector: INDUSTRY

The economic attributes of both conventional and decarbonised industrial technologies are derived directly from the literature. These denote the cost of producing one megaton of industrial commodity, expressed in million USD per megaton per year (MUSD/Mt). The reported values are used as benchmark investment indicators and do not explicitly incorporate context-specific financial considerations, such as subsidies, fiscal incentives, or regional financing structures.

For the i**ron and steel industry**, capital and variable costs of the MIDREX natural gas-based route are sourced from the IEA Technology Briefs (Iron & Steel, 2010), while investment costs for hydrogen direct reduction processes are extracted from the TNO Technology Factsheet (West, 2020).

In the **cement industry**, capital and fixed costs for both the conventional production route in addition to CCS-integrated pathways are obtained from the IEA-ETSAP Technology Briefs (Cement, 2010). Costs for hydrogen substitution in cement kilns are acquired from Lino et al. (2022).

For the **chemicals industry**, capital costs of ammonia production for both conventional and CCS-integrated routes are based on IRENA and the Ammonia Energy Association (2022). DAC-integrated costs are estimated following the same methodology as applied in the UPSTREAM and GTLREFINERIES sectors. Urea production costs are assumed to align with those of ammonia, adjusted for emissions intensity specific to urea production rate specific to urea unit production.

Finally, in the **petrochemicals industry**, the cost of ethylene production is extracted from IEA-ETSAP and IRENA Technology Brief (2013). Additionally, in **other industries** which consumes “other oil products” as reported in the IEA balance, indicative unit production costs are adopted from QT-TIMES model.

Demand Sector: TRANSPORT

As the transport service demand is represented in terms of vehicles kilometres travelled (VKT), the initial cost of meeting one unit of transport demand per year is calculated by dividing the average market price of a vehicle by the total service demand of the respective transport mode, as shown in Equation 3.19.

Equation 3.19

$$cap\_par_{road} = \frac{vehicle\ unit\ price\ (MUS\$)}{transport\ service\ demand\ (kvkt)}$$

For air transport, a similar approach is applied, with costs estimated separately for passenger and cargo services. For passenger aviation, the average capital cost of one passenger aircraft is divided by the annual air transport service demand, expressed in billion passenger-miles using Equation 3.20.

Equation 3.20

$$cap\_par_{airpass} = \frac{average\ capital\ cost\ of\ one\ passenger\ plane}{air\ transport\ service\ demand\ (bn - pass - miles)}$$

For cargo aviation, the same principal applies, using the cost of a dedicated freighter and the annual cargo service expressed in billion ton-miles using Equation 3.21.

Equation 3.21

$$cap\_par_{aircargo} = \frac{average\ capital\ cost\ of\ one\ cargo\ plane}{air\ freight\ service\ demand\ (bn - ton - miles)}$$

Input data for these calculations are retrieved from multiple references, such as Qatar Airways (2024) for aircraft fleet details, Qatar Airways Cargo (2024) for freighters specification, Aviation Intelligence Portal (2024) for aircraft operating costs, Statista (2024) for passenger and cargo statistics, and Qatar Airways database for flights distances. Detailed calculations are in Appendix E. Fixed and variable costs for both passenger and cargo aviation are set to zero, since investment decisions are primarily governed by technical parameters such as fuel efficiency, rather than operating cost structures.

Demand Sector: RESIDENTIAL

The cost of residential service demand is estimated based on the cost of electricity consumed by each technology type. The residential electricity tariff published by Kahramaa (2024) is used as the reference price index. A tariff of 0.08 QAR/kWh is converted to MUSD/PJ and subsequently multiplied by the electricity consumption rate (PJ/PJ) for each technology to reflect its service efficiency. For instance, the provision of "cooling" services from district cooling (DC) is more cost-effective than conventional air conditioning (AC) units, as the electricity intensity per unit of service is significantly lower for DC systems. A similar relationship is observed in lighting service demand, where the LCOE of LED lighting is lower than incandescent lighting due to higher electrical efficiency. Consequently, technologies with superior efficiencies are associated with lower costs in the model, and are therefore favoured under MUSE-QA investment logic.

Where electricity is not purchased from the grid but instead self-supplied from domestic renewable sources, the cost of energy provision is assumed to be negligible. In addition to electricity consumption, liquified petroleum gas (LPG) is included for cooking services. The benchmark price for LPG is 7 QAR per 5 kg cylinder, based on Woqod, the main distributor of domestic gas cylinders in Qatar (Qatar Fuel Company) retail pricing (Gulf Times, 2014). This value is converted to MUSD/PJ and multiplied by the service demand energy intensity to obtain the effective cost of cooking services.

No additional fixed or variable cost components are assigned at this sectoral level, as cost burden is fully reflected through energy tariffs and consumption intensities. The average technical life spans of technologies are drawn from the literature, such as Eveloy and Ayou (2019) for district and conventional cooling technologies, Glover et al., (2024) for domestic solar panels as appeared in Forbes Home, U.S. Department of Energy (2024) and Green Lighting (2024) for the extended lifetimes of LED compared to incandescent lighting, and Mead (2018) for the remaining house appliances life limits.

Demand Sector: SERVICE

A similar approach to the residential sector is applied to estimate service sector costs. In this case, the commercial electricity tariff published by Kahramaa (2024) is used as the

price index. The tariff value of 0.14 QAR/kWh is converted to MUSD/PJ and multiplied by the electricity consumption rate of each technology to capture the relative efficiency differences. For instance, district cooling technologies, with lower electricity intensity per unit of cooling service, are more cost-effective than conventional air conditioning units.

As with the residential sector, no additional fixed or variable costs are assigned, since the service provision cost is fully represented through the electricity tariff and consumption intensity. The technical life spans of technologies in this sector are aligned with those used in the residential sector, as both sectors rely on comparable appliances and cooling technologies.

EXPORT

As outlined in the preceding sections, the Export sector represents the demand side driver of petroleum commodity production. However, it does not impose additional economic attributes or cost burdens beyond those already accounted for in the oil and gas processing sector of the model.

3.1.6 Scenario Planning Framework

Scenario planning is a method of creating several plausible scenarios for the future without seeking to produce precise predictions (Keough and Shanahan, 2008). Instead, it provides a structured means to explore uncertainty by comparing outcomes across different assumptions and drivers. Within energy system modelling, scenario analysis is widely employed to assess economic feasibility and policy alignment, as alternative pathways are evaluated against cost-effectiveness criteria and climate policy objectives. (Prina et al., 2022).

In this study, three scenarios are developed to investigate the potential trajectories of Qatar energy transition. These scenarios are designed to align with the country's long-

term strategic frameworks, including the Qatar National Vision (QNV), the Nationally Determined Contribution (NDC), and the National Development Strategy (NDS).

3.1.6.1 Carbon Budget Representation

In MUSE-QA, energy transition is operationalised through the imposition of a carbon budget, defined as a user-specified emissions cap. System-wide environmental performance is therefore assessed by constraining cumulative emissions over time. The carbon budget is input as an exogenous trajectory of absolute values, which triggers an endogenous carbon pricing mechanism. This carbon price increases the LCOE of high-emitting technologies, thereby shifting investment decisions towards low-carbon alternatives. The model reallocates investment recursively until a market equilibrium is reached, ensuring consistent commodity pricing while maintaining emissions within the imposed limits.

The carbon budget is enforced numerically using the 'bisection' method. For each milestone year, a total emissions target is specified, with iteration frequency set to 50 at the midpoint of simulation iterations to balance accuracy and computational burden. Compliance with the budget is allowed within a $\pm$ 10% tolerance band. The initial seed price of CO_2 is defaulted at 0.01 MUSD/ktCO_2, after which the carbon price is adjusted endogenously until the defined emissions budget is satisfied (Giarola, 2022; Imperial College London, 2022).

3.1.6.2 Scenario Design

Three distinct scenarios are developed to explore the evolution of Qatar energy system within the dual ambit of domestic policy priorities and international climate governance frameworks, as follows:

- **Business as Usual (BAU):**

  This baseline trajectory assumes unconstrained development, with demand met without any environmental restrictions. The model selects technologies purely on the basis of optimised LCOE value, and adds new capacity only when required to

meet service demand. All technologies are available for investment after the base year.

- **Nationally Determined Contribution (NDC):**

  This scenario reflects Qatar's NDC commitment to reduce emissions by 25% relative to BAU by 2030. A carbon budget is imposed, mirroring the BAU emissions until 2030, after which they are reduced by 25% relative to BAU, and maintained at that level through to 2050.

- **Net Zero 50 (NZ50):**

  Aligned with the IEA global carbon neutrality outlook, this scenario introduces progressively stringent carbon caps post-2030, driving emissions to net-zero by 2050. Investment decisions in this pathway are no longer based exclusively on economic optimisation but are tightly bound to the environmental performance of technologies available in the system. Table 3.30 summarises the structure of the carbon budget assumed for the three scenarios.

Table 3.30: Carbon budget structure for the three scenarios in MUSE-QA. In the carbon capped scenarios, NDC enforces a linear reduction of emissions to 25% by 2030 onwards. NZ50 scenario, enforces a progressive reduction after 2030 towards zero by 2050

scenario	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU_{2015}	BAU_{2020}	BAU_{2025}	BAU_{2030}	BAU_{2035}	BAU_{2040}	BAU_{2045}	BAU_{2050}
NDC	BAU_{2015}	BAU_{2020}	BAU_{2025}	75% BAU_{2015}	NDC_{2030}	NDC_{2030}	NDC_{2030}	NDC_{2030}
NZ50	BAU_{2015}	BAU_{2020}	BAU_{2025}	NDC_{2030}	75% NDC_{2030}	50% NDC_{2030}	25% NDC_{2030}	zero

Together, these scenarios capture a comprehensive spectrum ranging from unconstrained continuation to strategically articulated policy pathways and, ultimately, deep decarbonisation. This framework ensures that the modelling exercise not only informs national policy development but also situates Qatar's energy transition within the broader international context.

3.2 Results and Discussion

This section presents the outcomes of simulating three scenarios for Qatar energy system. All scenarios share the same deterministic service demand trajectory, with investment choices shaped by the agent's least-cost LCOE preference under varying environmental constraints. The results are analysed across scenarios across sectors, comparing energy portfolio evolution, emissions performance, and economic outcomes. Through this comparative assessment, the analysis underscores the trade-offs between economic feasibility and emissions reduction targets, providing insights into the interplay between technology choices, policy levers, and long-term system sustainability.

3.2.1 National Energy Portfolio

The transition of Qatar energy system into a tailored energy mix by the end of the simulation timeframe delineates both the decarbonisation pathway and the broader system evolution. The configuration of the energy mix serves as the primary indicator of how this transition unfolds (Manuel et al., 2022). Within MUSE-QA, this mix is represented at two levels: *upstream*, through the procurement of primary energy vectors, and *downstream*, at the conversion stage where secondary energy vectors are produced and consumed.

Two milestone years emerge as pivotal in shaping the national energy portfolio. First, by 2030, a substantial portion of the system initial installed capacity reaches retirement, creating a critical window for large-scale reinvestment to meet growing demand; most notably the surge in LNG exports demand consistent with QatarEnergy expansion plans, as elaborated in previous chapters. Second, by 2050, the portfolio reflects a decisive checkpoint for environmental performance, with investment decisions reshaped to align with emissions reduction targets and long-term system sustainability.

3.2.1.1 Fuels in the system

Primary Energy Supply in the System

Primary energy commodities in the UPSTREAM sector remain the backbone of the system, largely driven by export demand for Qatari petroleum products. As can be seen in Figure 3.16, under the BAU scenario, conventional fossil capacity continues to expand, with total supply stock of crude oil, natural gas, and NGL increasing by approximately 66% relative to the base year by 2050.

By contrast, the NDC levers production towards CCS-integrated oil and gas facilities, which accounts for 28% of the total energy production stock by 2050. A larger CCS share is observed in the NZ50 scenario, where 88% of production is coupled with CCS technologies by 2050. However, the NZ50 pathway subsequently introduces large-scale investment in DAC, supplying up to 12% of energy commodity demand by mid-century. This strategic shift is triggered by rising endogenous carbon prices, which force the system to reduce its emissions aggressively.

Nevertheless, this reliance on CCS and DAC utilities amplifies natural gas requirements, since both technologies impose additional fuel demands to operate capture units. By 2050, system-wide decarbonisation under NDC increases natural gas flow by merely 1.5% compared with BAU, while NZ50 incurs a slightly larger increase of 6.3%. This outcome is consistent with similar findings in the literature, which highlight the gas-intensifying effect of capture technologies as in Manuel et al. (2022).

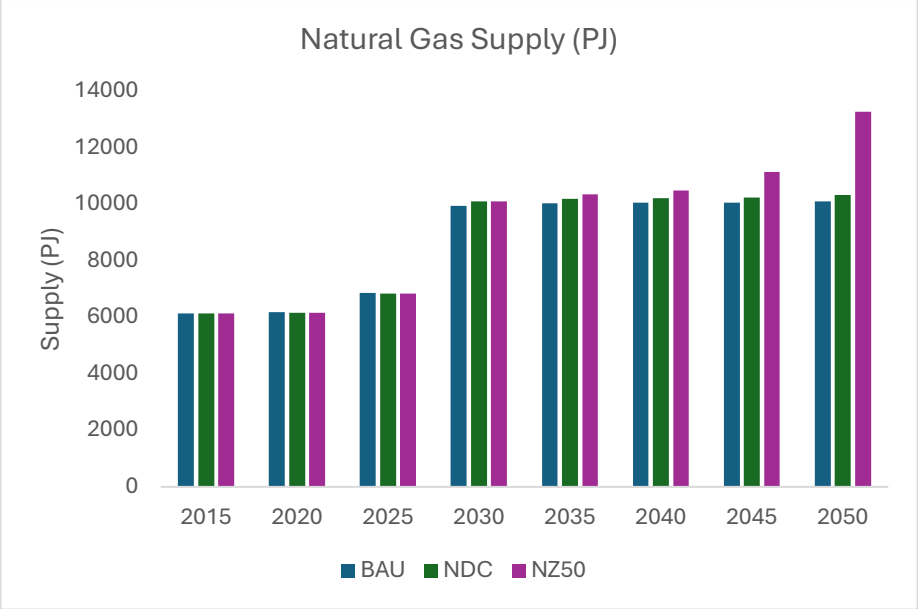


Figure 3.16 Natural gas supply in the system in the BAU, NDC, NZ50 scenarios projected towards mid-century.

Moreover, with respect to the other two primary energy vectors, crude oil and NGL, these commodities are supplied directly from the UPSTREAM sector either to the EXPORT sector or to the GTL-RFEINERIES sector, where they are further processed into petroleum products for both export and domestic consumption, primarily within the TRANSPORT sector, alongside marginal LPG consumption in the RESIDENTIAL sector. Consequently, these vectors predominantly serve two main end-use sectors: TRANSPORT and EXPORT.

Under the NZ50 scenario, the supply of crude oil and NGL exhibits a notable decline, primarily driven by transport-sector electrification and accelerated fuel-switching process, as illustrated in Figures 3.17 and 3.18. In contrast, the NDC scenario shows only a modest decrease in supply, reflecting limited transition in the transport sector.

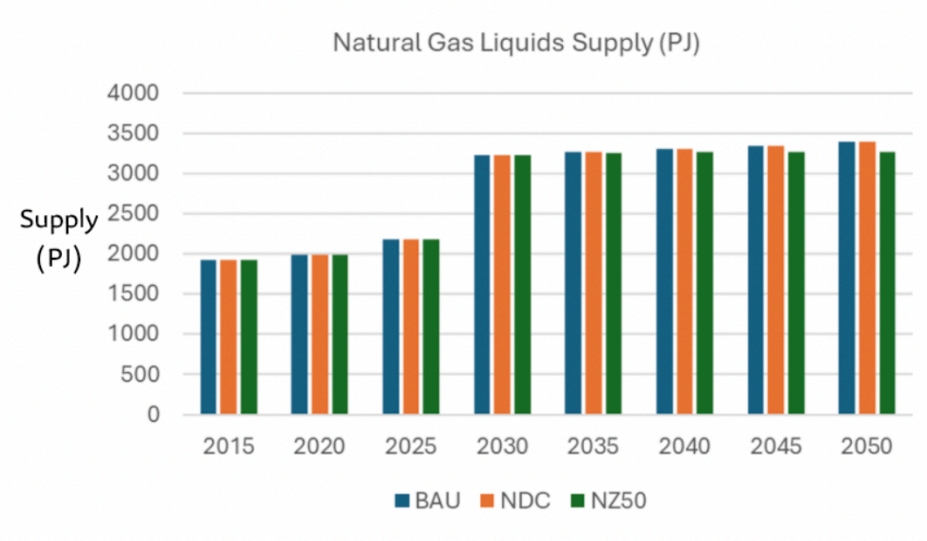


Figure 3.17: Natural gas Liquids supply in the system compared for BAU, NDC, NZ50 scenarios

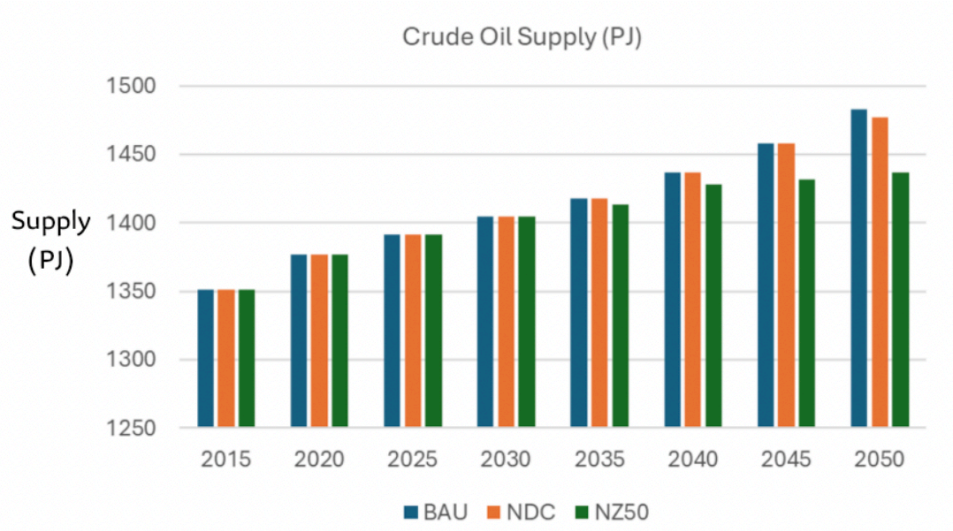


Figure 3.18: Crude oil supply in the system compared for BAU, NDC, NZ50 scenarios

Primary Energy Conversion into Secondary Energy

The processing of primary energy vectors into secondary energy carriers within the conversion sector (GTL-REFINERIES) occurs through three principal routes: the processing of crude oil and NGL in oil refineries and GTL plants, the liquefaction of natural gas in LNG facilities, and the production of hydrogen though a range of emerging technologies. The technology portfolio across these conversion routes exhibits distinct dynamics under varying emission-reduction targets, reflecting the influence of carbon budgets, technology costs, and policy incentives.

Firstly, the processing of crude oil and NGL demonstrates markedly different trends across scenarios. Under the BAU pathway, the model sustains a steady expansion of conventional petroleum production capacity throughout the modelling horizon, supported by cost-efficient levelised cost of energy (LCOE) values that favour established technologies in the absence of carbon taxation, estimated at 5.9 USD/GJ for LNG, 8.7 USD/GJ for GTL, and 3.6 USD/GJ for oil refining. In contrast, the decarbonisation of oil refineries and GTL plants is activated only under mitigation-oriented scenarios, where the carbon budget induces an endogenous carbon price. This carbon price progressively increases the LCOE of emitting technologies, thereby shifting investment preferences towards lower-emission alternatives.

Under the NDC scenario, by 2030, the model projects the adoption of GTL equipped with CCS, contributing approximately 33% of total output. This shift occurs when the LCOE of GTL-CCS falls to 11.8 USD/GJ, marginally below the 11.9 USD/GJ recorded for conventional GTL. This configuration persists until around 2045, when CCS-equipped units reach the end of their operational lifetimes, after which conventional GTL once again dominates production by 2050 at a competitive LCOE of 10.8 USD/GJ. Direct air capture (DAC) does not emerge as cost-competitive within this scenario, its LCOE ranges between 12.6-13.0 USD/GJ, as a tighter carbon budget and higher carbon prices are required to economically displace GTL and GTL-CCS.

In contrast, under the NZ50 scenario, a continuously tightening carbon budget and elevated carbon-price signals exceeding 920 USD/tCO2 drive a marked structural transition in the GTL portfolio. By 2050, the sector becomes fully decarbonised, with GTL-DAC accounting for 32% of production at LCOE 17.8 USD/GJ and GTL-CCS at LCOE 102.2 USD/GJ representing the remaining 68%, fully displacing conventional GTL route which the carbon price has increased its LCOE by manifold. Figure 3.19 illustrates the evolution of GTL technologies shares across the three scenarios. The emissions implications of upstream transitions are discussed in Section 3.2.3.

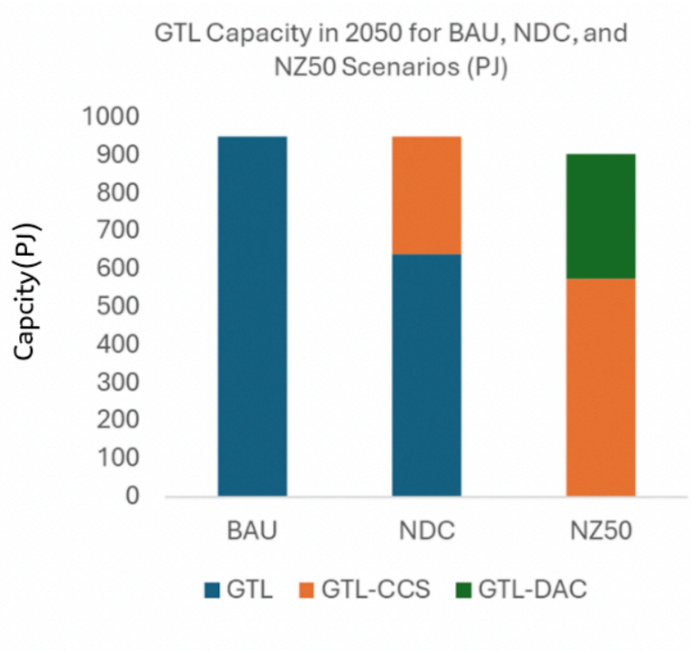


Figure 3.19: GTL technology mix in the target year 2050 across BAU, NDC, NZ50 scenarios. It shows that conventional GTL route is maintained in the less-environmentally stringent scenarios, but it is phased out in the carbon neutrality target scenario.

In addition to GTL production, the other major oil and gas processing technology within the conversion sector is *oil refining*. Conventional refineries remain both economically viable and operationally efficient toward the end of the modelling horizon under the BAU and NDC pathways, with a comparable levelised cost of energy of approximately 3.6 USD/GJ. This persistence is largely attributable to their lower emissions intensity per barrel of liquid product compared with GTL, enabling them to maintain a dominant share of liquid fuel production even under a moderate carbon budget such as the NDC scenario.

However, under the NZ50 scenario, refining activity undergoes a significant structural transformation. By 2050, conventional refinery capacity is reduced to less than half of total capacity, reflecting the stringent decarbonisation constraints imposed by the scenario. In this pathway, the decarbonisation of oil refineries occurs relatively late in the transition, with OILREF-DAC units entering the system around 2050 at an LCOE of 6.7 USD/GJ, compared with 7.1 USD/GJ for OILREF-CCS and 7.8 USD/GJ for conventional refining. These DAC-integrated refineries supply approximately 54% of total refining output. Figure 3.20 illustrates the oil refining technology mix across the three scenarios

by 2050, highlighting the delayed shift toward carbon-removal integration under deep decarbonisation conditions.

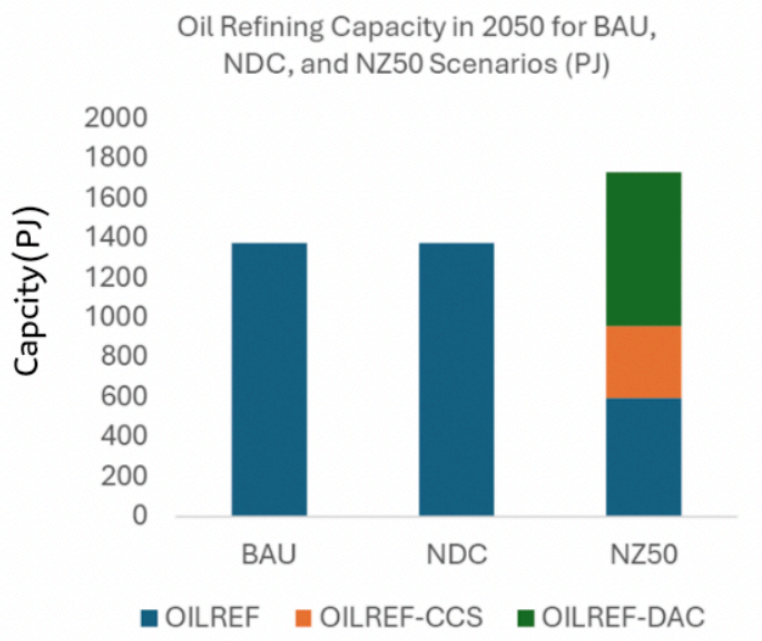


Figure 3.20: Oil refining technology mix in 2050 across the BAU, NDC, NZ50 scenarios. Conventional refining remains in the system even under the NZ50 scenario due to its lower environmental impact and higher energy efficiency compared to the Fischer-Tropsch process in GTL plants

Secondly, **natural gas processing** through liquefaction plants presents a more complex decarbonisation challenge compared with GTL and oil refining. The primary constraint arises from the long-lived nature of existing LNG production assets, which typically have operational lifetimes of 30 years, making early phase-out both technically and economically impractical.

Nevertheless, the planned 85% expansion in LNG production capacity by 2030, as announced by QatarEnergy, creates a strong momentum for investing in low-emission liquefaction routes under mitigation targets. Under the NDC scenario, the 25% emissions-reduction target results in a system-wide partial equilibrium carbon price of approximately 210 USD/tCO_2 by 2050, which progressively increases the LCOE of conventional liquefaction to 6.7 USD/GJ, reducing its share to 49% of total output. In

parallel, the LCOE of USPLNG-CCS declines to 7.1 USD/GJ, enabling it to supply the remaining 51% of total liquefaction capacity.

In contrast, under the NZ50 scenario, the late-stage retirement of legacy LNG assets necessitates a decisive shift toward full decarbonisation of the liquefaction process. By 2050, the system progressively phases out conventional UPSLNG plants entirely to LNG-CCS, which continues to dominate beyond 2050 due to the long operational life of the installed units. Although this transition delivers deep emissions reductions, it also introduces a lock-in effect which limits the deployment of next-generation low-carbon technologies, as the persistence of the new LNG-CCS infrastructure delays new investment cycles even under improved cost values, where the LCOE of UPSLNG-DAC is 10.7 USD/tCO2 compared to 41.5 USD/tCO2 for UPSLNG-CCS. This outcome highlights the significance of early action and long-term planning.

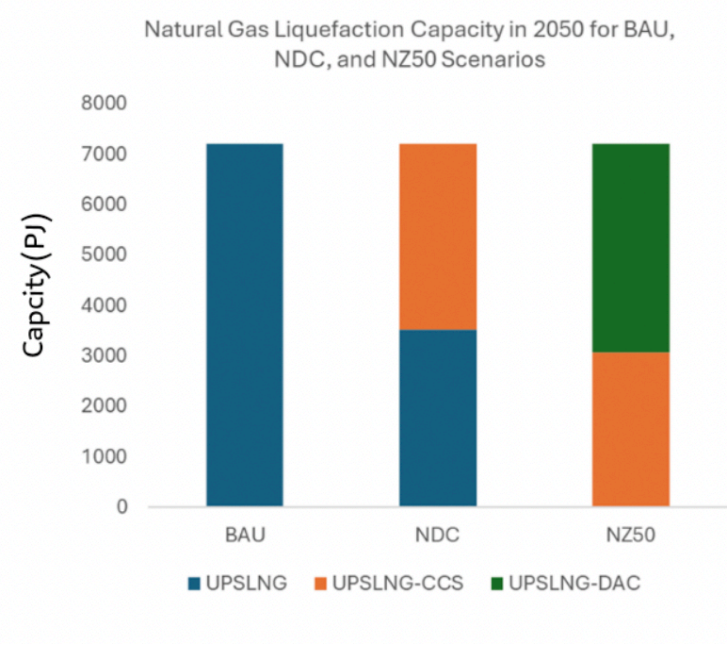


Figure 3.21: Natural gas liquefaction technology mix in 2050 across BAU, NDC, NZ50 scenarios.

Furthermore, beyond crude oil, natural gas, and NGL, a new commodity, hydrogen, emerges within the processing sector under the extreme decarbonisation pathway (NZ50), driven by an exceptionally high carbon price. Hydrogen represents a strategic low-carbon fuel option in this scenario. The model initiates investment in hydrogen

production from 2040, coinciding with the retirement of diesel-fuelled heavy-duty trucks reaching the end of their service lifetimes. To maintain transport service provision, a share of the fleet is progressively replaced with hydrogen-fuelled trucks, as detailed in section 3.2.1.3.

Under this pathway, hydrogen production is entirely derived from direct air capture (DAC)-integrated facilities, with an estimated LCOE 20.1 USD/GJ, reflecting a system-wide transition toward carbon-neutral fuel synthesis. Figure 3.22 depicts the conversion-stage technology mix under the NZ50 scenario, highlighting the emergence of hydrogen as a key enabler of deep decarbonisation within the transport sector. This outcome aligns with the IEA projections which identify hydrogen as a critical fuel for decarbonising long-distance and heavy-duty transport, where direct electrification remains technically challenging and economically constrained (IEA Hydrogen, 2024).

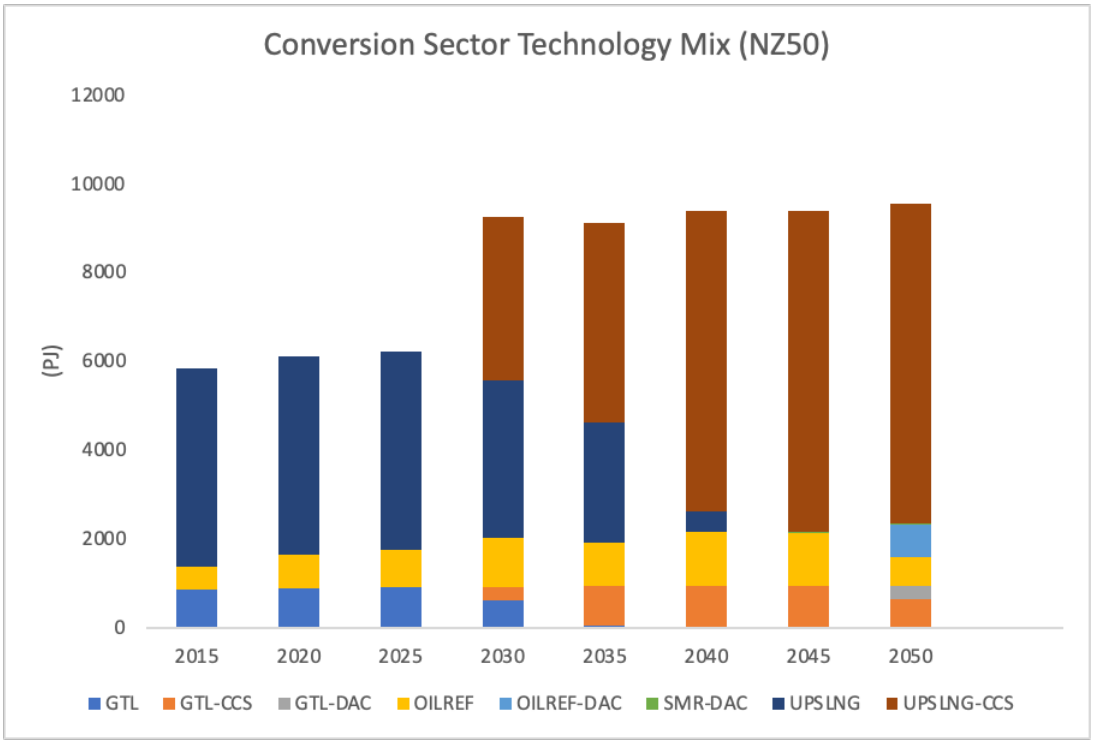


Figure 3.22: Technology mix in the conversion sector under the NZ50 scenario, showing the most diverse portfolio as hydrogen production is introduced into the system's energy commodity output.

3.2.1.2 Electricity in the system

Electricity generation in MUSE-QA is explicitly represented within the energy conversion sector. Across all scenarios, BAU, NDC, and NZ50, natural gas remains the dominant energy source for electricity generation, underscoring its entrenched role in the national power mix. Under emissions-reduction targets, combined-cycle gas turbines (CCGT) and their low-emission variants continue to exhibit cost-competitiveness with renewables, providing reliable and dispatchable power to meet steady-state demand. Their sustained presence in the system is reinforced by their recognition in the EU Green Taxonomy as a legitimate pathway for low-carbon electricity generation (Bui et al., 2023).

In the baseline (BAU) pathway, electricity demand increases by approximately 70% over the modelling horizon, supplied exclusively through conventional CCGT plants, as shown in Figure 3.23. The NDC scenario follows a comparable electricity demand trajectory, due to marginal electrification measures in the system, however, it incorporates a more diversified generation portfolio. Notably, Al Kharsaah Solar Power Plant enters the system in the 2025 investment period. By 2030, when the carbon budget constraint becomes active, solar achieves cost-competitiveness with an LCOE of 4.6 USD/GJ, compared with 21.4 USD/GJ for CCGT-CCS. However, owing to the diurnal variability of solar output, the plant's effective utilisation factor remains below 50%, resulting in solar energy contributing only about 3% of total electricity demand by 2050.



Figure 3.23. Power mix in BAU (top), NDC (middle), and NZ50 (bottom) scenarios showing continued reliance on fossil-based power generation as decarbonisation is applied through carbon removal utilities

In the NZ50 scenario, the power sector technology mix diversifies significantly by 2050, as shown in Figure 3.23. Low-carbon CCGT plants equipped with CCS and DAC provides 62% of electricity generation, maintaining their role as the system's dispatchable backbone. Renewables, including standalone solar, solar with storage, and onshore wind, contribute the remaining 38%, marking a notable departure from the gas-dominated portfolio observed in BAU and NDC.

This expansion is necessary to accommodate a 14% increase in electricity demand relative to BAU, reflecting the additional burden imposed by end-use electrification across transport, residential, and service sectors. The shift is largely driven by the steep rise in carbon prices, which reallocates investment away from conventional fossil-fuel routes towards low- and zero-emission options.

Enforced uptake of solar power in the NDC scenario contributes only marginally to the power mix. Even under carbon budget constraints, the system continues to prioritise fossil-based generation routes. By contrast, only the zero-emission NZ50 target provides a sufficiently strong trigger for diversification in generation technologies. By 2050, the NZ50 power mix comprises 30% CCGT-CCS, 32% CCGT-DAC, 3% ESOLPV, 26% ESOLPV-ES and 9% WIND-ONSHORE. The persistence of CCGT-CCS in the system reflects early investments made to comply with the more relaxed carbon cap in 2030. At the same time, the partial decommissioning of standalone solar, exogenously enforced into the mix as per Al Kharsaah solar power plant, is followed by the commissioning of solar-with-storage technologies, which smooth the supply curve and enhance system reliability.

At this scale of deployment, solar requires an estimated ~128 to 192 km^2 of land. This means, the land required for this new investment is at least twelve folds the size of the current Al Kharsaah solar farm which accommodates 1.8 million panels within 10 km^2 block (Marubeni, 2020). To put this in context, this expansion would require an area comparable to the entire city of Doha (WB, 2020). Similarly, the modelled onshore wind capacity of 2.9 GW in 2050 requires a land area of approximately 360 – 717 km^2; equivalent to roughly three times the size of Doha; or approximately 5% of the total land area of Qatar. Despite these substantial land requirements, utilisation rates remain

modest, with only ~27% of installed solar and ~24% of installed wind capacity effectively exploited.

3.2.2 Sectoral Technology Profile

The steadily rising service demand toward mid-century strongly influences investment choices across both upstream and downstream sectors. Capital requirements, environmental costs, and system constraints serve as critical triggers that determine which technologies retain competitiveness and which are phased out.

In MUSE-QA, these dynamics are captured in the evolving technologies mix under different scenario settings. This section presents the model outcomes, focusing on investment behaviour in key service demand areas, highlighting where technologies are adopted, expanded, or retired along the decarbonisation pathways

INDUSTRY sector

In the **baseline scenario (BAU)**, the industrial technology mix remains fully unchanged throughout the timeframe, reflecting a consistent preference for conventional production routes. This persistence is primarily driven by the LCOE investment logic, under which conventional options retain cost advantages due to lower capital requirements and the absence of carbon pricing. Existing installed capacities and established operating performance further entrench their position, as these technologies do not incur the additional fuel penalties or efficiency losses associated with carbon removal integration.

In the **low-carbon scenario (NDC),** conventional assets remain prominent, but the introduction of a carbon budget in 2030 initiates a carbon price that triggers CCS deployment. Once commissioned, CCS-equipped facilities continue to operate until the end of their technical lifetimes, after which they are replaced by conventional technologies if carbon allowances permit.

The most pronounced transition occurs in the chemicals segment, where ~96% of the ammonia production shifts to CCS-integrated routes by 2030, driving an 87% emissions reduction in this subsector relative to BAU. Smaller CCS investments come on stream for ethylene and steel production, though their impact is limited due to the relatively small share of petrochemicals in the overall industrial portfolio. Cement manufacturing, by contrast, remains entirely conventional, reflecting the continued cost advantage of traditional processes over emerging low-carbon alternatives.

Under the **net-zero pathway (NZ50)**, industrial production is progressively reconfigured around DAC-based processes, which become the economically optimal choice across chemicals and petrochemicals, and other industrial segments. This transition reflects the strong carbon price signal, which renders DAC economically competitive relative to both conventional and CCS technologies, accelerating its dominance in the portfolio. Figure 3.24 depicts the industrial technology portfolio for BAU, NDC, and NZ50.

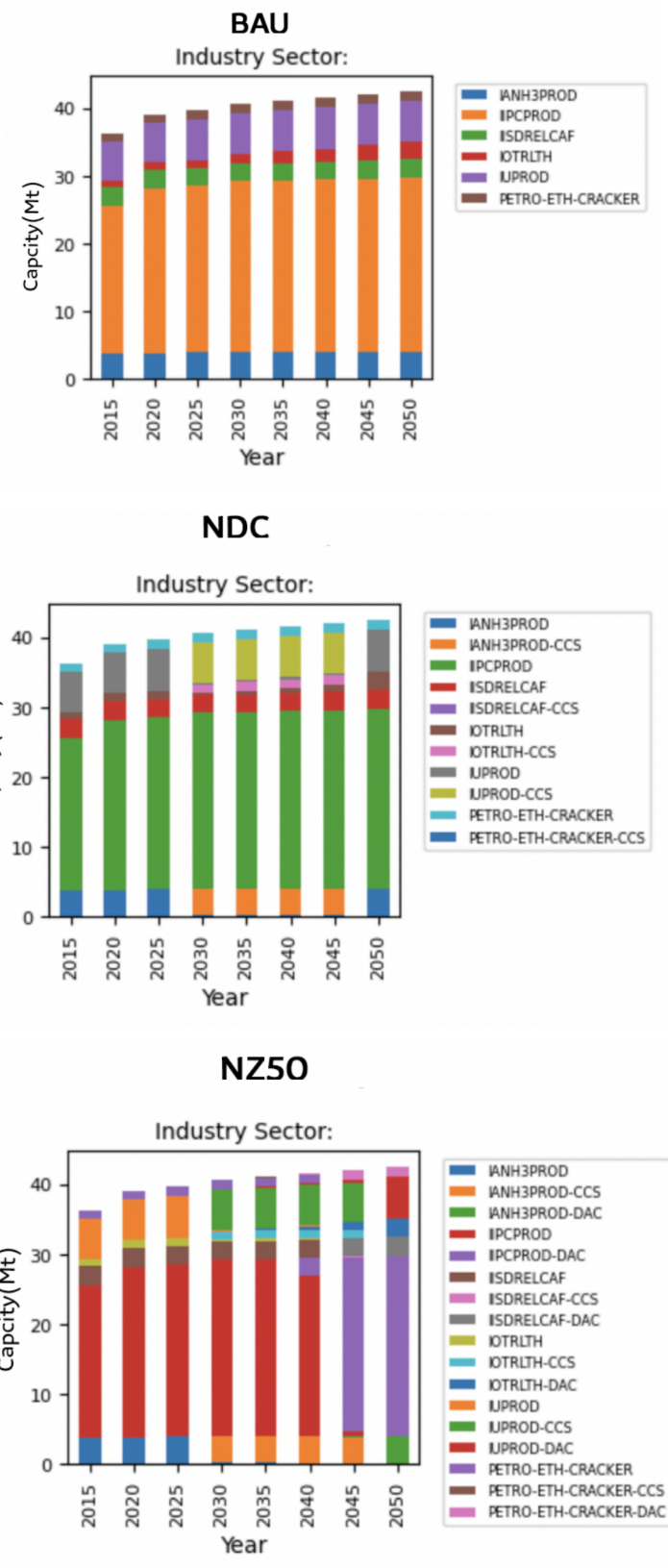


Figure 3.24: Industrial technologies mix in BAU (top), NDC (middle), and NZ50 (bottom) scenarios levering future investments to gradually shift away from conventional routes towards CCS integration and then DAC units as the carbon budget becomes tighter and the carbon price becomes higher

WATER DESALINATION sector

Across all three scenarios, the model indicates a clear transition from multi-effect distillation (MED) and multi-stage flash (MSF) towards seawater reverse osmosis (SWRO) once the initial installed capacities reach retirement, as illustrated in Figure 3.25. This outcome reflects the higher efficiency and stronger economic performance of SWRO compared to thermal desalination technologies, a finding consistent with the techno-economic attributes outlined in Section 3.1.5.3.

The literature, however, highlights an important trade-off. While MSF typically delivers superior water quality, SWRO often requires additional post-treatment to achieve the same standard (Gacem et al., 2012). These post-treatment requirements are not considered in this study, as investment decisions are assessed solely on the basis of the capital, and operating, costs of producing one million cubic metres of desalinated water per year. This signals an area requiring further investigation to ensure policy design is evidence-based and avoid overambitious assumptions.

To address this limitation, Chapter 4 applies additional modelling constraints. This approach aligns with QT-TIMES framework and reflects more recent national decarbonisation strategies, ensuring that desalination planning is evaluated under more realistic techno-economic conditions.

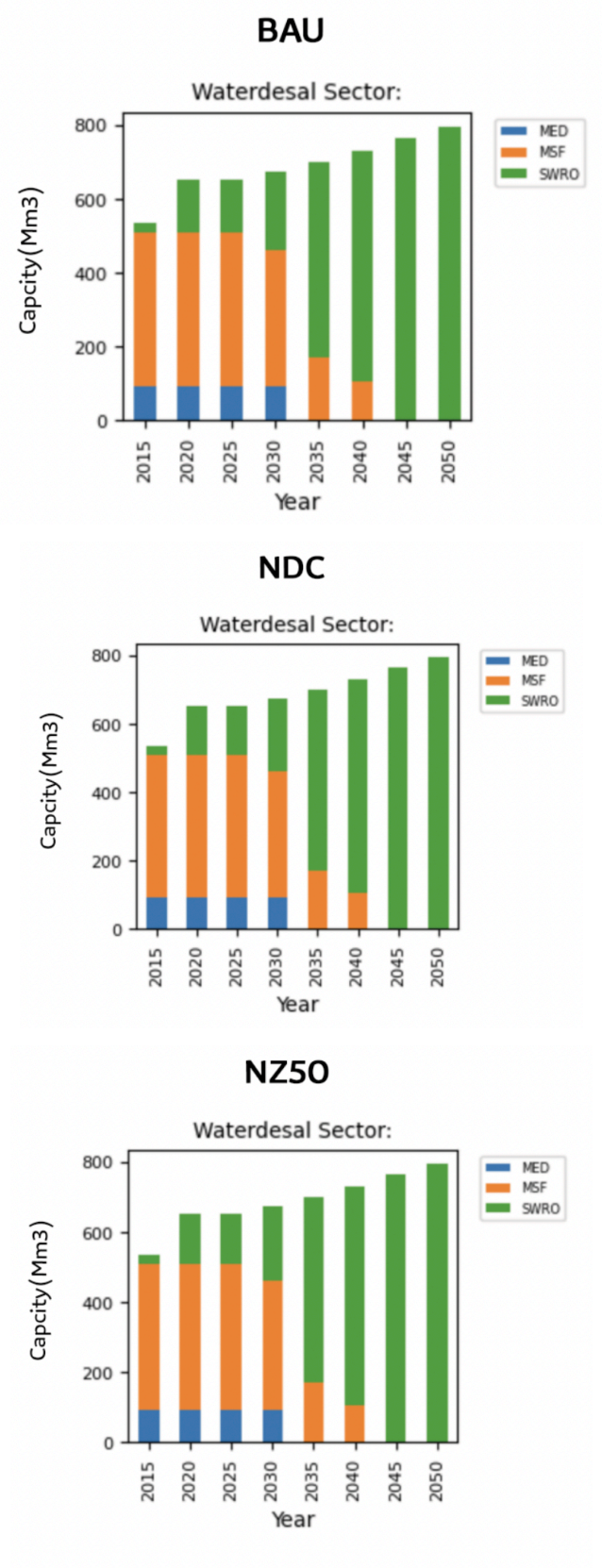


Figure 3.25: Water desalination technology mix in BAU (top), NDC (middle), and NZ50 (bottom) scenarios exhibit similar investment patterns, with thermal desalination technology being phased out in favour of membrane desalination.

TRANSPORT sector

The results reveal that deep decarbonisation of the transport sector materialises only under the stringent NZ50 carbon budget. In this pathway, large-scale electrification and a switch to hydrogen fuel enable a structural transformation of the fleet mix. By contrast, fossil-fuelled vehicles remain cost-competitive in both BAU and NDC scenarios, where no significant transition occurs.

In the NDC case, carbon pricing places greater priority on upstream decarbonisation measures rather than direct electrification or hydrogen adoption in transport. Large-scale investment in hydrogen production and electricity generation to power alternative drivetrains is not cost-competitive relative to maintaining fossil-fuel-based fleets. Consequently, emissions from transport remain within the NDC carbon budget, effectively relegating deep decarbonisation measures in this sector. Figure 3.26 illustrates the technology mix in the transport sector across the BAU, NDC, and NZ50 scenarios.

Under NZ50, however, a combination of electrification and hydrogen uptake compels major investments in supporting infrastructure. This shift avoids 95.6 PJ of gasoline and 129.2 PJ of diesel consumption, easing pressure on oil refineries, while requiring an additional 35 PJ of natural gas for hydrogen production and 0.9 GW of electricity capacity. These demands are partly offset by higher renewables penetration, underscoring the interdependence between transport transition and upstream supply dynamics. Figure 3.26 illustrates the sectoral technology mix across BAU, NDC, and NZ50 scenarios.

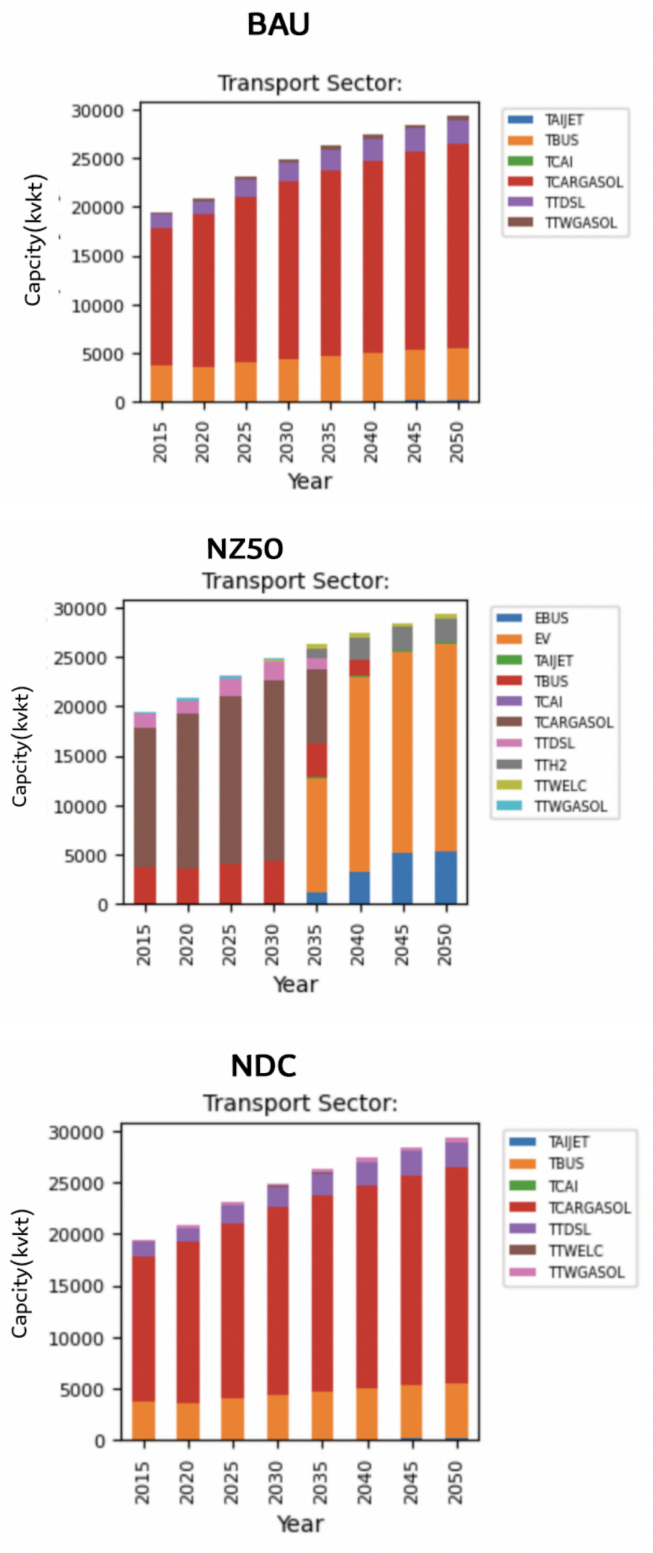


Figure 3.26: Simulation results for the transport sector in BAU (top), NDC (middle), and NZ50 (bottom) scenarios. indicate that its decarbonisation is deprioritised, with mitigation efforts shifted towards higher impact emissions reduction opportunities in the supply and conversion segments of the energy system.

RESIDENTIAL and SERVICE sectors

The residential and service sectors in Qatar are already largely electrified, with the exception of a small residual share of LPG fuel used for domestic cooking. Across all scenarios, investment decisions are primarily driven by efficiency improvements rather than carbon pricing, which plays only a marginal role. For instance, LED lighting consistently replaces incandescent bulbs, electric stoves displace LPG-fuelled ovens, and rooftop solar water heaters are preferred over conventional electric water heaters. Collectively, residential and service demands account for approximately 31% of total domestic energy use.

In the residential sector, space cooling remains the single largest energy demand. Across all scenarios, this demand is rapidly redirected towards district cooling (DC), recognised as the most energy-efficient and cost-effective option. By 2050, DC capacity expands progressively until it achieves full diffusion by 2050, supplying more than 6.5 TR of residential cooling demand. Figure 3.27 depicts the simulation results for the residential sector under the three scenarios. While DC is technically and economically viable for new residential developments, the model does not differentiate between cooling requirements in new and existing housing stock. In practice, retrofitting DC into densely populated or low-income housing areas may pose significant challenges, highlighting a gap that warrants further research to inform targeted policy interventions.

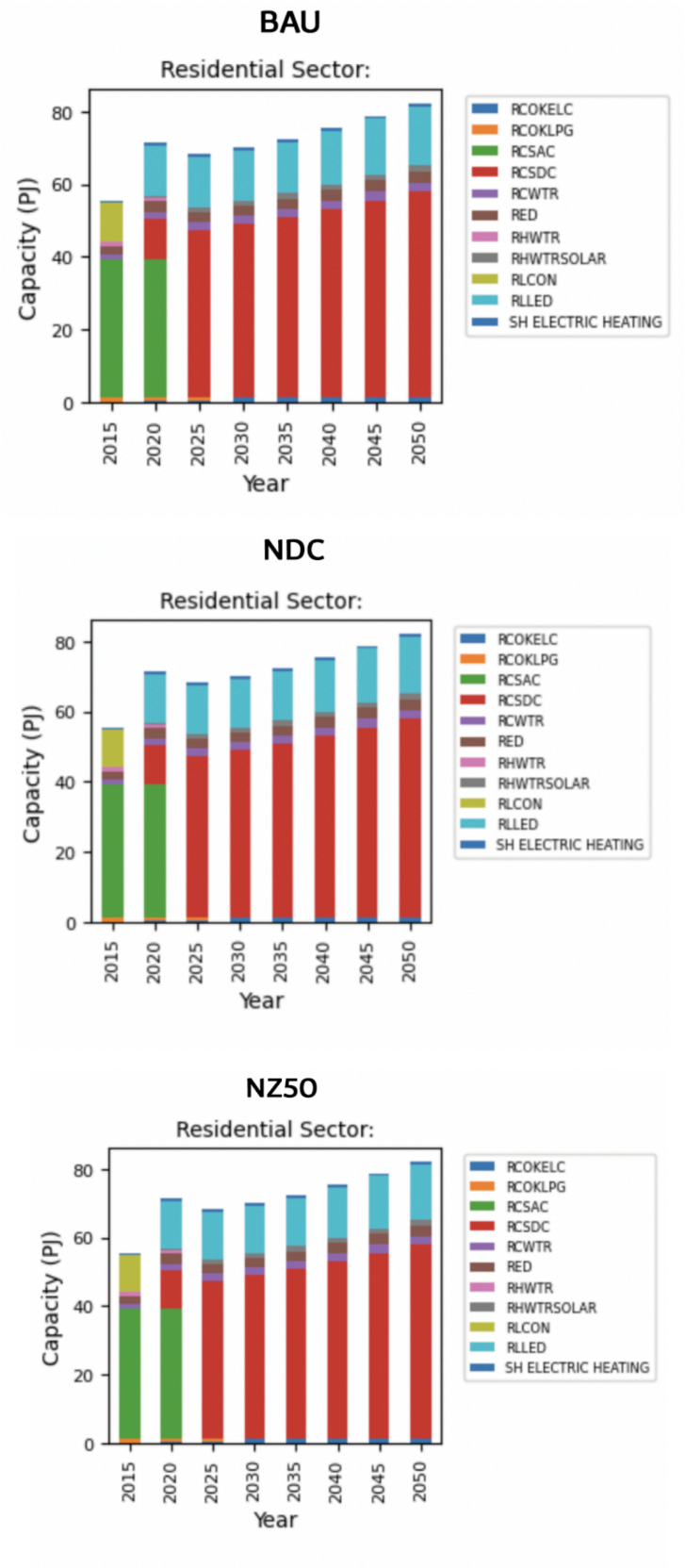
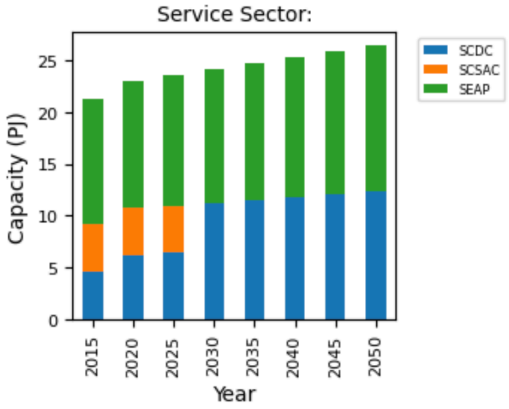


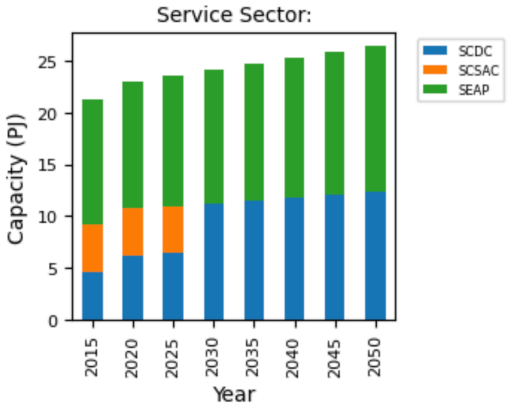
Figure 3.27: Simulation results of the residential sector in BAU (top), NDC (middle), and NZ50 (bottom) scenarios, showing that the system consistently prioritises the most technically and economically viable technologies in a sector that is already predominantly electrified.

A similar investment trend is observed in the commercial service sector. Here too, district cooling replaces air-conditioning systems, expanding steadily until it supplies the entirety of commercial cooling demand by 2050. Figure 3.28 depicts the simulation results.

BAU



NDC



NZ50

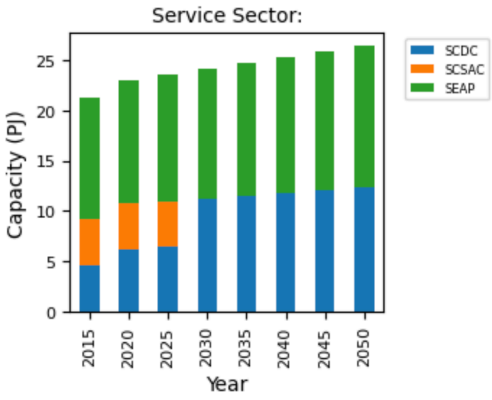


Figure 3.28: Simulation results of the commercial service sector in BAU (top), NDC (middle), and NZ50 (bottom) scenarios, reiterating the trend in the residential sector and selecting District Cooling over AC to meet space cooling demand.

3.2.3 Emissions in the system

The results demonstrate a clear reduction in system-wide emissions under the two mitigation scenarios, as shown in Figure 3.29. By contrast, the baseline scenario (BAU) exhibits a steady rise in emissions, with total CO_2 output increasing by 55% relative to the base year. A marked spike occurs in 2030, coinciding with QatarEnergy LNG export expansion, which alone adds approximately 21 $MtCO_2$ to total emissions.

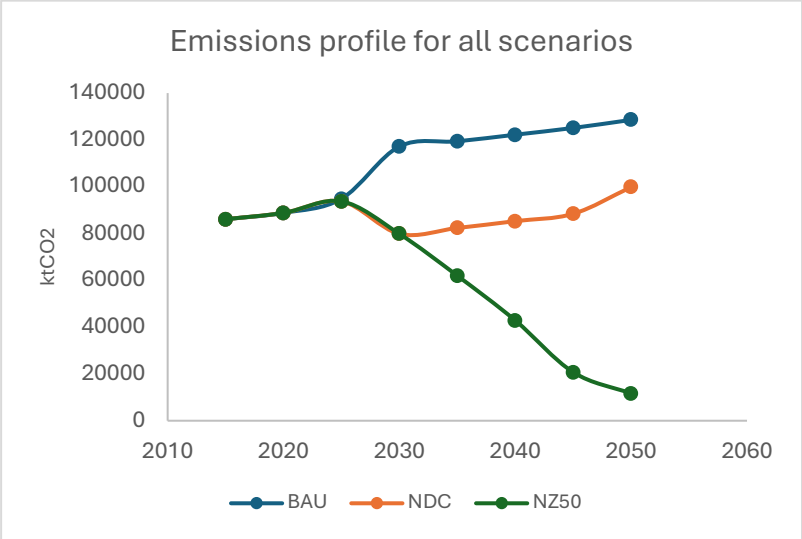


Figure 3.29: Projected system emissions trajectories under the three scenarios: BAU, unconstrained scenario; NDC, targeting 25% emissions reduction; and NZ50, targeting carbon neutrality.

Sectoral dynamics further accentuate this baseline trajectory. Industrial activity elevates emissions by 30% in 2050 compared to the base year, while the transport sector records a 52% increase, equivalent to an additional 6.7 $MtCO_2$, driven primarily by growth in fossil-fuelled road transport. The power sector contributes a 61% rise in emissions, reflecting its continued reliance on dispatchable natural gas-based power generation. Upstream, persistent dependence on natural gas leads to an 85% increase in extraction-related emissions. Figure 3.30 illustrates the BAU emissions trajectory, highlighting Qatar's sustained high per capita emissions. These remain well above historical levels observed in neighbouring countries such as the Saudi Arabia and the UAE (World Bank, 2024).

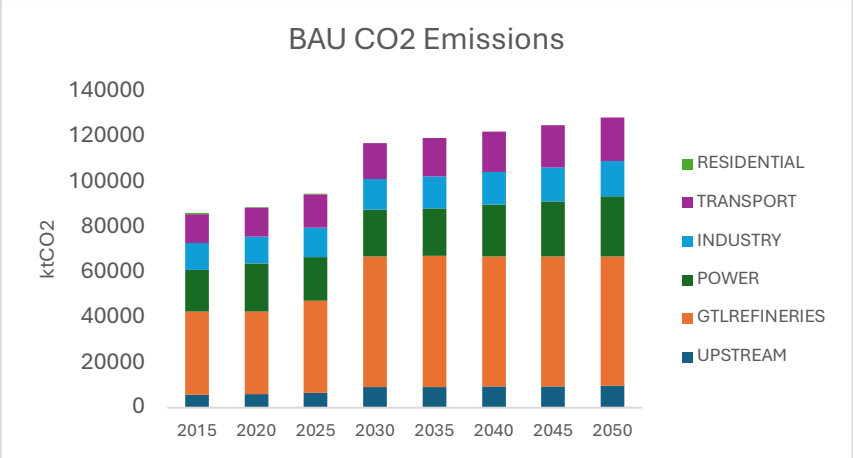


Figure 3.30: BAU sectoral emissions trajectory

Emissions under the NDC scenario, which imposes a 25% reduction target by 2030, demonstrate a significant improvement in Qatar's overall carbon footprint. By 2030, large-scale deployment of carbon capture utilities in the oil and gas processing sector; particularly across GTL and liquefaction plants, abates approximately 25 $MtCO_2$. A further ~6 $MtCO_2$ is offset in the power sector, underscoring the complementary role of renewable energy alongside carbon capture in achieving near-term targets. Additional reductions of 3.3 $MtCO_2$ and 2.7 $MtCO_2$ are achieved in the industrial sector and oil and gas extraction sector, respectively. Collectively, these measures reduce total emissions in 2030 to 9% below the mandated carbon budget, remaining within the model's 10% tolerance threshold specified exogenously at the beginning of the simulation.

Minor reductions also arise from the transport and residential sectors, where marginal uptake of electric motorcycles and electric cooking displaces fossil-based options. At this milestone, per capita emissions fall by 32% relative to the BAU case. Moreover, early adoption of carbon removal technologies by 2030, which persist through the modelling horizon, delivers further gains by mid-century. By 2050, total per capita emissions are reduced by 22% compared to BAU. Figure 3.31 presents the sectoral emissions profile under the NDC scenario.

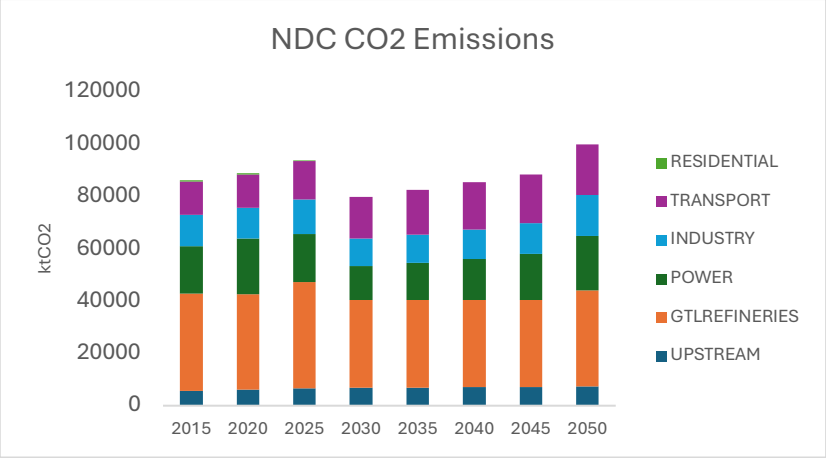


Figure 3.31: Salient decrease of emissions in 2030 is attributable mitigation strategies enacted under the NDC emissions reduction target of 25%.

The more stringent emissions constraint under the NZ50 scenario, which targets carbon neutrality by 2050, drives accelerated system-wide reductions. In this scenario, the simulation yields a more diverse decarbonisation pathway. During the early decades, the relatively lenient carbon budget enables CCS-coupled units to progressively replace retiring conventional capacities. However, as the budget rapidly tightens towards mid-century, the system is compelled to upscale DAC deployment across energy- and emissions-intensive sectors.

In the power sector, emissions are mitigated through substantial renewable integration, avoiding approximately 5 $MtCO_2$. A further 8.1 $MtCO_2$ is abated through CCS and DAC facilities, although a residual 0.9 $MtCO_2$ persists from legacy CCS units that remain in operation. This highlights both the contribution and limitations of CCS, particularly under stringent carbon constraints.

Transport emissions decrease by 74% relative to the base year, achieved through widespread electrification of public and private fleets, and a fuel switch to hydrogen for heavy-duty trucks. This transformation reflects the role of demand-side electrification in complementing upstream carbon removal.

Figure 3.32 illustrates the steep trajectory of emissions reduction under the NZ50 pathway, where deep decarbonisation across multiple sectors converges to meet neutrality by mid-century. Renewables play a central role in this process, alleviating emissions while diversifying the power mix and reducing dependence on natural gas-based generation.

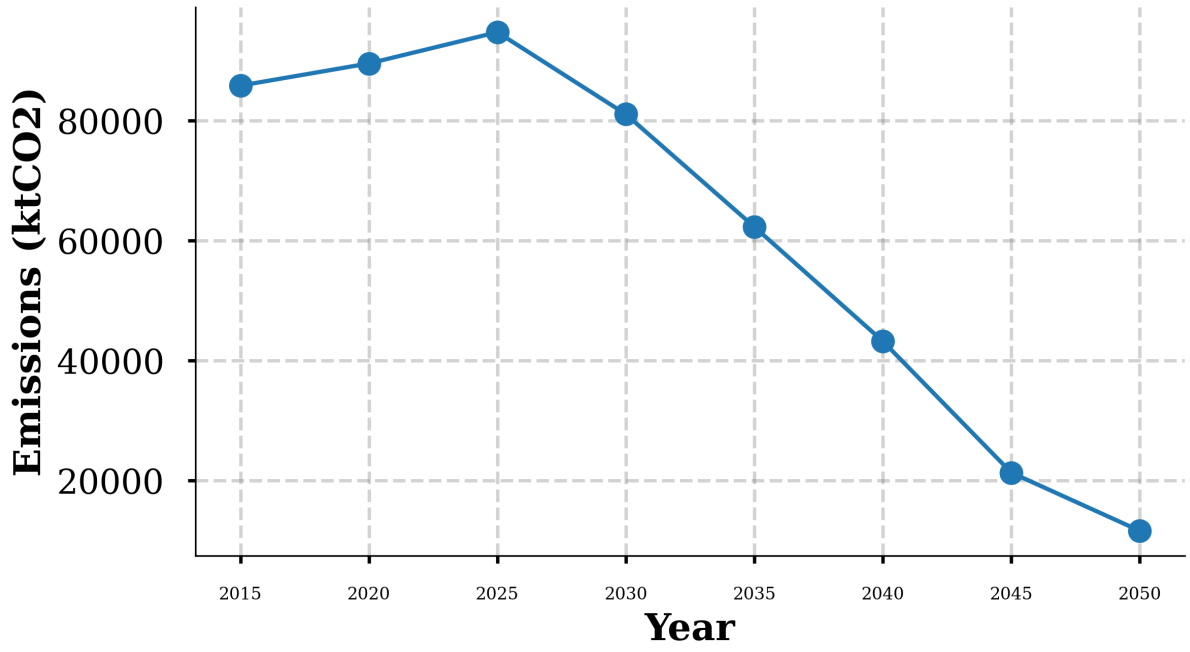


Figure 3.32: Aggressive emissions decrease in NZ50 scenario targeting carbon neutrality by mid-century

Per capita emissions reinforce these trends. Under BAU, emissions remain elevated at 41.7 tCO_2/capita in 2030 and 39.7 tCO_2/capita in 2050. In contrast, the NDC scenario reduces these values to 28.4 tCO_2/capita in 2030 and 30.8 tCO_2/capita in 2050, representing a 21% reduction relative to the base year. The NZ50 scenario further accelerates this decline, reaching 3.5 tCO2/capita by mid-century.

3.2.4 Emissions Removal Technologies

The Carbon budget under the mitigation scenarios, NDC and NZ50, is enforced from 2030 onwards. In response, MUSE levies a carbon price mechanism that elevates the LCOE of conventional technologies, thereby triggering investment in low-emission alternatives. As demonstrated in the sectoral technology portfolios in Sections 3.2.1 and 3.2.2, the bulk of decarbonisation is concentrated in the energy-intensive segments of the system, particularly extraction, processing and industrial activities linked to primary energy vectors. Once initial installed capacities retire, CCS utilities are progressively introduced in response to the tightening carbon budget.

In the NDC scenario, integrating CCS across oil and gas extraction and processing sectors achieves 60% reduction in sectoral emissions, contributing to an overall system emissions decline of 36% by 2030, and 18% by 2050 relative to BAU. By 2050, approximately 46% of natural gas is produced with CCS integration. Liquefaction facilities constitute the largest share of abatement, capturing 20.7 $MtCO_2$ annually, while CCS-equipped gas-to-liquid (GTL) plants remove an additional 4.6 $MtCO_2$ until the end of their technical lifetimes.

In the industrial sector, CCS integration provides a further ~3.3 $MtCO_2$ per year of abatement from 2030 onwards, reinforcing the role of carbon removal in offsetting emissions from energy-intensive processes. Figure 3.33 illustrates annual carbon removal requirements under the NDC scenario, highlighting the persistence of CCS as a cornerstone of mitigation efforts within this pathway.

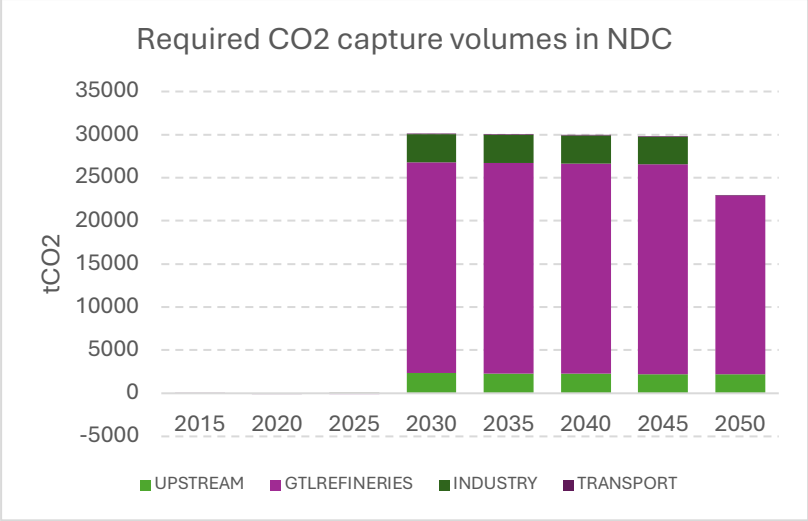


Figure 3.33: Carbon capture volumes through CCS utilities in NDC, centralised in the oil and gas extraction and processing, and industrial sectors.

At a tighter carbon budget and higher carbon price in the NZ50 scenario, further CO_2 reductions are achieved through large-scale deployment of Direct Air Capture (DAC). Initially, in the crude oil extraction sector, DAC displaces the conventional route by 2050, while a residual 24% of CCS capacity remains in operation due to its technical lifetime. For natural gas and NGL, DAC reaches 55% of total extraction activity, though earlier incumbent CCS investments persist throughout the timeframe.

At the processing stage, oil refining adopts DAC for 54% of its capacity, while GTL integrates DAC at 32%. LNG production, however, remains fully reliant on CCS, because of earlier large-scale uptake and the persistence of installed assets in the system. In addition, hydrogen production is supplied through steam methane reforming (SMR), divided evenly between DAC and conventional routes. Collectively, these decarbonisation measures in the processing sector abate 19.1 $MtCO_2$, equivalent to 31% of total system-wide carbon removals.

Residual CCS capacities from prior investment cycles constrain the overall pace of DAC diffusion. By 2050, DAC contributes 57% of CO_2 removals in extraction, 11% in oil and gas processing, 21% in power, and 86% in industry, capturing 61.6 $MtCO_2$ in total. Figure 3.34 illustrates annual CO2 removals through both of CCS and DAC across the system.

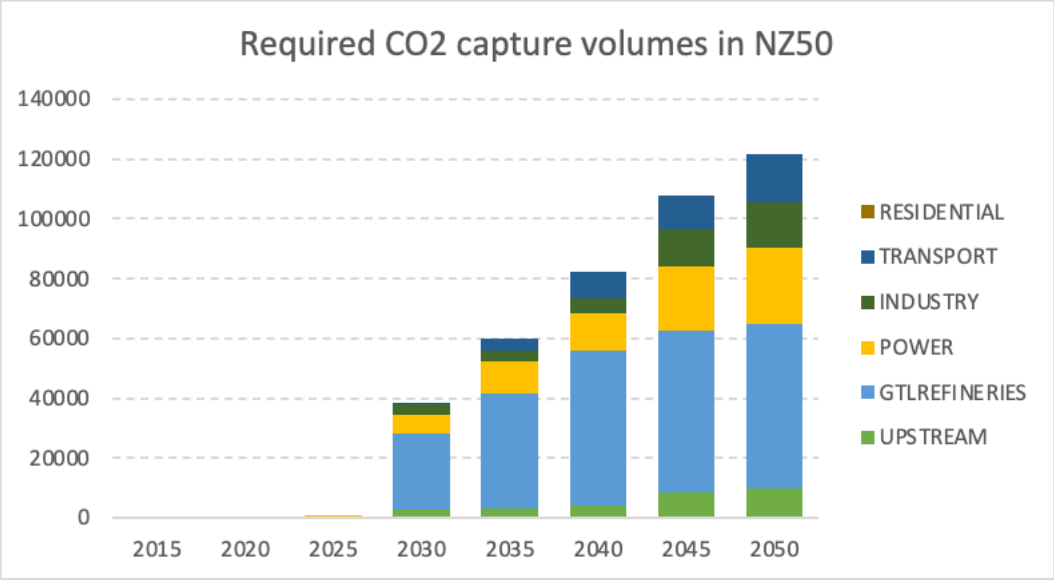


Figure 3.34: Carbon capture volumes through CCS and DAC utilities in NZ50.

3.3 Sensitivity Study

Sensitivity analysis represents a key tool to examine how the uncertainties in the energy system model inputs can impact the model outcomes. It can assist in identifying the input variables with the greatest leverage over the system performance and transition pathways (Usher, 2015). Sensitivity assessment can be conducted through global approaches, such as Morris Method, or through local approaches, such as one-at-a-time (OAT) method. The OAT method is a computationally efficient approach that relies on the permutation of a single variable at a time without accounting for its interaction with other input variables (Usher, 2015). It is a common approach in energy system model studies, and it is precedented in the decarbonisation study of the transport sector in Qatar (Alishaq, 2024). Building on this foundation, this section applies sensitivity analysis to investigate how variations in selected input parameters affect the simulation results of Qatar energy system, thereby providing insights into transition dynamics and supporting evidence-based policy formulation.

3.3.1 Method

In the OAT sensitivity analysis, selected economic and technical parameters are perturbed individually one at a time to evaluate their impact on the model results, particularly on the uptake of solar power within the power mix in the system. This approach provides insight into how variations in key assumptions may steer the transition and trigger renewables penetration in a heavily fossil-reliant energy system of Qatar, thereby safeguarding against overly ambitious targets or inadequately defined strategies. For this study, four levers are examined to evaluate the sensitivity of the model results: the discount rate, the future demand trajectory, the technical lifetime of installed capacities, and the learning curve of new technologies. Variations to these levers reveal distinct impacts on the LCOE, which governs the investment decision-making in the MUSE model for Qatar energy transition.

In this sensitivity study, MUSE v1.5.2 was employed, by varying the following parametric levers under the NDC and NZ50 scenarios.

Discount rate

The discount rate is one of the most influential parameters in energy system modelling, which reflects both economic uncertainty and underlying policy choices (Garcia-Gusano et al., 2016). It has a direct influence on the system investment preferences by altering the LCOE value of future technologies where higher discount rates result in higher LCOE ranges (Lazard, 2024), thereby weakening the economic viability of capital-intensive low-carbon options, while lower rates favour long-term decarbonisation pathways.

In this analysis, a range of discount rates is adopted following precedents from climate and energy modelling studies. The IPCC (2022) employs a range of 3%-10%, where the lower bound of 3% represents a long-term social discount rate commonly used in global climate assessments, and the upper bound of 10% reflects private-sector investment perspectives in developing economies or high-risk projects (Harden, 2014). Gebremeskel et al. (2023) tested four different discount rates between 5% and 15% in their sensitivity analysis of investment choices in power generation mix. The Stern Review assumed a notably lower social discount rate of 1.4% (Stern Review as cited in Steinbach & Staniaszek, 2015). Given that MUSE-QA adopts a general discount rate of 4.5% to model Qatar energy system transition, applying a lower bound of 1.4% may reveal more visible pronounced effects, while an upper bound of 15% captures the influence of high-risk investment environments.

Exploring this spectrum highlights the extent to which financing conditions and policy interventions can steer technology uptake. A lower social discount rate implies the need for supportive frameworks such as mandates, subsidies, or concessional financing to accelerate the penetration of renewable power, while higher private discount rates underline the challenges of attracting investment in capital-intensive projects without targeted policy incentives.

Demand Projection

The demand projection profile reflects the expected economic growth of the system, driven by future industrial activities and energy requirements. Variations in this trajectory

have a direct and immediate impact on emissions, which in turn alter the environmental cost component of the levelised cost of energy (LCOE). This affects both technology adoption and potential upscaling. Demand variation at high and low limits has previously been used as a sensitivity metric for optimising Qatar energy system in Bohra & Shah (2019). Similarly, in the TIMES-QA model, scenario design captures demand shifts through "Manufacture Growth" and "Service Growth" pathways, representing ambitious and slow economic performance. An equivalent approach can also be used in the sensitivity analysis for MUSE-QA.

Economic growth is therefore modelled within a calibrated range, with an upper bound reflecting accelerated industrial expansion, and a lower bound indicating slower industrial performance. For the baseline trajectory, the permissible variation range is set at $\pm$10% relative to the reference case. The lower bound captures events of reduced activity such as the decline in steel production following the completion of major construction projects around the FIFA World Cup 2022-Qatar, as well as periods of disruption including lower oil and gas output during the 2016 blockade on Qatar and the global downturn caused COVID-19 (IEA energy balance 2019). Such conditions, reflecting sluggish economic growth, directly influence the Market Clearing Algorithm and endogenous LCOE outcomes, potentially impeding the uptake of higher-cost technologies in favour of existing and more affordable capacities.

Conversely, the upper bound of the demand forecast exerts additional pressure on the upstream side of the system, requiring greater energy supply and resulting in higher tailpipe emissions. This will open avenues for investing in alternative technologies to mitigate emissions while optimising overall system costs.

Life limit of existing and future technologies

The operational lifetime of existing capacities in the system represents a significant determinant of new capacity uptake. Investment in new technologies is triggered either by rising demand, by the retirement of ageing assets, or by a combination of both. To meet this new demand, the model calculates the required energy commodities, dispatches production accordingly, and derives the supply cost through LCOE framework. These

costs in turn inform the endogenous setting of updated market prices. Flexible technologies, in particular, adapt to the most cost-efficient available energy commodity, thereby ensuring economic optimisation (Imperial College London, 2024).

In this study, to assess the impact of asset lifetime, a technical life-limit profile with upper and lower bounds is introduced at ±10 years. This will ensure that assets will occupy a minimum of one timestep at the lower bound, and a maximum of three timesteps at the upper bound. This represents a conservative assumption, reflecting the reality that carbon-intensive assets typically constitute large capital investments and are unlikely to be decommissioned significantly earlier than their designed economic life.

Unlike the TIMES optimisation platform, the MUSE simulation framework does not enforce premature decommissioning of assets; instead, the persistence of initial capacities must be accounted for within the model structure. Varying the lifetime within the specified bounds enables MUSE to explore alternative investment choices, particularly in cases where an asset may realistically be phased out earlier than intended, such as when rising operating costs render continued operation uneconomic.

Technology Learning Curve

Technology innovation and market maturation can have a significant influence in reducing capital and other investment costs, thereby improving the energy efficiency and environmental footprint of the system. In the IEA *Sustainable Development Scenario (SDS)*, learning effects have been to drive rapid uptake of advanced technologies alongside direct reduction in emissions (IEA Clean Energy Innovation, 2020). Within MUSE, where investment decisions are governed by the LCOE framework, temporal perturbations in technology costs strongly influence adoption. As renewable technologies reach cost parity, or fall below the costs of conventional options, their penetration within the system increases significantly.

For the purpose of this analysis, two levels of cost reduction are introduced to represent different learning trajectories: a moderate reduction of 20% and and aggressive reduction of 45%, based on forecasts reported in the IEA SDS. These reductions serve as proxies to

examine how different rates of technological progress can shape the evolution of Qatar energy system.

The deployment of these four levers, summarised in Table 3.31, enables a systematic one-at-a-time sensitivity analysis. By varying each factor independently, the analysis identifies the most influential driver shaping investment choices in Qatar energy transition. This approach provides clear insights into the leverage points at which policy intervention or targeted technological investment can exert the greatest impact. The findings are intended to guide the uptake of solar renewable power within Qatar broader decarbonisation roadmap, while informing both policy formulation and the practical realisation of long-term sustainability objectives as articulated in the Qatar National Vision 2030.

Table 3.31: Synopsis of levers employed in the sensitivity analysis for MUSE-QA energy system transition

Scenario	Bound	Target Year	Discount Rate	Demand Trajectory	Lifetime	Learning Curve
NDC	Base	2050	central	central	central	central
NDC	Lower	2050	1.4%	-10%	-10 years	-30% IEA
NDC	Upper	2050	15%	+10%	+10 years	N/A
NZ50	Base	2050	central	central	central	central
NZ50	Lower	2050	1.4%	-10%	-10 years	-30% IEA
NZ50	Upper	2050	15%	+10%	+10 years	N/A

3.3.2 Results of sensitivity analysis

The results of the one-at-a-time (OAT) sensitivity analysis underscore the degree to which investment decisions within the simulation model respond to variations in key input parameters. The findings reveal nuanced interplay between factors under different carbon budget constraints, demonstrating that the **technology learning curve** and **demand trajectory** exert the most significant influence on solar renewable energy uptake within the system.

Under the NDC scenario, representing a moderate emissions-reduction pathway, the technology learning curve exerts a clear influence at its upper bound. An aggressive decline in technology costs results in a 51% increase in solar diffusion relative to the baseline case. In this instance, renewable technologies become economically more attractive than fossil-based power generation, as their LCOE values drop significantly below those of conventional options. Conversely, when learning rates are only marginally improved, solar technologies remain within the baseline case range, with thermal processes continue to dominate the power mix under a moderate carbon constraint.

This effect is further amplified under a more stringent carbon budget, as represented by the NZ50 scenario. In this case, the technology learning curve emerges as a decisive factor in accelerating solar deployment under both moderate and aggressive cost-reduction trajectories. By elevating the relative cost of emitting technologies through the imposition of a carbon price, the system endogenously shifts investment preferences toward low-carbon alternatives such as solar, which simultaneously benefit from declining costs and improving competitiveness. These results underscore the critical role of technological learning curve as a policy lever in advancing the energy transition and support the broader argument that innovation cost dynamics are a central element of the policymaking toolkit (IEA, 2000).

The demand trajectory, as a sensitivity lever, exhibit a subtle yet positive influence across both emissions scenarios. Under the moderate emissions budget of the NDC scenario, a lower system-demand profile alters the overall power-mix composition and load shape, favouring a greater solar uptake, 18% above the baseline case, as solar generation effectively serves daytime-biased electricity demand. Whereas higher demand profile distributes increased system electricity requirements across all diurnal timeslices, including night-time periods when solar output is intermittent. Therefore, the model refrains from expanding solar beyond its baseline level, instead compensating for additional electricity needs through dispatchable and reliable power generation technologies.

However, it is more pronounced under the NZ50 scenario, where energy consumption and emissions intensity are directly linked to demand fluctuations. At both demand bounds, solar capacity expands by 80% and 97%, respectively, relative to baseline case, reflecting the system's heightened sensitivity to demand variation under a strict carbon budget. In the lower-demand case, reduced energy consumption allows conventional technologies to persist longer within the system, as the emissions budget is not immediately exhausted. Renewables and carbon removal technologies become necessary only as the carbon constraint tightens toward neutrality. In contrast, under the higher-demand case, overall electricity requirements rise across all timeslices, and emitting technologies are heavily penalised by the carbon price. This dynamic drives the increase in solar uptake as solar becomes a cost-effective option to complement sectoral emissions reduction in addition to carbon removal technologies.

These findings suggest that fluctuations in demand exert a profound influence on investment direction within the power sector. Consequently, two-pronged strategies are recommended: first, demand management through public awareness initiatives such as *Tarsheed* programme, and through the introduction of smart metering and tariff systems to promote efficient consumption; and second, targeted investment mandates to accelerate renewable integration while preventing overcapacity planning.

The technical and financial parameters, namely, the technical lifetime and discount rate, are less influential on solar investment decisions, because the carbon budget itself becomes the dominant lever under both emissions scenarios. For the technical lifetime lever, shorter asset lifespans reduce the availability of solar capacity by 34% in the NDC and 10% in the NZ50 scenario by the target year 2050. Conversely, extending asset lifetimes assist in stabilising investment under the NDC pathway and induces only a modest increase in solar deployment under NZ50, reflecting that lifetime effects are secondary to carbon price and cost-learning dynamics. Furthermore, as for the discount rates, it supresses investment in solar due to increased financial risk and reduced project attractiveness. Under the NDC scenario, lowering the discount rate enhances solar competitiveness, yielding an 8% increase in solar capacity relative to the baseline. This illustrates that the model retains sensitivity to the cost of capital, aligning with the

observed influence of the technology learning curve lever, where financial parameters play a key role on determining renewables market penetration.

To wrap up, under the NDC scenario, solar deployment remains relatively inelastic, showing only modest variation even under favourable assumptions. In contrast, under the NZ50 scenario, solar uptake becomes highly elastic, particularly in response to changes in demand growth and technology cost assumptions. This shift reflects the heightened importance of innovation and system-wide electrification when stringent carbon budgets are enforced.

Policy implications derived from these findings emphasise the need to stimulate research and development (R&D) in solar technologies, foster capacity building and knowledge transfer, and accelerate the progression from prototype to utility-scale deployment. Complementary demand-side electrification policies, for example, industrial electrification and electric-vehicle infrastructure, can amplify solar penetration by expanding electricity demand that aligns with renewable generation profiles.

Financial levers such as discount-rate reductions can support solar adoption under moderate carbon targets, such as the NDC scenario, but are less decisive under stringent carbon budgets as in the NZ50 scenario, where policy constraints and transition management dominate investment decision-making.

Overall, the findings indicate that under a moderate emissions cap, renewables penetration in the power sector is only marginally affected, largely due to investment preferences geared towards carbon-capture deployment throughout the time horizon, producing partial lock-in effects. This postulates the impact of cost dynamics, demand growth, and carbon budget stringency. To avoid over-reliance on a single energy source, policies should mandate minimum renewable shares, support innovation-driven cost reduction, and ensure diversification of the power mix.

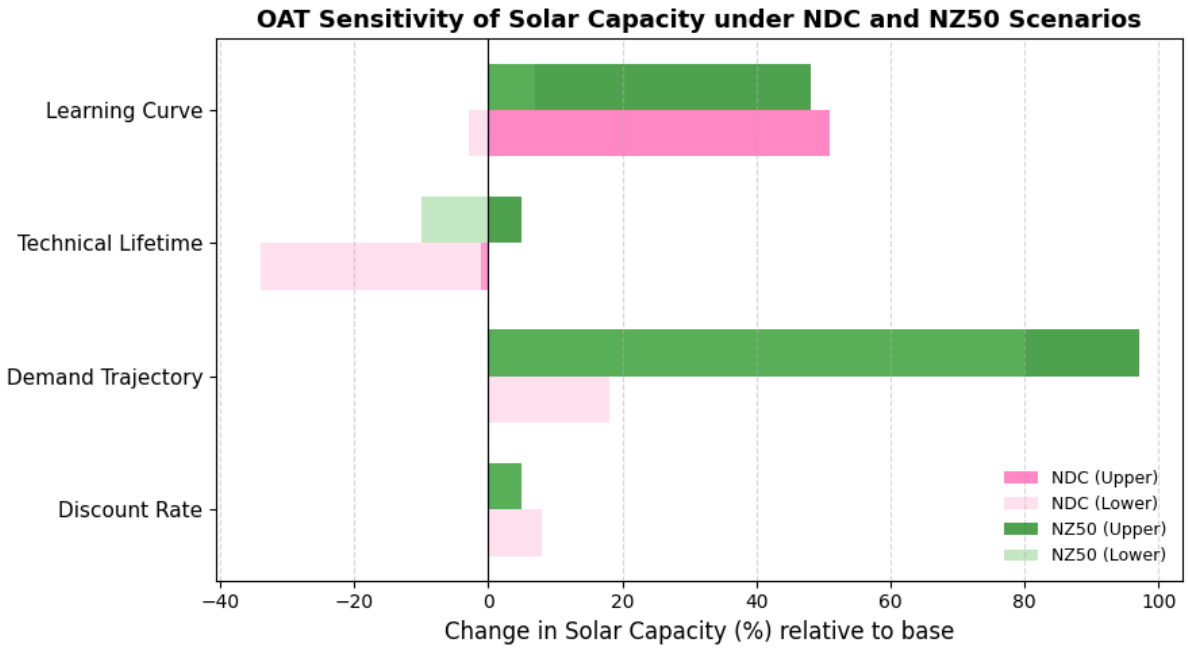


Figure 3.35: OAT sensitivity analysis results comparing different levels of impact from four main levers on two distinct environmental scenarios: NDC and NZ50

3.4 Discussion

The analysis presented in this chapter has assessed the implications of energy system transitions under different emission-reduction targets: the NDC scenario, which reflects Qatar's near-term ambition toward 2030, and the NZ50 scenario, representing a more stringent global climate objective, both benchmarked against a business-as-usual (BAU) pathway. Together, these scenarios provide a comprehensive narrative of the transition dynamics, illustrating how different policy ambitions shape technology deployment, emissions trajectory, and system-wide decarbonisation outcomes.

The concept of levelised cost of energy (LCOE) plays a central role in understanding these transitions, as it provides insight into how commodity and technology costs evolve over time (Manuel at el., 2022). LCOE remains a widely adopted indicator in international scenario analyses, most notably within IEA and NREL databases, and has also been applied to Qatar-specific studies, such as solar-energy transition assessments (Alashqar

et al., 2022), and broader MENA-region electricity transition scenarios (Bamisile et al., 2025).

The findings indicate that Qatar short-term emissions reduction goal for 2030 can be achieved primarily through the integration of carbon capture and storage (CCS) across energy- and emissions-intensive sectors, particularly within hydrocarbon production, processing, and industry, complemented by a moderate expansion of solar power in the electricity sector. The early uptake of CCS exerts a long-term impact on system-wide emissions, with benefits extending toward 2050 and beyond. This configuration is particularly prudent given that electricity demand trajectory remains relatively unchanged from the BAU pathway, while natural gas consumption increases only marginally by 2% due to the energy requirements of CCS operations.

Early CCS deployment by 2030 delivers a substantial reduction in cumulative system emissions, such that even after these units reach their technical lifetime, the system can revert back to certain conventional technologies without breaching the moderate carbon budget. This finding highlights the critical importance of early mitigation action in securing long-term environmental gains through centralised decarbonisation, and emphasises the need for policymakers to establish a more detailed sector-specific roadmaps to guide progress toward Qatar's NDC target.

When compared with the global neutrality pathway, the results reveal a trade-off between rapid emissions reduction and the economic cost of technological transformation. For a fuel-based economy, achieving carbon neutrality does not necessarily entail a wholesale departure from fossil fuels or premature retirement of operating assets. Instead, the transition can be achieved through decarbonising fossil fuel production and investing in next-generation carbon removal technologies, thereby enabling hydrocarbons to remain an integral component of the low-carbon transition.

Across all scenarios, fossil fuels continue to represent a central pillar of the system. Their persistence is driven by the abundance of domestic resources, the long operational life of existing infrastructure, and their relatively low production costs, as delineated in

Chapter 2. Under the NDC scenario, fossil fuel assets remain indispensable: the carbon budget constraint steers emissions mitigation efforts toward carbon capture pathways, instead of large-scale investment in renewable deployment or fuel switching. By 2030, the initiation of centralised CCS capacity, implemented to offset supply shortfalls from decommissioned assets and to remain within the NDC carbon limit, is projected to curb around 36% of the anticipated increase in system emissions, largely driven by QatarEnergy LNG expansion programme. Early CCS investment ensures these facilities operate throughout their full technical lifetimes, enabling the system to maintain carbon-budget compliance through a financially prudent pathway.

The NDC target has a generally positive impact on system-wide emissions, contributing to an improvement in per-capita performance relative to historical levels. Yet the outcome presents a twofold perspective. First, while the current strategies designed to implement this goal appear effective to a certain extent, they remain insufficient to fully realise the NDC objective, underscoring the need, again, to intensify and coordinate national efforts to scale up a more comprehensive transition strategy across the entire energy value chain.

Second, although the NDC target produces a notable reduction in near-term environmental impacts, its influence is modest compared with the potential long-term benefits of deeper decarbonisation. The projected post-2030 emissions remain considerably higher than the achievable reductions under more stringent scenarios, highlighting the necessity of a medium-term transition plan to follow the current 2030 target. Such a plan would serve two critical purposes: first to prevent a reversion to conventional, high-emitting pathways once the carbon budget relaxes as evidenced in the results, and second, to monitor and accelerate technological innovation that enhances system performance through the adoption of mature, reduced-cost, low risk technologies.

While the NDC target remains both admissible and nationally appropriate, however, it is essential for Qatar, even without a formal commitment to a net-zero NZ50 target, to evaluate the potential implications of pursuing such a pathway. This consideration is

particularly critical given that Qatar's economy is heavily reliant on energy exports. Any global shift in market dynamics arising from international decarbonisation policies, whether through carbon pricing mechanisms or declining fossil fuel demand, would have a direct impact on Qatar's economic stability and export competitiveness, as discussed in Chapter 5.

Under the carbon neutrality (NZ50) target, a clear trade-off emerges between emissions ambition and system cost. The model's imperfect foresight captures the lock-in effects from earlier investments, which delay the uptake of emerging low-carbon technologies. By the end of the modelling horizon, as the carbon budget converges to zero, the system is forced to adopt high-cost technologies with low technology-readiness levels (TRLs), such as the adoption of hydrogen-fuelled heavy trucks , even though high-flow-rate hydrogen refuelling systems remain at TRL 4 according to the IEA (International Transport Forum, 2023). This substantially raises both system costs and infrastructure requirements.

This accelerated shift also leads to the expansion of technologies not currently prioritised in Qatar's national strategy, such as onshore wind, highlighting the sensitivity of technology deployment to planning horizons and carbon-price signals. These findings reinforce the importance of early and coordinated policy intervention, fostering synergy between government institutions and major emitters to design a phased and adaptive decarbonisation roadmap that balances economic competitiveness with long-term environmental integrity.

Consistent with its optimisation structure, the model consistently favours fuel-efficient and economically optimal technologies, as LCOE values remain unaffected by carbon pricing in the baseline case. This behaviour aligns with a core characteristic of Integrated Assessment Models (IAMs), which typically incorporate efficiency enhancements even in the absence of explicit climate policy drivers (Ghambir et al., 2019). As a result, the model prioritises the most cost-effective and energy-efficient options across sectors.

In the residential sector, for instance, under the BAU scenario, space cooling demand is predominantly met through district cooling (DC) systems instead of conventional air-conditioning (AC) units. From both a practical and economic standpoint, however, such systems are more feasible for new urban developments than for retrofitting older, high-density residential areas. Similarly, in the water desalination sector, the model favours seawater reverse osmosis (SWRO) over thermal desalination technologies, owing to its superior energy and environmental efficiency and operational performance. Nevertheless, the model does not account for the additional post-treatment costs associated with SWRO, which may lead to an overly optimistic bias in its selection relative to choosing SWRO over MSF.

At a more ambitious reduction levels, domestic decarbonisation efforts and international mitigation strategies can act synergistically to reinforce mutual climate benefits and energy symbiosis. The NZ50 scenario demonstrates this interaction, featuring greater electrification, particularly within the transport sector, alongside expanded emissions removal measures across upstream and industrial processes. As global markets are projected to rely on natural gas well beyond mid-century, especially when paired with carbon removal technologies, Qatar is well-positioned to remain a competitive and credible supplier of low-carbon energy.

This trajectory aligns with the IEA (2023) Outlook for Gas Markets and Investment for the G7, which anticipates a continued reliance on natural gas in tandem with carbon management solutions. Under such a framework, Qatar could further consolidate its position as a global leader in the production and export of lower-carbon energy commodities, thereby balancing economic resilience with environmental responsibility.

Pursuing alignment with global climate objectives such as NZ50 also presents new opportunities for Qatar to leverage its existing expertise and infrastructure in hydrogen production to facilitate domestic energy transition. The findings indicate that capital investment in hydrogen technologies becomes increasingly attractive as demand arises within the transport sector. Notably, diesel-fuelled heavy-duty trucks, which account for

approximately 38% of total transport-related emissions, present a significant decarbonisation opportunity. Under a strict carbon budget, the emissions cost associated with maintaining conventional diesel supply becomes uneconomically high, making hydrogen-fuelled trucks a viable and cost-effective alternative.

An early rollout of hydrogen-based transport, supported by steam methane reforming (SMR) integrated with carbon capture facility, could substantially reduce transport emission by ~6.8 MtCO2 while advancing in decarbonising the transport sector and reinforcing Qatar's position as a regional leader in low-carbon fuel innovation.

Overall, this discussion section contextualises the simulation model results by interpreting the findings on Qatar's current energy system dynamics, future projections, and potential decarbonisation pathways that carry both domestic implications and international significance. The discussion establishes clear links between the quantitative model-based insights with national policy priorities, offering a nuanced understanding of how Qatar can advance environmental sustainability while safeguarding its economic strength and ensuring long-term system resilience.

3.4.1 Sensitivity study discussion

In the one-at-a-time (OAT) sensitivity analysis, the lever with the highest influence on solar penetration within the power mix is the technology learning curve, which exhibits a strong positive correlation with system-wide electricity consumption. As technology costs decline over the modelling horizon, the learning effect significantly accelerates solar deployment, underscoring the central role of innovation and cost reduction in shaping investment behaviour. Next in strength is the demand trajectory lever, which also demonstrates a notable influence on renewable uptake through its impact on load shape and total energy requirements. Other levers such as the technical lifetime and the discount exhibit comparatively lower sensitivity, indicating that financial and operational

parameters are less decisive than technological progress and demand evolution in driving renewable adoption.

Ultimately, the sensitivity analysis serves as a critical instrument for addressing uncertainties and potential fluctuations within the modelled framework. It provides structured basis for integrating contingency planning into the design of decarbonisation pathways and the formulation of robust, adaptive energy policies (Alishaq, 2024). Given the inherently uncertain and dynamic nature of energy transitions, adaptive transition management emerges as a pivotal approach for guiding long-term policy design that is flexible and responsive to evolving market and technological conditions, by accounting for both incremental adjustments and radical system transformations (Owoola et al., 2024).

The sensitivity of the model to the technology learning curve underscores the potential effectiveness of policies that promote innovation, research and development (R&D) in accelerating renewable energy deployment. Leveraging investment in research-driven technological advancements can significantly enhance scalability and competitiveness of renewables within the energy system. This also presents an opportunity for regional capacity building and knowledge exchange with neighbouring countries at varying stages of technological maturity, positioning the energy transition as both a domestic transformation and a catalyst for international collaboration that recognises the human and institutional dimensions of innovation.

Accelerating the renewable technology learning curve and improving utilisation factors through continuous innovation can increase the generation of green electricity, thereby reducing reliance on fossil-based routes, with or without carbon removal coupling, and consequently lowering emissions. Accounting for such dynamic changes within the policy framework reinforces the importance of adaptive transition management, enabling policies to evolve as technologies mature and costs decline.

The sensitivity analysis results reveal that system-wide increases in electricity demand exert a nuanced yet influential impact on the overall energy system, primarily governed

by the stringency of the carbon budget. When aiming for carbon neutrality, the system intensifies mitigation efforts across all sectors under any demand profile. Therefore, stimulating electrification, not only in the transport sector, but also across industrial activities, can reallocate energy requirements to the power sector, thereby reducing fossil fuel consumption and total system emissions while promoting capital investment in renewables.

This inter-sectoral relationship becomes less pronounced under a moderate carbon budget, where relaxed constraints reshape the load profile, utilisation factors, and curtailment dynamics. In such settings, higher electricity demand can be accommodated through dispatchable fossil-based routes, with decarbonisation measures redirected elsewhere in the system. Therefore, implementing targeted incentives to promote solar utilisation, such as feed-in tariffs, grid buy-back schemes, or exemptions from metering charges, can collectively reduce reliance on fossil-fuel-based electricity generation across varying emissions targets.

Moreover, the influence of the technical lifetime lever is relatively limited, as the model operates on a short-foresight paradigm and triggers investment through partial equilibrium, thereby maintaining control over capacity additions. As demand increases, the persistence of installed capacity has only marginal effect on overall system behaviour. Furthermore, the discount rate lever also indicates that the simulation prioritises technological innovation, demand management, and structural energy-efficiency measures over financial profitability. As the carbon budget tightens, meeting the emissions constraint takes precedence over costs considerations. In practice, this mirrors Qatar's demonstrated willingness to pursue high-risk, high-impact low-carbon investments, exemplified by the commissioning of Al Kharsaah Solar Power Plant and the development of first world's largest blue ammonia facility, which underscores the nation's commitment to leading in the deployment of clean technologies and achieving its emissions-reduction objectives.

The sensitivity analysis offers valuable insights into the intricacies of energy system transitions and the uncertainties that shape system evolution under varying emissions–

reduction targets. These findings inform both investment decision-making and policy formulation by illustrating how different parameters, such as technology costs demand trajectories, and carbon budgets, influence solar adoption and system behaviour. Ultimately, the results underscore the pivotal role of policy in initiating and accelerating renewable energy penetration, while also revealing the associated trade-offs between cost, emissions reduction, and system resilience.

3.5 Chapter Summary

This chapter introduced the development and application of a novel simulation framework for Qatar energy system, MUSE-QA, designed to evaluate the country's potential transition pathways under alternative environmental targets and limited foresight into the future. The model spans the entire energy value chain, including supply, conversion, and demand segments; covering upstream extraction, conversion and liquefaction, power generation, industrial production, transport, water desalination, residential and commercial sectors.

Equipped with high technological and temporal resolutions, the model minimises total system cost at each investment period up to the end of the time horizon in 2050. The model generates endogenously determined technology choices through partial equilibrium across discrete time periods. This configuration captures lock-in effects from existing assets, realistically reflecting real-world inertia where premature decommissioning of capital-intensive infrastructure is unlikely under normal conditions.

A central mechanism with MUSE is the carbon budget constraint, which induces an endogenous carbon price. This carbon price represents the environmental cost of emissions and directly increases the LCOE of carbon-intensive technologies, thus improving the competitiveness of low-carbon alternatives. As the carbon budget tightens, the endogenous carbon price rises, driving the progressive replacement of emitting technologies with low-carbon options. New investments are, therefore,

triggered when existing capacities are insufficient to meet demand under these revised cost dynamics.

Under the baseline scenario (BAU), total emissions are projected to increase by approximately 55% relative to the 2015 base year. In contrast, the NDC scenario, which targets a 25% emissions reduction by 2030, demonstrates that such as goal can be achieved through a set of enhanced mitigation measures extending beyond those currently articulated in national policy. Specifically, this involves a combination of solar-renewable integration and carbon capture and storage (CCS) deployment, concentrated within high-emission sectors, particularly oil and gas processing in GTL and liquefaction plants, and energy-intensive industries. These mitigation efforts are primarily centralised on the supply and conversion side of the energy system, whereas demand-side transitions, such as in the transport sector, remain comparatively limited within this timeframe.

At a more stringent NZ50 scenario, the system shifts toward a more complete transformation of the energy landscape. The tightening carbon budget and escalating carbon price drive the phasing-out of conventional technologies, excessive expansion of CCS and DAC capacities, and deep electrification of the transport sector, coupled with an increased share of renewable energy in power generation. The results highlight a marked increase in natural gas demand for CCS operations by roughly 70% under the NDC and 76% under the NZ50 scenario, relative to the base year. This demonstrates the trade-offs between mitigation ambition and resource dependency. Within this context, hydrogen emerges as a strategic energy vector, helping to offset fuel-combustion emissions in the transport sector.

Collectively, the simulation results fulfil the research objective of developing a system-level modelling framework for Qatar and evaluating alternative decarbonisation pathways that can inform policy and regulatory design. The insights derived from the MUSE-QA analysis underscores the importance of integrated and adaptive policy coordination across sectors, calibrated to both time horizons and target levels. These recommendations contribute directly to the overarching goal of this thesis; to provide

strategic model-based evidence for policy formulation in support of Qatar's national climate commitments and long-term sustainability vision.

Addressing the main research question, the findings demonstrate that Qatar's current NDC target can deliver a meaningful short-term reduction in emissions through incremental solar deployment and early CCS integration. However, the current strategy remains insufficient for achieving disruptive reductions aligned with global net-zero trajectories, which could in turn affect the country's future energy-production infrastructure and export competitiveness. Therefore, the study emphasises the importance of transition management, advocating for a measured and well-sequenced approach that mitigates the risks of costly mid-century adjustments while sustaining economic resilience and system stability under evolving environmental obligations.

Chapter 4

4 Dual Models Comparison

A single policy question can be approached distinctively in multiple ways depending on the modelling framework and data assumptions employed (Siala et al., 2022). The variations in the yielded solutions are rooted in the underlying structure of the selected modelling approach. Ultimately, energy system modelling seeks to anticipate future system developments and inform investment decisions under uncertainty (Prina, 2020). In pursuit of this objective, two most common archetypal modelling paradigms are simulation and optimisation (Lund et al., 2017). Optimisation models aim to identify global optimal solutions for a predefined context, whereas simulation models evaluate system performance under alternative configurations (Subramanian, 2018; Mahbub, 2016). The complementarity of these paradigms enhances inferential robustness and guards against misleading policy insights. This chapter conducts a comparative analysis of these two distinct approaches for the context of Qatar energy system; contrasting the simulated results of MUSE-QA, as outlined in Chapter 3, with those of QT-TIMES, which is developed at Hamad Bin Khalifa University (HBKU). Both models are designed to capture the current structure and future evolution of Qatar energy system. The comparison seeks to validate results across frameworks, justify methodological choices, and provide evidence to support effective policy formulation.

4.1 Goal and scope

In support of shaping energy policy of Qatar, optimisation modelling results developed through capacity building with the modelling team at HBKU are used alongside simulation outcomes to cross-validate both approaches. This comparative exercise is important because different modelling paradigms can yield divergent insights depending on their assumptions, scope, and treatment of uncertainty. By contrasting MUSE-QA and QT-TIMES, the analysis highlights key differences in modelling assumptions, decision-

making processes, the role of foresight, and the ways each framework handles constraints and uncertainty. This addresses a gap in the literature where simulation and optimisation approaches are often applied independently, with limited systematic comparison in the context of hydrocarbon-dependent economies. The objective is to generate robust evidence on alternative pathways for a sustainable energy future for Qatar, to test the consistency of results across methodologies, and to strengthen the dialogue between researchers and policy makers. In doing so, the chapter contributes to better-informed energy policy design and adds depth to the discussion on the evolving role of the hydrocarbon industry in Qatar sustainable transition, as elaborated in Chapter 3.

4.2 Models comparison in the literature

Given the inherent uncertainty surrounding future energy system evolution, model validation through comparison is widely recognised in academic research as a means to enhance the robustness and quality of modelled outcomes (Siala et al., 2022). In fact, reliance on single modelling framework is marred by uncertain or even misleading conclusions, whereas synthesising insights from multiple models adds value by weighting convergences and discrepancies in their results (DeCarolis et al., 2016; Prina et al., 2022). For example, Johannsen et al. (2023) applied both optimisation and simulation paradigms to a Belgian municipal energy system and found the results to be broadly comparable and complementary, concluding that model choice should be problem-specific. Similarly, in the policy domain, the Danish Energy Agency (DEA) has a longstanding tradition of employing both optimisation and simulation models. This expertise has not only informed national energy strategy but has also been transferred internationally, with the Danish National Energy Strategy Agency (DEA) supporting energy policy development in countries across Asia and Europe (ENS, 2018).

4.3 Method and modelling specifics

The MUSE simulation model for Qatar, as introduced in Chapter 3, was initially developed in parallel with a TIMES optimisation modelling project at Hamad Bin Khalifa University (HBKU). Both initiatives were founded on a common reference energy system derived from the IEA energy balance for Qatar and applied to future scenarios consistent with announced national targets. This methodological alignment creates an opportunity for comparability between results and enables validation across two distinct modelling paradigms. Such a comparative framework not only enhances the credibility of modelling outcomes but also strengthens the evidence-based policy deliberations, ensuring that insights drawn from the analysis are both rigorous and relevant to decision-making in Qatar energy transition.

4.3.1 The Optimisation Model for Qatar: QT-TIMES

The TIMES (The Integrated MARKAL-EFOM System) model is an analytical modelling platform that is developed under the IEA Energy Technology Systems Analysis Program (IEA-ESTAP) for the purpose of analysing energy dynamics of a system based on its technical, economic, and environmental characteristics (Loulou, 2016). It utilises a bottom-up, linear programming approach to optimise the economic performance of an energy system over a defined timeframe, subject to exogenous constraints (ETSAP TIMES, 2005).

The economic rationale underpinning TIMES is grounded in the welfare economics of consumers and producers, where the objective is to maximise total surplus while reducing system costs. Total surplus is defined as the difference between revenues and costs of meeting demand. TIMES achieves this by computing a partial equilibrium between energy supply and service demand at each time step through the construction of corresponding curves. Demand for commodities, such as energy carriers and emissions, is represented through endogenous functions with specified price

elasticities, allowing the model to reflect dynamic responses to cost and policy signals. (Loulou et al., 2016)

Supply, meanwhile, is generated through existing technologies or portfolios of technologies until their capacity is exhausted. At that point, the model triggers investments in new assets, selecting the optimal scale and timing to satisfy demand efficiently. This process occurs at the intersection of supply and demand, where equilibrium prices and quantities correspond to maximised total surplus. Through this iterative mechanism, TIMES simultaneously accounts for technology expansion, and emissions constraints, and market dynamics, generating a cost-optimal trajectory of system evolution across alternative policy and demand scenarios. (Loulou et al., 2016)

Building on this, TIMES assumes a competitive market structure in which neither producers not consumers exert direct influence over equilibrium prices. Instead, prices and quantities are determined solely by the interaction of supply and demand, with the price of each commodity aligning with its marginal value. Under the assumption of perfect foresight, future price signals are known in advance, enabling the model to deploy any technology at any scale, provided it contributes to an overall cost-optimal solution. This assumption simplifies the decision environment but also has implications for how investment dynamics and technology adoption are represented in long-term system, planning. (Loulou et al, 2016)

In the case of Qatar, the model is implemented as QT-TIMES, which is broadly comparable to MUSE-QA framework owing to their shared foundations in the reference energy system setup, the use of scenario-based future targets, and reliance on similar technology portfolios and input datasets.

4.3.2 The Simulation Model for Qatar: MUSE-QA

This study employs MUSE-OS version 1.4.2, an upgraded release compared with version 1.2.0 used in Chapter 3. Several key improvements distinguish this release. First, the

carbon budget bisection method has been refined to allow for an initial carbon price of zero, addressed in v1.2.1. Second, the *MaxCapacityGrowth* parameter has been updated to compound growth rather than linear, addressed in v1.2.3. Third, the LCOE calculation was corrected to avoid inflating commodity prices in timeslices with low levels of production, addressed in v1.3.2. In addition, several bug fixes and usability improvements have been implemented by the MUSE development team at Imperial College London.

Full details of these releases are openly available in the MUSE-OS documentation (Imperial College London, 2024) and the source github repository (EnergySystemsModellingLab, 2025).

4.3.3 Data harmonisation

Both MUSE-QA and QT-TIMES are on a par in using the IEA energy balance for Qatar, using 2015 as the common base year. This ensures consistency in representing energy supply and consumption throughout the entire system value chain, and allows replicability. Demand profiles for the service demand sectors are collated from comparable local and international open sources and publications. Inevitably, imputed data are prone to minor variations subject to ballpark figures estimations, calculation methods and numerical rounding practices.

Disaggregation of the aggregated IEA energy balance into sectoral demands required modeller judgement, which led to some differences in assumptions. For example, in MUSE-QA, steel demand is taken directly from Qatar Steel reports as final output, while QT-TIMES disaggregates production into intermediate square billets which subsequently processed into rebars. Nonetheless, these differences do not materially affect results, as energy and emissions intensities are recalibrated to preserve comparable sectoral profiles across both models.

Technology profile and techno-economic datasets are also broadly consistent between frameworks. Adjustments were made to reflect the most recent policy integration in both models, resulting in updating the MUSE-QA version introduced in Chapter 3. For instance, while wind power was proposed in Qatar Renewable Energy Policy, it was later removed from the Qatar Renewable Energy Strategy (Kahramaa, 2025). Therefore, both models are updated to excluded wind power in this comparative study. Table 4.1 summarises the modelling constraints as imposed on MUSE-QA and QT-TIMES.

Table 4.1 Summary of modelling constraints exogenously imposed on both MUSE-QA and QT-TIMES based on announced mitigation strategies such as NDC and QRES

Constraint	MUSE-QA	QT-TIMES
Environmental	Carbon budget in absolute values	Emissions constraint in percentage reduction
Sectoral (Power)	0.8 GW solar in 2030, expanding by 1GW per annum up to 20 GW cap	
Sectoral (Transport)	NDC: 10% EV penetration per year NZ50: unconstrained	NDC: 10% EV penetration per year NZ50: start by 10% in 2030, then 30%, 50%, 75%, 100%
Sectoral (Water)	Reverse Osmosis capped at 55%	

Scenario assumptions in both models are anchored in Qatar's announced mitigation commitments, reflected in the NDC scenario, in addition to more stringent targets, represented by the NZ50 scenario. QT-TIMES additionally explores alternative narratives, including high and low manufacturing activity and delayed mitigation pathways; however, these scenarios are excluded from the present comparison to maintain alignment between the two frameworks.

4.3.4 System boundaries and investment requirements

The principal discrepancy between QT-TIMES and MUSE-QA is embedded in their economic decision-making mechanisms. QT-TIMES seeks to achieve system-wide emissions target by solving a global optimisation problem, inferring an optimal solution through a single overarching objective function (Loulou et al, 2016). In contrast, MUSE-QA is configured as an agent-based simulation model, where decision-making is guided

by heuristic rules (Giarola et al, 2022). As explained in Chapter 3, however, the single dominant agent in the Qatari context pursues the minimisation of energy costs, measured through the levelized cost of energy (LCOE), which offers admissible grounds for comparison between the two frameworks.

Another discernible distinction is rooted in the assumed foresight in the two models. Perfect foresight in TIMES optimises investment and shutdown decisions across all time steps simultaneously. MUSE, by comparison, applies imperfect foresight to simulate each time step independently while respecting the scheduled retirement of assets. This distinction influences investment timing; which means that TIMES may choose to defer investments if they are not required in future periods, while MUSE invests sequentially based on sector-specific heuristics. (Siala et al, 2022).

Discrepancies also emerge in the treatment of negative emissions technologies and emissions circularity in the models. In QT-TIMES, direct air capture (DAC) is modelled as a standalone system component that offsets residual emissions at the system level. In MUSE-QA, technologies are modelled with multiple variants, some of which integrate CCS or DAC units. Although MUSE's representation is more linear and distributed, it can be interpreted as the aggregate DAC capacity required to offset industrial or system-wide emissions.

Further discrepancies stem from sensitivity to input data. TIMES identifies the optimal least-cost system configuration based on perfect knowledge of input assumptions such as technology costs, fuel prices, and demand projections. As a result, it is highly sensitive to small changes in inputs such as costs, efficiencies, or policy constraints. This can lead to significantly different shifts in system configuration as the model gravitates towards the most cost-effective option. This means that uncertainty in input assumptions can strongly influence outcomes (Strachan, 2011; Pfinninger et al., 2014). On the contrary, MUSE embeds agent-based behavioural decision-making that combines costs with preferences and sector-specific decision rules. As such, the system evolves more gradually and is less sensitive to small input changes, providing path-dependent

representation of technology uptake (Giarola et al., 2022). Table 4.2 summarises key properties of the two paradigms.

Table 4.2: Key properties of TIMES optimisation model and MUSE simulation model

	MUSE	TIMES
Type of analysis	simulation	Optimisation
Equilibrium type	partial	partial
Decision making	heuristics	Profit optimisation
Foresight	myopic	perfect
Output time resolution	User-defined timeslices	
Easy to use	User manual	Training course
Free license	Open source at Github	No
Spatial representation	Yes	Yes
Temporal resolution	diurnal	Diurnal
Decision Logic	Exploratory	prescriptive

4.3.5 Predefined modelling frameworks and features

The technology dataset for installed capacities is harmonised across both models for the base year 2015. Assumptions for post-2015 technology uptake include sector-specific carbon removal options, renewable energy deployment, electrification measures, and fuel-switching alternatives. These technology options differ across sectors in terms of techno-economic properties; such as energy requirements, efficiencies, investment costs, and operational lifetimes, but are restricted to high Technology Readiness Levels (TRL) in order to avoid overstating the costs or timing associated with early-stage innovation. Technologies not prioritised in national development strategies, such as onshore and offshore wind and nuclear power, are excluded from the modelling framework, to preserve alignment with Qatar stated policy outlook.

Furthermore, the policy and technology constraints are aligned across both models to ensure consistency with national strategies. Solar capacity additions are limited to 1 GW per year, with a cumulative ceiling of 20 GW, in line with consultations between the TIMES teams and the Ministry of Environment and Climate Change (MoECC). Electric vehicles (EV) penetration is restricted to 10% of annual activity levels, reflecting the targets of

2021 Electric Vehicle Strategy (MOT, 2025). In the water sector, reverse osmosis is capped at 55% of total desalination capacity by 2030, consistent with the Qatar National Environment and Climate Change Strategy (QNECCS, 2021). Direct Air Capture (DAC) is modelled as available for deployment in MUSE-QA from 2040 onwards, while in QT-TIMES it is left unconstrained, as its high costs naturally delay its uptake within a least-cost optimisation framework.

Finally, some modelling features are deliberately excluded from both frameworks. Direct and indirect subsidies, for instance, are not modelled, despite Qatar's energy market being heavily subsidised. While subsidies represent a significant "wasteful to the national economy" in Bohra (2020), this study argue that their primary impact is as an opportunity cost value. In MUSE-QA, surpassing this cost parameter is particularly applicable because the market clearing algorithm (MCA) strikes breakeven at the value of LCOE and is therefore driven by investment costs under free-market assumptions. Similarly, Siala et al. (2022) have also negated this parameter arguing that the main leverage for system transition is the CO_2 price.

4.4 Results and discussion

Having established the methodological alignment and key assumptions of MUSE-QA and QT-TIMES in the preceding sections, this section proceeds to introduce a comparative assessment of the results. The analysis examines areas of convergence and divergence in the results generated by the simulation and optimisation paradigms for Qatar energy system. Both models are harmonised and calibrated to a common base year of 2015, ensuring consistency in their technical and economic configurations. Capacity expansion begins in response to projected demand growth, with investment decisions implemented at five-year intervals and extending to 2050. The comparison aims to highlight where methodological differences lead to distinct system pathways, in addition to identifying where results reinforce one another thereby strengthening the robustness of insights for policy and planning towards transition.

4.4.1 Decision logic and technology adoption

Overall energy system transition pathways

The trajectory of installed capacities reveals the clearest distinction between the optimisation and simulation approaches. In QT-TIMES, capacity expansion is driven by the optimisation of annual system costs through least-cost dispatch strategies, whereas in MUSE-QA investment decisions are shaped by agent-based preferences that emulate realistic investor behaviour, while still seeking to minimise overall system costs. Figure 4.1 illustrates the upscaling of low-carbon capacities in the industry sectors across both models. It shows a critical inflection point which occurs in 2030, when all industrial assets reach retirement in parallel with the onset of carbon budget constraints. Therefore, in MUSE-QA, this transition acts as a decisive lever for emissions reductions, with new capacity largely replaced by CCS-integrated technologies. On the contrary, QT-TIMES prioritises minimising sectoral costs, avoiding widespread investment in high-cost low-carbon alternatives, and instead only replaces the most carbon-intensive asset which is ammonia production, while deferring broader low-carbon uptake.

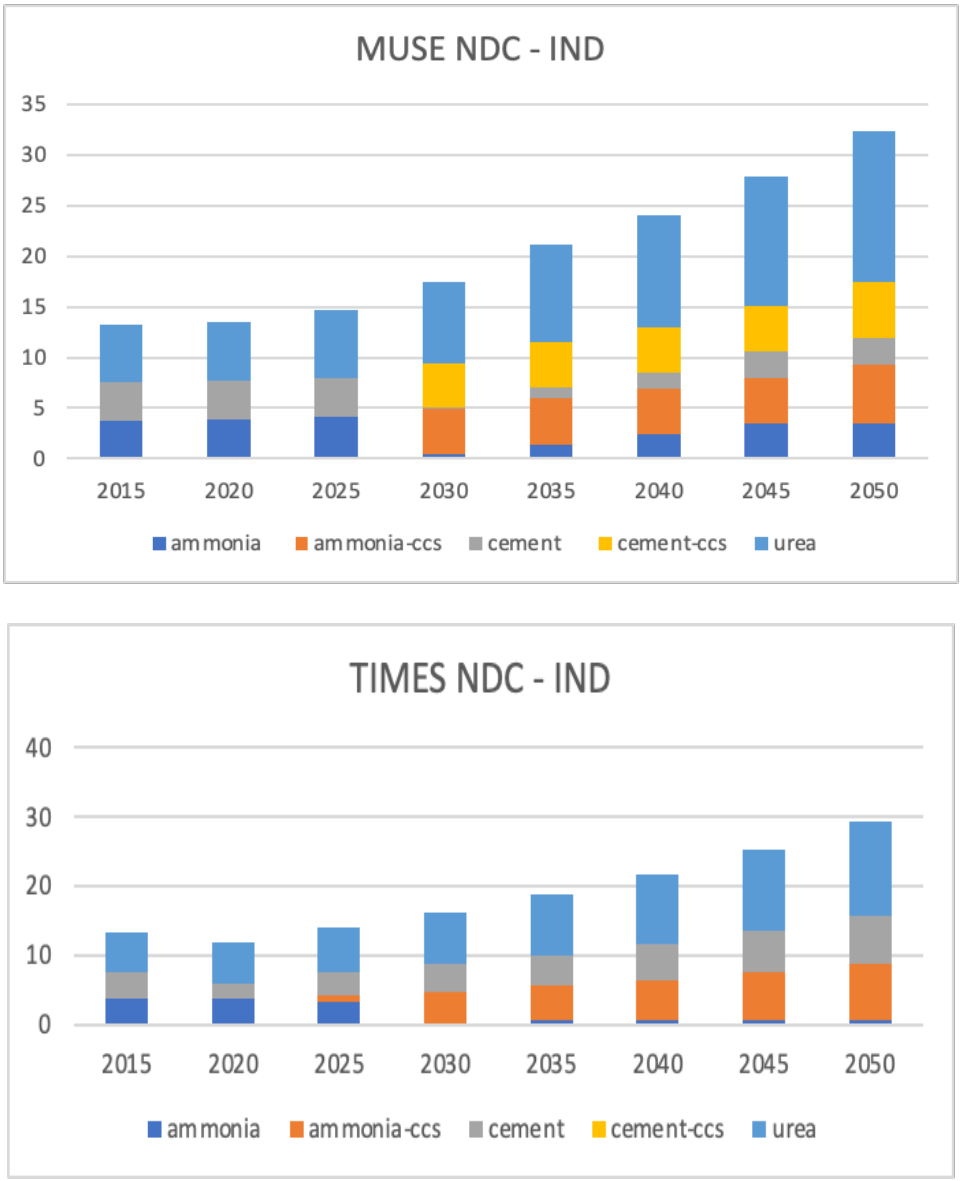


Figure 4.1: Technology portfolio in the industry sector in MUSE-QA (top) and QT-TIMES (bottom) under NDC scenario

A similar logic is also observed in the NZ50 scenario. Figure 4.2 depicts the evolution of industrial technologies under this more stringent climate target. In QT-TIMES, decarbonisation is prioritised by fully abating the highest-emitting technology, which is under chemicals and petrochemicals production, while deferring the decarbonisation of relatively lower emitting processes for when DAC is introduced in the system. By contrast, MUSE-QA, introduces CCS-integrated technologies in a concentrated wave, which accelerates emissions reduction in the near-term but simultaneously creates risks of technological lock-in. As carbon budget tightens towards the end of the modelling

horizon, this lock-in effect may constrain flexibility for adopting further decarbonisation measures, underscoring the trade-offs between early action and long-term adaptability.

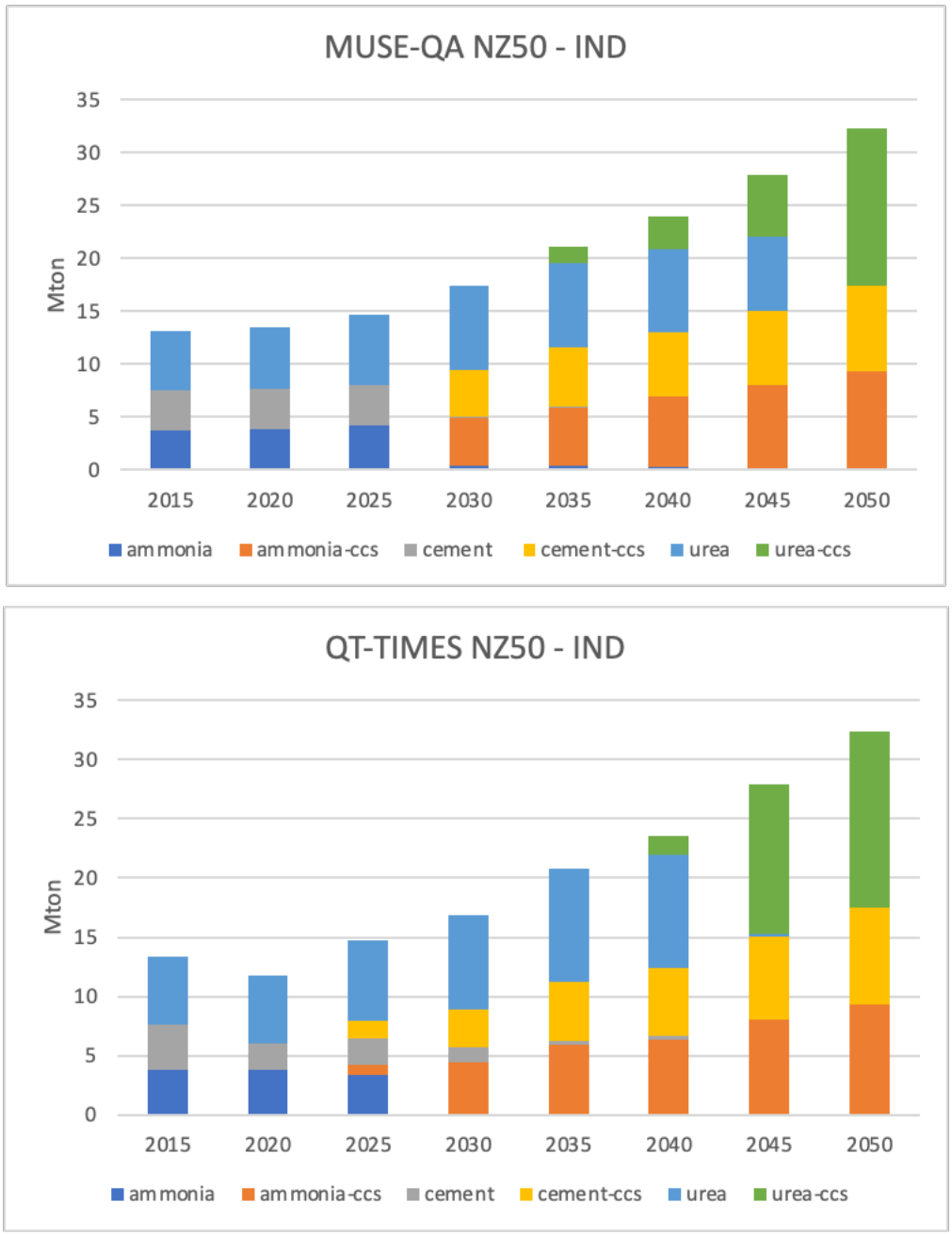


Figure 4.2: Technology portfolio in the industry sector in MUSE-QA (top) and QT-TIMES (bottom) under NZ50 scenario

This divergence in decision-making logic is less pronounced in the decarbonisation of the transport sector, where electrification is primarily governed by policy constraints embedded in the NDC scenario; which is the 10% electric vehicle penetration cap and

the full electrification of public transport. As depicted in Figure 4.3, the overall evolution of the transport sector is therefore more closely aligned across both models.

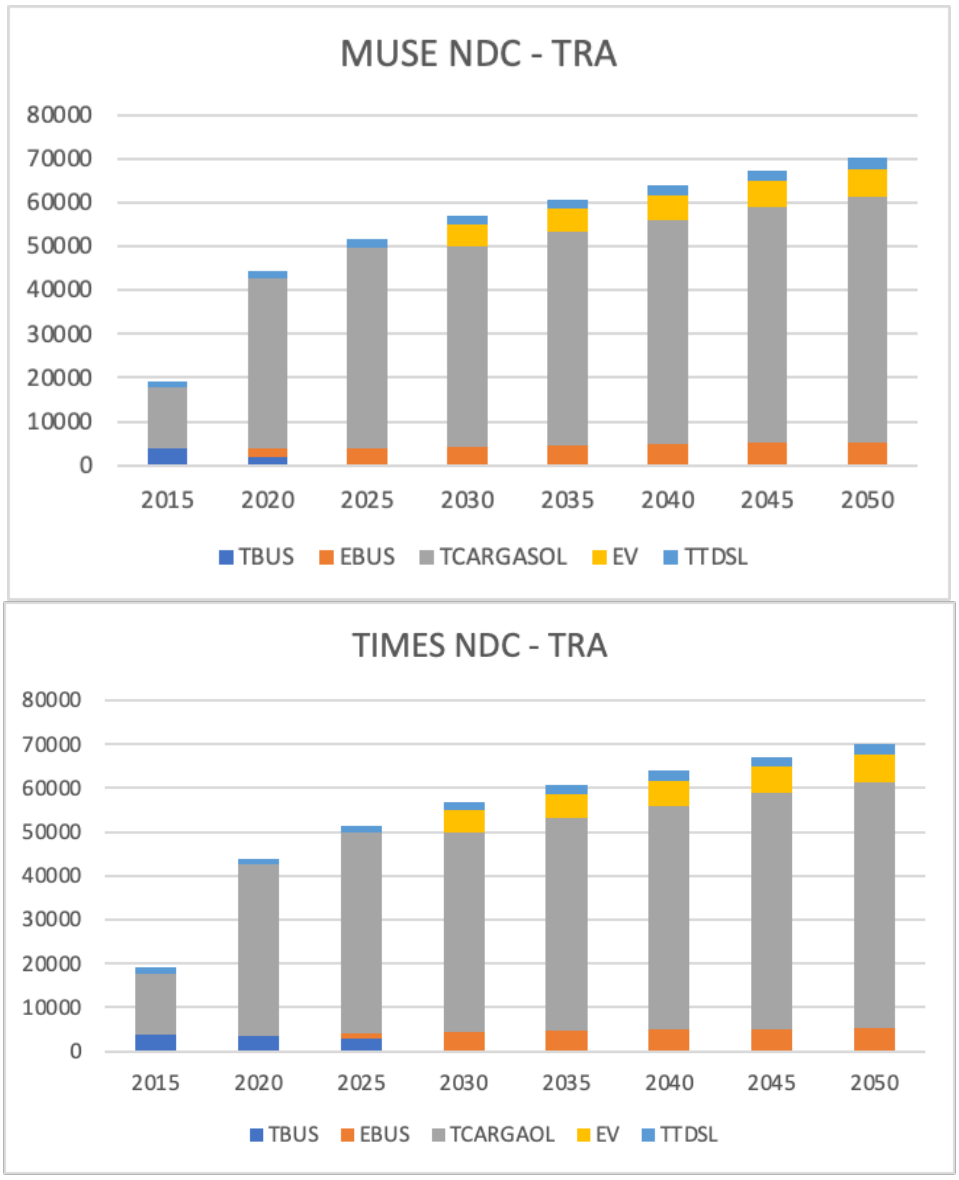


Figure 4.3: Technology portfolio in the transport sector in MUSE-QA (top) and QT-TIMES (bottom) under NDC scenario

Nevertheless, under more stringent climate targets, subtle divergences in the pace and sequencing of adoption become evident across the two models. Figure 4.4 illustrates transport sector dynamics under the NZ50 scenario, where full electrification of both private vehicles and public transport becomes inevitable by 2050. In MUSE-QA, the penetration rate is faster, driven by the phase-out of existing assets; whereas in QT-TIMES,

the transition follows a more systematic trajectory shaped by user-imposed penetration constraints. Both models also project a fuel switch to hydrogen, though their treatment diverges; in MUSE-QA, hydrogen fully displaces diesel trucks once all incumbent assets retire, while in QT-TIMES hydrogen penetration plateaus at around 40%, with the remaining diesel trucks retained as an economically rational choice offset by compensatory carbon removal elsewhere in the system through DAC. This highlights the treatment of the energy system as an integrated matrix in which capital allocation is evaluated across sectors, balancing investments priorities against- economy-wide mitigation requirements.

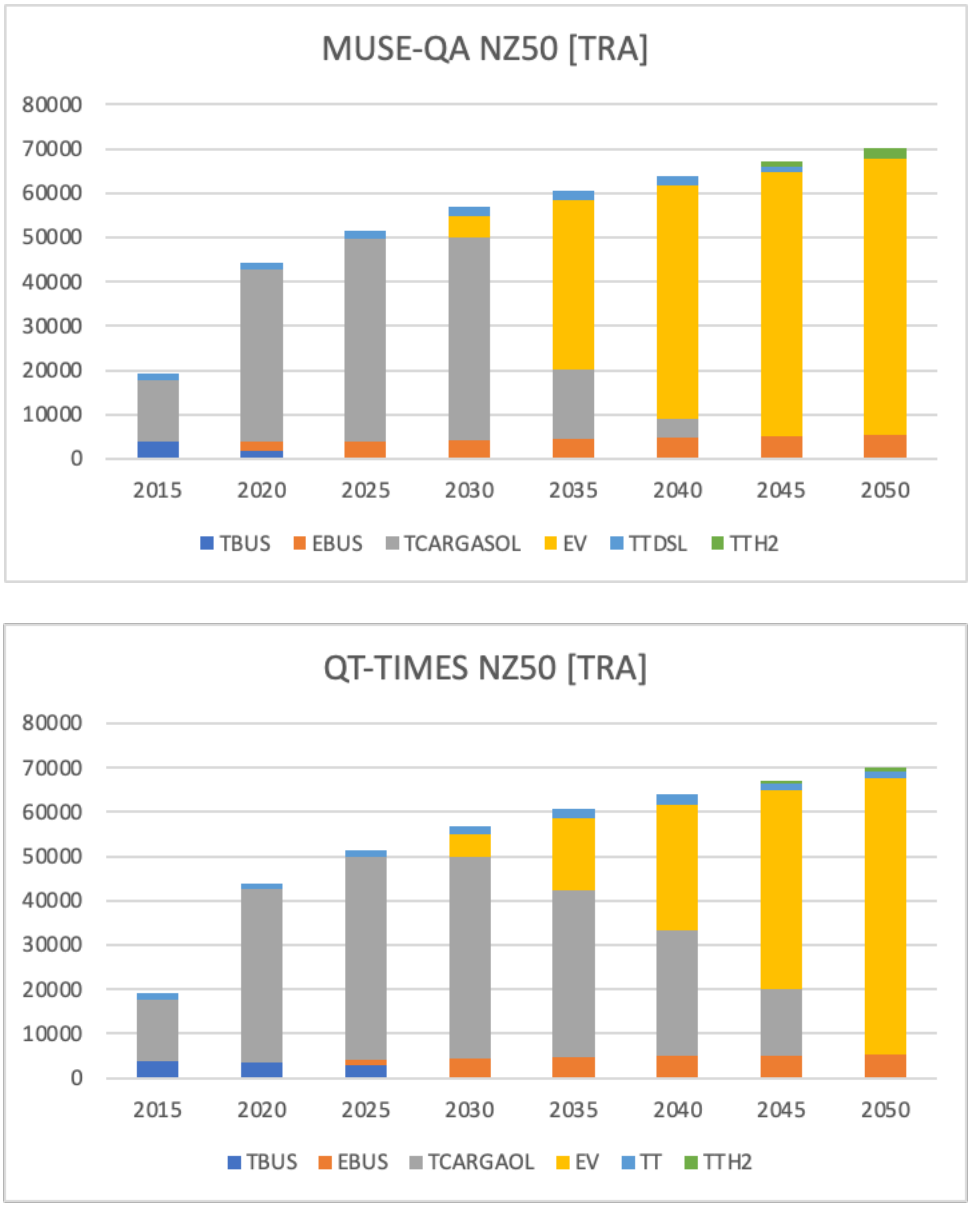


Figure 4.4: Technology portfolio in the transport sector in MUSE-QA (top) and QT-TIMES (bottom) under NZ50 scenario

4.4.2 The influence of perfect and imperfect foresights on energy mix

The results reflect the endogenous supply of energy within the system, shaped by the underlying modelling paradigm and its treatment of foresight. In optimisation frameworks such as QT-TIMES, perfect foresight assumes full knowledge of fuel prices and demand trajectories across the entire planning horizon, whereas in simulation frameworks like MUSE-QA, imperfect foresight limits decision-making to the bounded investment time step. This distinction is particularly evident in the evolution of the power mix across the two models.

In the power sector, under the NDC scenario, as illustrated in Figure 4.5, QT-TIMES tends to extend the lifetime of the cost-efficient OCGT plants, whereas MUSE-QA phases it out completely once it reaches retirement. Both models retain CCGT as the dominant source of power generation, with solar emerging as the primary low-emission alternative. By 2050, CCGT accounts for 77% of the power mix in MUSE-QA, reflecting the persistence of new CCGT capacities carried forward across successive time steps. Nevertheless, solar penetration in MUSE-QA reduces fossil fuel consumption by 22% relative to baseline. Under this paradigm, increased electricity demand within a given period creates only a limited window for additional solar capacity, which constrains its penetration. By contrast, QT-TIMES reduces the role of CCGT to 69% by 2050, enabling greater integration of solar into the system and a 30% reduction in natural gas consumption relative to baseline.

Under the NZ50 scenario, QT-TIMES establishes solar generation at a relatively steady capacity of ~ 4.3 GW, as illustrated in Figure 4.6, with emissions mitigation achieved primarily through the integration of CCS with CCGT. In MUSE-QA, however, solar uptake remains more opportunistic and closely tied to incremental demand growth, reinforcing the path dependency of system evolution under imperfect foresight and incurring a marginal reduction in fuel requirement of about 1% only. A further distinction in modelled results is evident in electricity demand; where QT-TIMES projects demand to be roughly 39% higher than in MUSE-QA, signalling deeper electrification activity, particularly within the industry sector. This additional electrification raises fuel consumption in the power

sector by 27%, but simultaneously reduces fuel use in industry by 15%, indicating a sectoral shift in energy demand and associated emissions burdens.

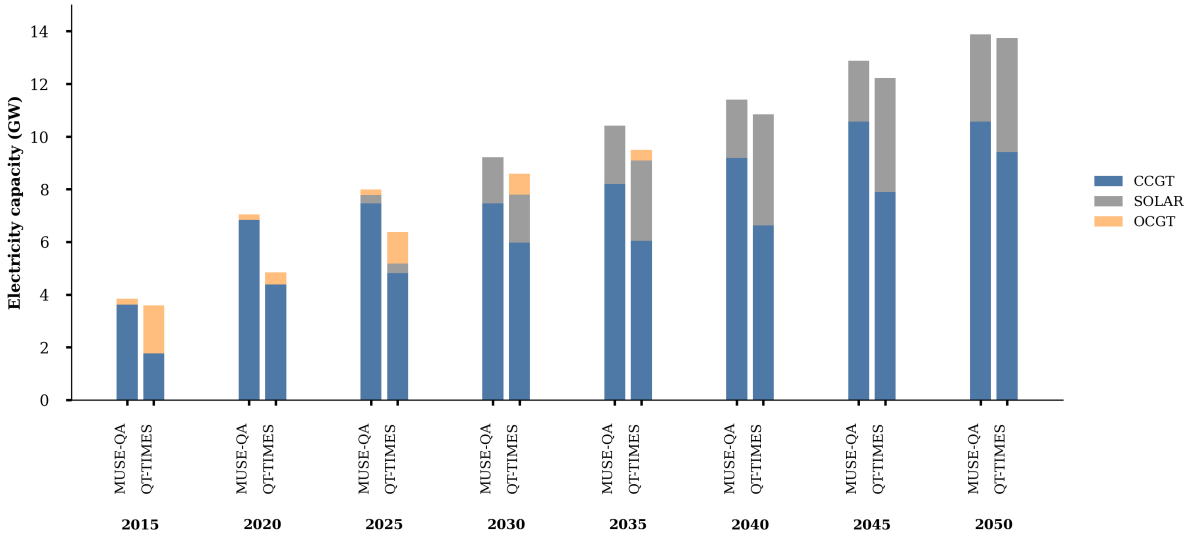


Figure 4.5: Power mix in MUSE-QA and QT-TIMES under NDC scenario

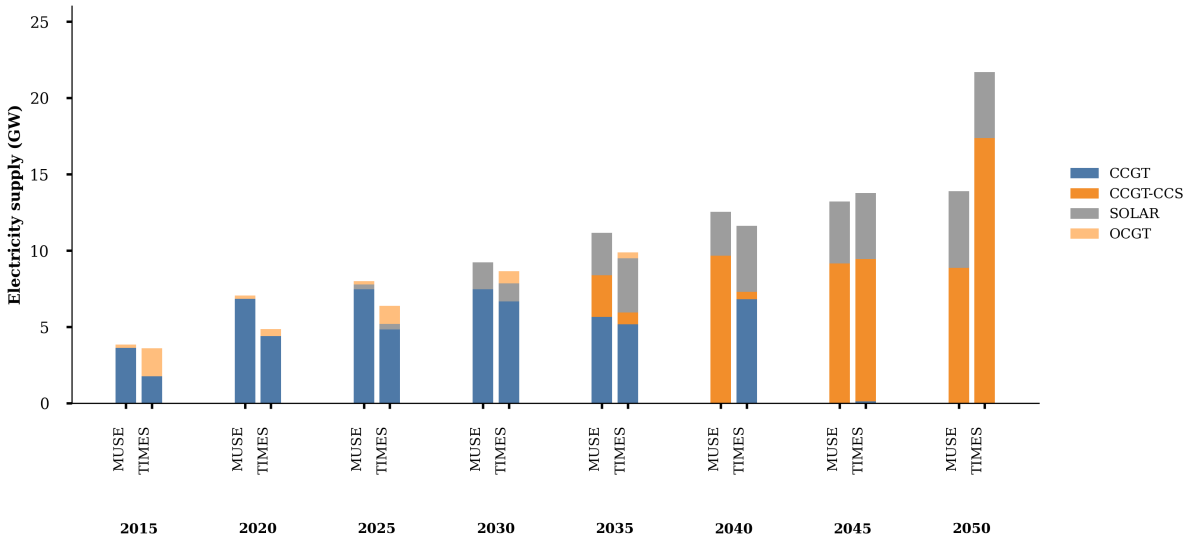


Figure 4.6: Power mix in MUSE-QA and QT-TIMES under NZ50 scenario

This influence of foresight assumptions extends to the energy mix upstream, which is strongly shaped by fuel requirements in the power generation sector. Figures 4.7 and 4.8 illustrates natural gas use in the system across scenarios as represented in both models.

Under the NDC scenario, grid dynamics in MUSE-QA results in a 10% reduction in system-wide fuel requirements by 2050, whereas QT-TIMES achieves 20% reduction owing to a higher penetration of renewables. By contrast, the divergence between the models becomes more pronounced under the stringent emissions constraints of the NZ50 scenario. In MUSE-QA, the integration of carbon removal utilities drives a 56% increase in fuel requirements, as technologies that appear cost-effective in the short term persist into the long term under imperfect foresight. By contrast, perfect foresight into the future results in greater electrification in end-use sectors, particularly in industry, which is highly energy-intensive, thereby concentrating energy demand within the power sector and delivering an overall 15% reduction in natural gas consumption at the system level.

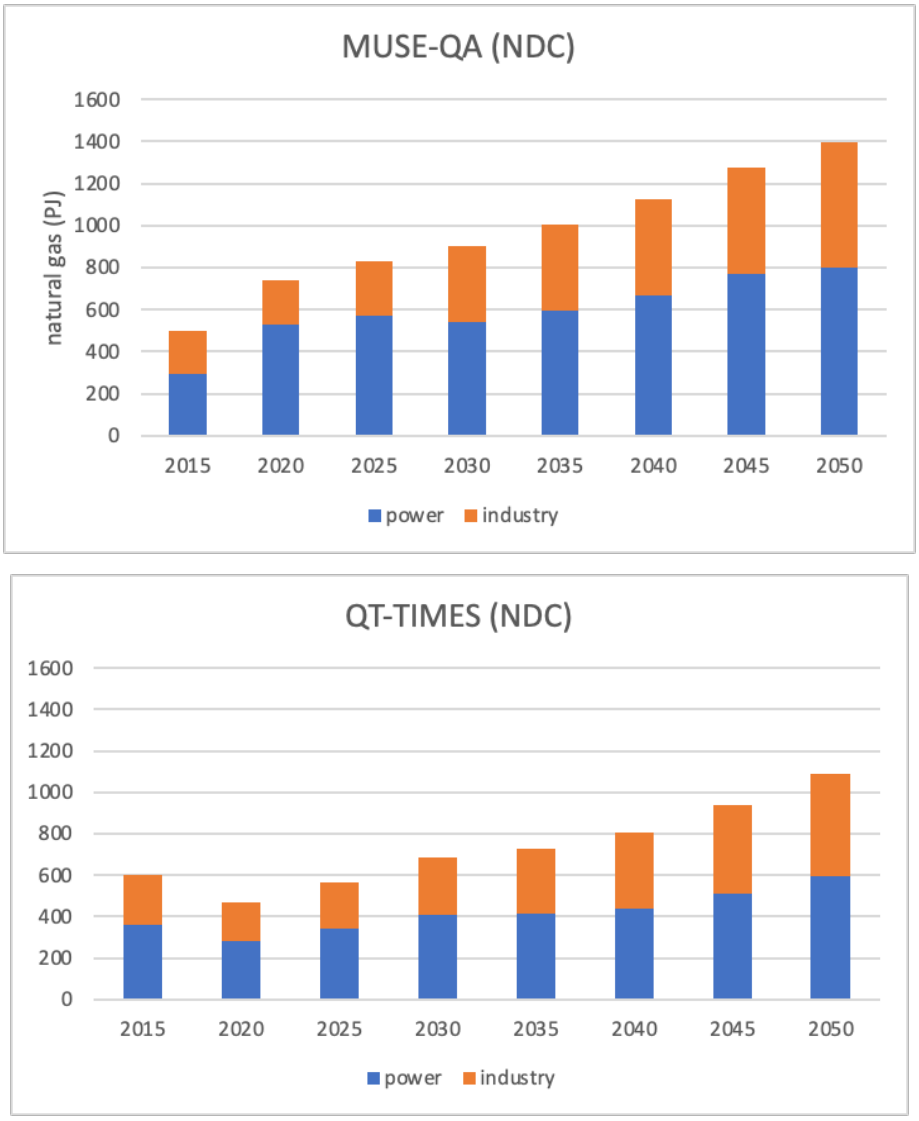


Figure 4.7: Energy consumption under the NDC scenario compared between MUSE-QA (top) and QT-TIMES (bottom)

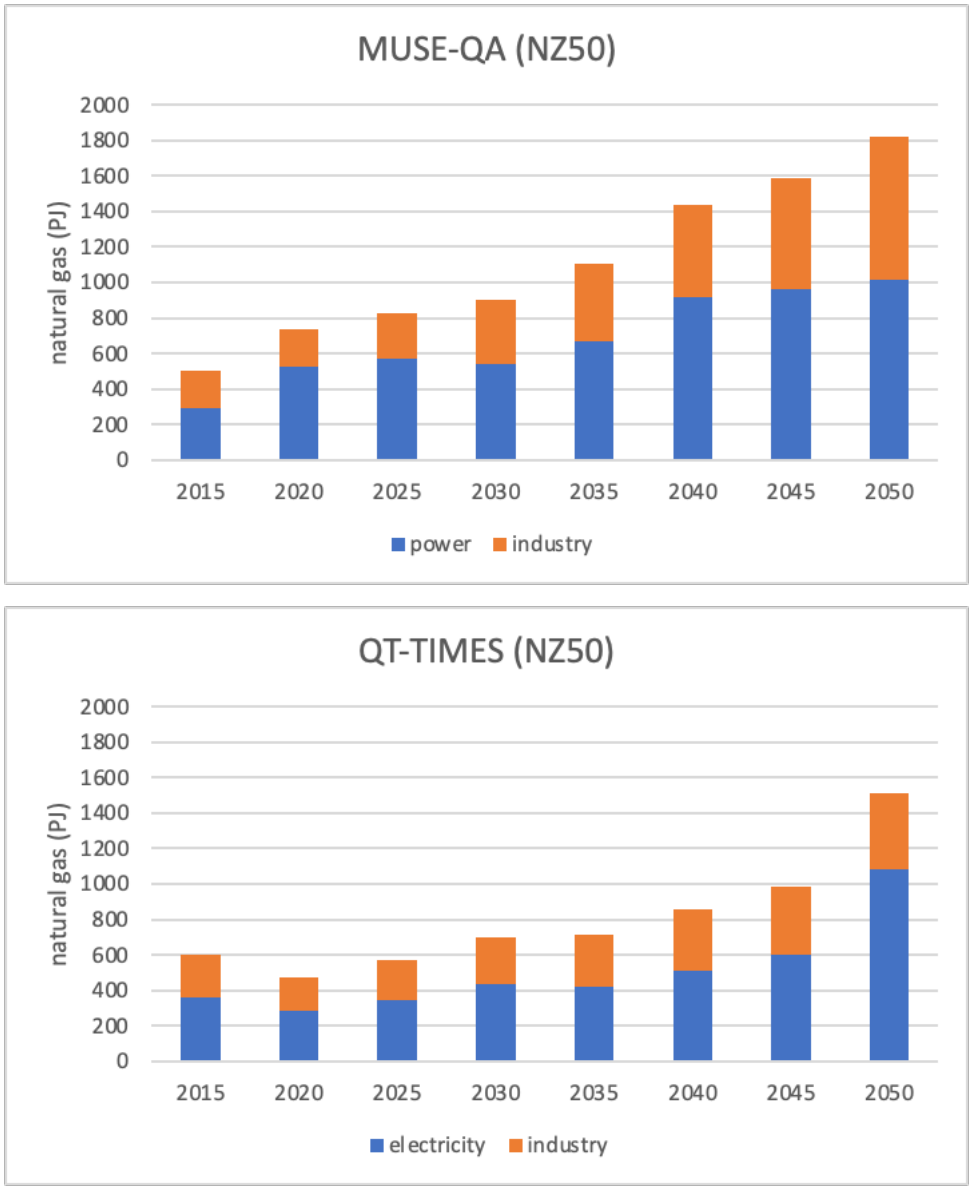


Figure 4.8: Energy consumption under the NZ50 scenario compared between MUSE-QA and QT-TIMES

4.4.3 Optimality and market dynamics in shaping emissions trajectory

The baseline scenario indicates that the largest contributor to system emissions is the hydrocarbon production and processing sector, followed by the industrial sector. Accordingly, both models underscore that carbon removal is most cost-effectively deployed when it is centralised within energy- and emissions- intensive sectors. Under a moderate transition represented by the NDC scenario, both frameworks converge on the industry sector as the primary focus of carbon removal, as shown in Figure 4.8. In MUSE-QA, an average of approximately 27 MtCO2 per annum must be captured from 2030 onwards to implement the NDC mitigation target, while QT-TIMES requires a slightly lower capture volume of around 25 MtCO2 per annum. In the simulation model, capture volumes increase abruptly from 27 MtCO2 in 2045 to 33 MtCO2, whereas in the optimisation model capture levels follow a smoother trajectory. This divergence reflects differences in the pace of technology uptake, with MUSE-QA more exposed to lock-in effects than QT-TIMES. It also reflects TIMES model ability to optimally allocate capacity investments across timesteps under perfect foresight.

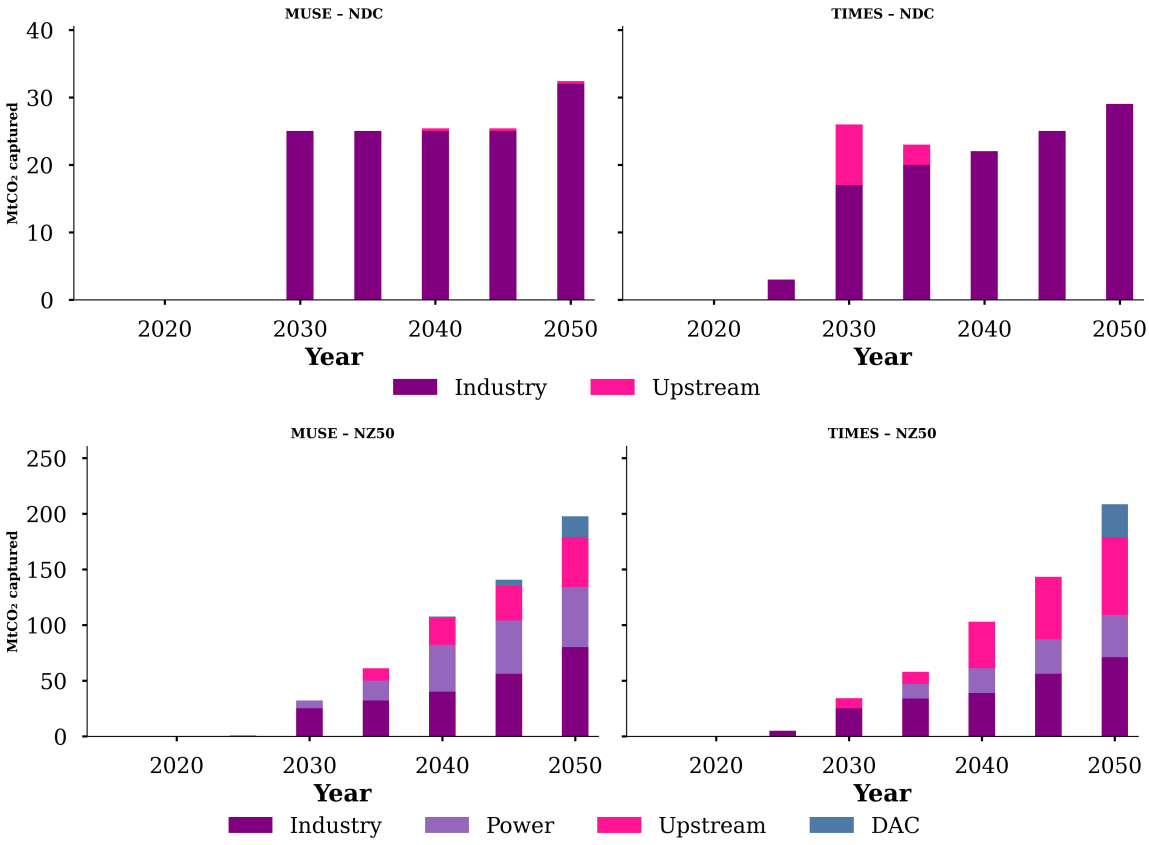


Figure 4.9: Carbon removal volumes in MUSE-QA and QT-TIMES under NDC and NZ50 scenarios

Moreover, a prominent structural distinction lies in how each paradigm enforces the emissions constraint. In the simulation model, compliance is permitted within a user-specified tolerance band around the absolute carbon budget. By contrast, in the optimisation model a percentage reduction target is imposed, and the system is reconfigured to achieve it at least cost. Therefore, as shown in Figure 4.10, the TIMES emissions trajectory follows a smooth decline consistent with the NDC target, achieved through optimised capacity expansion decisions. In MUSE-QA, however, the emissions trajectory is more irregular, reflecting the persistence of existing assets that investors may be unwilling or unable to retire prematurely.

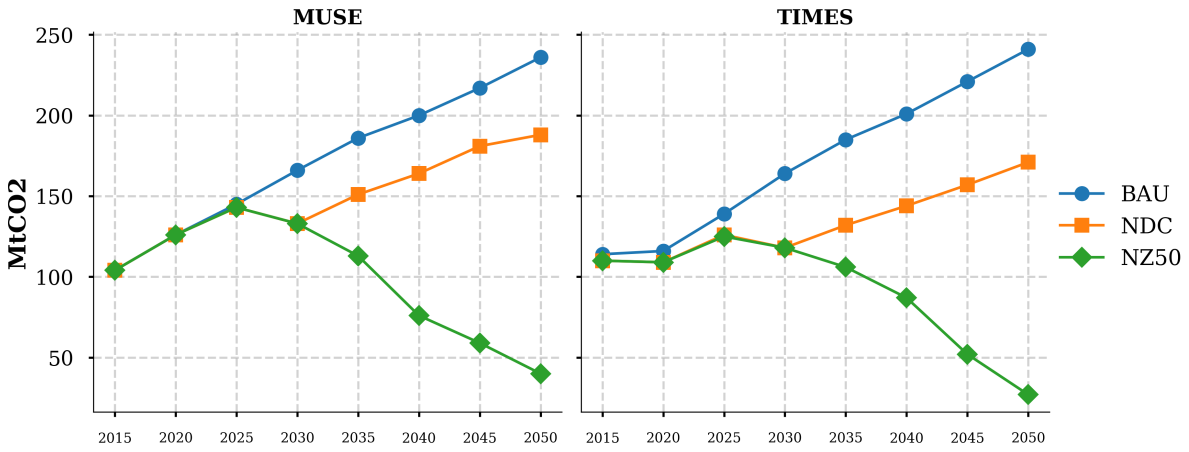


Figure 4.10: Emission trajectories in MUSE-QA and QT-TIMES under BAU, NDC and NZ50 scenarios

Under the more stringent NZ50 scenario, QT-TIMES is capable of reaching net zero emissions by mid-century through radical sectoral transitions towards energy- and emissions-efficient alternatives, whereas MUSE-QA suggests that achieving this target would be highly challenging due to structural inertia and lock-in effects embedded in the simulation approach emulating real-life hurdles, underscoring the trade-off between achieving ambitious decarbonisation targets and safeguarding economic resilience.

Over the entire transition period, cumulative emissions trajectories in Figure 4.11 highlight clear differences in transition timing between the two modelling paradigms. Under both emissions targets, cumulative emissions in the MUSE-QA pathway are approximately 12-13% higher than in the QT-TIMES pathway, reflecting delayed

abatement arising from sequential decision-making under imperfect foresight. This divergence underscores policy timing risk; while QT-TIMES identifies a cost-optimal pathway to a specific emissions mitigation target, MUSE-QA reveals how market inertia and investment dynamics can postpone abatement. Therefore, under the more stringent target of NZ50, delayed early action translates into stronger late-stage interventions to compensate for accumulated emissions.

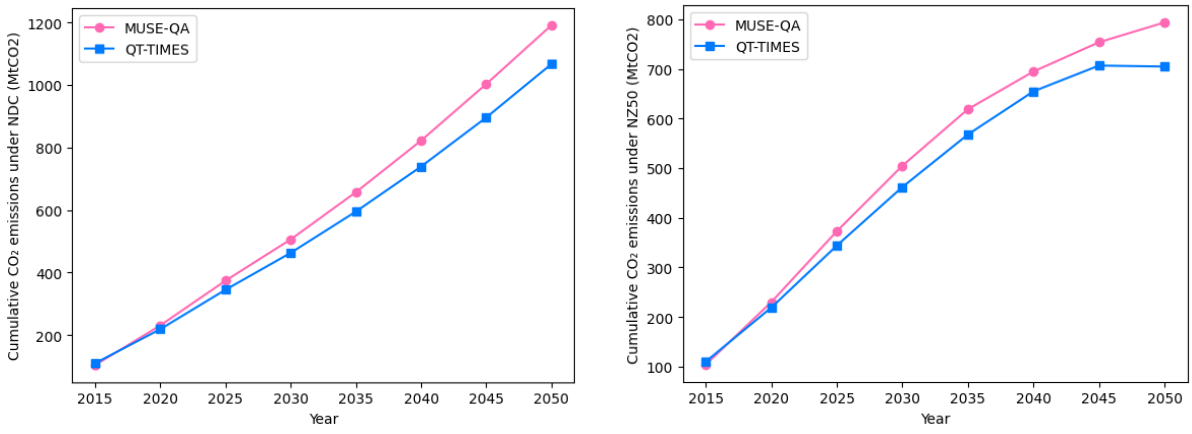


Figure 4.11: Cumulative emissions compared in both MUSE-QA and QT-TIMES for the period (2015-2050) under (a) NDC and (b) NZ50 scenarios

4.4.4 Strengths and limitations

The two modelling platforms; MUSE-QA and QT-TIMES, while methodologically distinct, are equally valuable for energy system analysis. Each approach contributes complementary strengths in exploring Qatar energy system evolution pathways. Perhaps QT-TIMES excels in offering the least-cost pathway for system transition. In MUSE-QA, the model captures the heterogeneity of the market actors which levers towards more realistic system evolution. Moreover, the perfect foresight of QT-TIMES engenders clear divergence in technology selection sensitive to change in cost and policy constraints. The imperfect foresight of MUSE-QA is rather impacted by investment dynamics and risk aversion. This decision-making preference in QT-TIMES is based on an explicit and detailed techno-economic dataset for precise technology contender. This is also valid

for MUSE-QA in addition to its flexible market representation and sectoral contextualised policy narratives.

In contrast, each of the modelling platforms exhibit limitations that must be elucidated for transparency and accurate policy shaping. In QT-TIMES, sensitivity to data inputs engenders significant variations in results, even in response to minor changes in cost or in policy assumptions. On the contrary, MUSE-QA shows slower response to policy shocks. Also, QT-TIMES assumes perfect foresight of the future which is not likely to occur as assumed. Unlike MUSE-QA, it also negates investors market behaviour seeking economic optimality. However, MUSE-QA tendency to respond to market imperfections is likely to raise the cost of transition. This makes direct cost comparison between the two models challenging. MUSE-QA requires exogenous detailed behavioural assumptions of market actors which can introduce subjectivity in results. Therefore, while QT-TIMES excels in generating optimisation-driven insights, MUSE-QA captures the behavioural-driven perspective, underscoring the value of their complementarity in shaping robust policy discourse.

4.4.5 Policy Implications

In the remit of the strengths and limitations of simulation and optimisation modelling, synthesised insights can add value to policy drafting. Although arguably, policy making is inclined towards inferring policy drafts from optimisation results which are objective and rational (Lund et al, 2017); however, valuable insights emerge when the two models converge. Both QT-TIMES and MUSE-QA agree that natural gas will remain a valuable asset in the long run. Therefore, in order to mitigate the concomitant emissions footprint, intensive carbon removal utilities must be inaugurated and centralised at the energy and emissions intensive sectors; that are upstream, power, and industry sectors. This indicates that substantive efforts must be fostered beyond the current NDC directions to adeptly impede emissions towards neutrality. Moreover, the pace and timing of transition emerge as critical determinants of feasibility. At key target milestones, both models

exhibit abrupt structural changes in order to comply with emissions caps, particularly in trajectories aiming for net zero by 2050. This finding suggests that delayed action may in some cases be more implementable and economically prudent, as reflected in the strategies of neighbouring countries such as Saudi Arabia, which has set a 2060 net zero target, and India, which has set 2070 (Climate Action Tracker, 2025).

4.5 Discussion

The preceding sections have assessed the transition of Qatar energy system under both the NDC and the NZ50 targets, drawing on insights from the simulation-based MUSE-QA and the optimisation-based QT-TIMES. Particular attention was given to the drivers of convergence and divergence between the two frameworks, enabling a systematic cross-validation of outcomes. The results provide a structured comparison of proposed decarbonisation pathways, highlighting how distinct investment logics and modelling paradigms shape system evolution and guide policy.

A key distinction between the two approaches is rooted in their underlying paradigms. Optimisation frameworks identify an optimal pathway by applying economically driven rules and constraints, whereas simulation frameworks rely on user-defined preferences. Consequently, the outcomes can be broadly compared, though they are not directly equivalent (Lund et al, 2017). The comparison proves useful in examining how the variations in investment logic and foresight assumptions influence the balance between economic stability, emissions reductions, and policy design in terms of speed, pace and ambition of transition.

The results reveal that stepwise planning risks deferring necessary investments early in the time horizon, thereby leading to higher capital requirements later on (Keppo & Strubegger, 2010). Under the moderate emissions reduction target in the NDC scenario, while both models exhibit relatively similar cumulative capture volumes; however, the optimisation frameworks, with its perfect foresight, initiates early capital deployment and adapts flexibly to evolving capture needs. In contrast, the myopic foresight

embedded in simulation framework keeps capture capacity nearly constant across most of the time horizon, with no significant additions until the final period. At that stage, it triggers an abrupt increase in capture capacity as volumes increase from 25 MtCO2 in 2045 to 33 MtCO2 in 2050, a shift that is largely contingent on the extent of mitigation achieved in other sectors.

The milestone of 2030, under a moderate emissions cap, represent a turning point in the system evolution. Both models reveal commonalities, although their underlying mechanisms differ. MUSE-QA exploits opportunities to reinvest at the retirement of vintage assets, whereas QT-TIMES accelerates the phase-out of high-emitting assets and transitions to low-emission alternatives to remain within the carbon budget. This underlines the significance of initiating transition measures early, even under moderate emissions caps. Notably, both models converge on two strategic priorities: the central role of carbon capture and storage (CCS) in the industrial sector, and the scaling-up of solar deployment in the power sector. The moderate target thus leads to a cautiously prudent and phased transition that aligns with Qatar NDC strategies and current initiatives, such as Al Kharsaah solar plant.

The distinction between paradigms becomes more pronounced under more stringent carbon-neutrality targets. QT-TIMES converges on an optimal system configuration to meet neutrality with perfect foresight, whereas MUSE advances step by step through partial equilibrium, constrained by myopic investment foresight. As the available carbon budget tightens, MUSE is challenged to meet rising demand with low-emission alternatives that cannot easily displace existing capacities. Although deviations from optimal trajectories are associated with higher system costs (Siala et al., 2022), they capture the imperfect, path-dependent decision-making that often characterises real-world transitions.

This divergence is evident in sectoral pathways. In TIMES early shutdown of emitting assets brings forward electrification and low-carbon alternatives whenever economically optimal, driving significant shifts toward electric technologies. TIMES shows additional electrification in the industrial sector supported by its perfect foresight-

based investment logic, saving approximately 1.3 Mton of natural gas in industrial fuel use. By contrast, MUSE maintains higher reliance on fossil fuels, which increases system emissions (Keppo & Strubegger, 2010) and necessitates greater carbon removal capacity. This, in turn, raises natural gas requirements by 5.3 Mton, nearly four-fold higher than the simulation baseline. In TIMES, however, natural gas is redirected to the power sector to meet electrification needs, requiring an additional 2.9 Mton.

While TIMES pathway may appear appealing in terms of emissions reductions and efficiency gains, these benefits are counterbalanced by the substantial upfront capital investment required to deliver them. By contrast, simulation pathways, while less optimal in a purely economic perspective, capture the incremental and imperfect investment choices that are more consistent with real-world policy and market behaviour. However, this approach is also associated with strong lock-ins, which limit flexibility in adapting to changes in environmental regulations and technology innovation (Keppo & Strubegger, 2010). Therefore, the aim of this comparison is to emphasise that model selection requires careful consideration by both modellers and policymakers. The objective is not to claim superiority of one paradigm over the other, but rather to demonstrate how their complementarity broadens the range of potential pathways and strengthens the reliability of scenarios (Johanessen et al, 2023).

4.6 Chapter summary

The energy transition in Qatar was assessed by comparing outputs from two distinct modelling approaches. This builds on the simulation analysis presented in Chapter 3 with MUSE-QA, here complemented by the optimisation-based QT-TIMES. The comparison was undertaken because these two frameworks are currently the only system-wide models tailored for the Qatari context, up to our knowledge, and both also hold international applications, which provides robustness and allows for regional comparability.

To ensure consistency, both models were harmonised under identical emissions reduction targets. They were calibrated to the 2015 base year using the IEA energy balance for Qatar and run against demand trajectories derived from GDP growth and historical trends. Three scenarios were developed: a business-as-usual (BAU) baseline, an NDC pathway aligned with Qatar official strategy, and an NZ50 scenario reflecting a stringent carbon neutrality target by mid-century.

The comparative analysis reveals both convergence and divergence, reflecting the different decision-making logics of the two paradigms. In optimisation, perfect foresight of commodity prices, market dynamics, and demand trajectories enables QT-TIMES to configure the system optimally to comply with the carbon budget. In contrast, the myopic foresight in MUSE-QA produces a series of partial equilibrium solutions, resulting in incremental adjustments over short planning horizon.

Meeting the NDC target of a 25% reduction in system-wide emissions is feasible under both frameworks, but requires expansion of solar generation and the deployment of carbon removal technologies. CCS emerges as a critical technology in both models, particularly in energy- and emissions-intensive industries and in upstream hydrocarbon processing. Average annual capture requirements are estimated at 27 MtCO2 in MUSE-QA and 25 MTCO2 in QT-TIMES. In MUSE-QA, CCS is introduced from 2030 coinciding with asset retirements and the enforcement of the carbon budget. Capacity remains largely flat thereafter until the final time period, when it is increased by 31% due to its relative cost-effectiveness compared with other mitigation measures such as solar. By contrast, QT-TIMES deploys CCS in a more flexible and adaptive manner, varying capture volumes continuously between 2025 and 2050, consistent with its foresight-based optimisation logic.

The other area of convergence is solar power expansion beyond the current 0.8 GW AlKharsaah plant. By mid-century, solar capacity reaches approximately 3.3-4.3 GW, equivalent to a ten-fold increase in MUSE-QA and a twelve-fold increase in QT-TIMES. Simulation requires relatively less solar than optimisation, reflecting a higher reliance on

capture technologies, while QT-TIMES favours greater solar deployment to achieve an optimal balance.

Differences become more pronounced under the NZ50 scenario. Both models converge on the need to achieve neutrality but diverge in the pace and sequencing of transition. MUSE-QA expands solar capacity to 5 GW by 2050, compared with 4 GW in QT-TIMES. CCS deployment alone is insufficient and must be complemented by DAC. In MUSE-QA, residual emissions from CCS-integrated plants are further abated by ~18.8 MtCO2 through DAC as early as 2040, while QT-TIMES postpones DAC deployment until 2050 due to its high costs, resulting in 29 MtCO2 captured through DAC units. Both frameworks also converge on full electrification of transport, with EV penetration rising from 10% under the NDC to 100% by 2050. In the industrial sector, QT-TIMES shows earlier diversification towards electrification and CCS integration, whereas MUSE-QA delays such shifts until asset retirements, favouring capture over efficiency improvements.

Taken together, the findings suggest that Qatar current NDC strategy must be enhanced through greater penetration of renewables and expansion of carbon removal capacity. Under more stringent environmental requirements, deeper transformations are necessary, including higher electrification of transport, integration of CCS and DAC across multiple sectors, and accelerated deployment of solar generation. These insights provide valuable direction for policymakers by highlighting the trade-offs between incremental and optimal investment logics, thereby informing strategies to strengthen Qatar climate commitments while maintaining economic stability.

Chapter 5

5 A Hydrogen Pathway

Qatar's natural resource endowment coupled with accruing revenues represent an enshrined economic cornerstone that is not envisaged to be marred by transitioning away from fossil fuels. Hydrogen, however, represents a transformative vision for a sustainable, low-carbon future. It is envisaged to potentially play a prominent role as a versatile energy carrier and fuel, where it can replace fossil fuels in hard-to-abate sectors (IEA Hydrogen, 2024; Hydrogen Council McKinsey & Company, 2021), and can store electricity from Variable Renewable Energy sources (VRE) (Chapman et al., 2019).

Globally, hydrogen is increasingly gaining momentum. Germany has prioritised it in the aftermath of the Russian oil crisis (Germany Federal Government, 2023); Japan has promoted hydrogen to alleviate dependence on energy imports and diversify its energy sources (Japan Agency for Natural Resources & Energy, 2014); and South Korea has advanced hydrogen use to meet fuel-switching targets (IEA Korea, 2020). By 2020, the European Union, and at least nine other countries, had published National Hydrogen Strategies (World Energy Council, 2020), signalling the emergence of hydrogen as a central pillar in future energy systems.

Although hydrogen seems like a promising avenue for future energy trade, Qatar does not yet have a clear plan for hydrogen integration within its energy system, despite that it already possesses long-standing installed capacity for hydrogen production through natural gas reforming. This gap underscores the importance of assessing how hydrogen could be integrated into Qatar future energy export landscape. In this section, MUSE-QA is modified into MUSE-HiQ to answer the 3rd question in Chapter 1; which explores to what extent can hydrogen emerge as a viable export commodity in Qatar energy transition, and how does its integration reshape the investment and technology pathways of the energy system?

This chapter builds upon the literature foundation established in Section 2.7, which examined the current state of hydrogen development and its anticipated role in enabling the transitioning toward a low-emissions global energy future. It extends this discussion by assessing Qatar's prospective positioning within the emerging global hydrogen economy. To address these considerations, the chapter utilises the MUSE-HiQ simulation framework, an enhanced and modified version of MUSE-QA model developed in Chapter 3, incorporating tailored scenario assumptions and updated technological parameters relevant to hydrogen pathways. The analysis explores hydrogen production, trade competitiveness, and infrastructure implications under alternative transition trajectories. Finally, the chapter concludes by presenting and discussing the key results, drawing insights into the broader implications of a hydrogen-based energy future and Qatar's strategic system response to this evolving energy market landscape.

5.2 Method and scope of study

Qatar's heavy reliance on petroleum exports exposes its economy to two intertwined risks: volatile hydrocarbon price and intensifying global decarbonisation pressures (Mendez & Contestabile, 2025). Against this backdrop, hydrogen emerges as a strategic opportunity for accelerated transformative progress towards sustaining economic resilience and meeting environmental targets. In this sense, emissions mitigation targets are assessed through the simulation platform of MUSE to provide insightful inferences on the impact of hydrogen on the pace, direction, and cost-effectiveness of Qatar energy transition under different policy and market conditions. Tailored for the context of Qatar, the model will be referred to as MUSE-HiQ.

As hydrogen emerges as a potential export commodity producible within the existing infrastructure in Qatar, the model is expanded to allow exports in three alternative forms: LNG, liquid hydrogen (LH_2), and ammonia. This enables assessment of Qatar's ability to remain competitive in the future hydrogen export market under varying emissions mitigation scenarios

This modelling assumption reflects the prevailing uncertainty regarding the preferred derivative of hydrogen in international markets. The World Energy Outlook WEO (IEA, 2024b) highlights the lack of clarity about whether LNG, ammonia, or LH_2 will dominate future trade. Current political agreements and emerging hydrogen strategies indicate potential demand; however, these do not necessarily guarantee corresponding commercial activity (Mendez & Contestabile, 2025). Therefore, rather than predetermining which commodity will dominate, the scenarios are designed to capture how the system evolves under different mitigation pathways and carbon budget constraints.

5.2.1 Technology options and technoeconomic specifications

The reference energy system of Qatar, as modelled in MUSE-QA in Chapter 3, is retained for this analysis. It represents energy flows for both domestic demand and export, while incorporating current system configuration alongside portfolios of technology options. Hydrogen production occurs at the upstream supply sector through existing Steam Methane Reformers (SMR), in addition to future alternative technologies, and can compete with LNG for export demand. It is also assumed that hydrogen can be exported through a carrier such as ammonia, which is currently produced at the industry sector through Haber-Bosch process.

5.2.1.1 Technology Profile

Table 5.1 presents the set of technologies and their techno-economic parameters as incorporated into the MUSE-HiQ framework. These estimates are drawn from values reported in the literature and encompass key processes such as reforming and carbon removal integration. Conventional ATR process is not considered here as only blue hydrogen is assumed to be aligned with future energy demand. Alternative production routes, including electrolysis for green hydrogen, are excluded from this modelling exercise, as the focus lies on evaluating the contribution of hydrocarbon-based pathways

to hydrogen production during the transition. Similarly, methane thermal pyrolysis is disregarded due to its low technology readiness level (TRL), high energy intensity, and uncertainty in cost profiles (Oni et al., 2022).

Table 5.1: Summary of hydrogen production routes and associated techno-economic parameters as modelled in MUSE-HiQ

	SMR (grey)	**SMR (blue)**	**SMR (blue)**	**ATR (blue)**	**ATR (blue)**
Description	Methane and steam catalytic reaction followed by water gas shift	SMR + CCS	SMR + DAC	ATR + CCS	ATR + DAC
Output	H_2 and CO_2	H_2 with 90% CO_2 capture	H_2	H_2 with 90% CO_2 capture	H_2
Qatar context	Dominant	Future technology	Future technology	Future technology	Future technology
Capital cost (MUSD/PJ)	24.31	33.83	42.86	26.47	48.88
Technical Life (years)	20	20	20	20	20
References	IEA (2024c)	IEA (2024c)	Calculated as illustrated in Chapter 3	US DOE NETL (2022), Oni et al. (2022)	Calculated as illustrated in Chapter 3

Figure 5.1 depicts the assumed linear hydrogen flow within Qatar energy system, extending from the point of production to the point of export. Downstream processes such as conditioning, compression, liquefaction, distribution, storage, regasification and further conversion at importing hubs are not explicitly modelled with technical specifications. Incorporating these steps would introduce an additional layer of complexity that is difficult to capture within the linearity assumptions of MUSE, while also increasing computational burden and uncertainties. As these details do not directly serve the objectives of this chapter, they are considered beyond the scope of the present analysis.

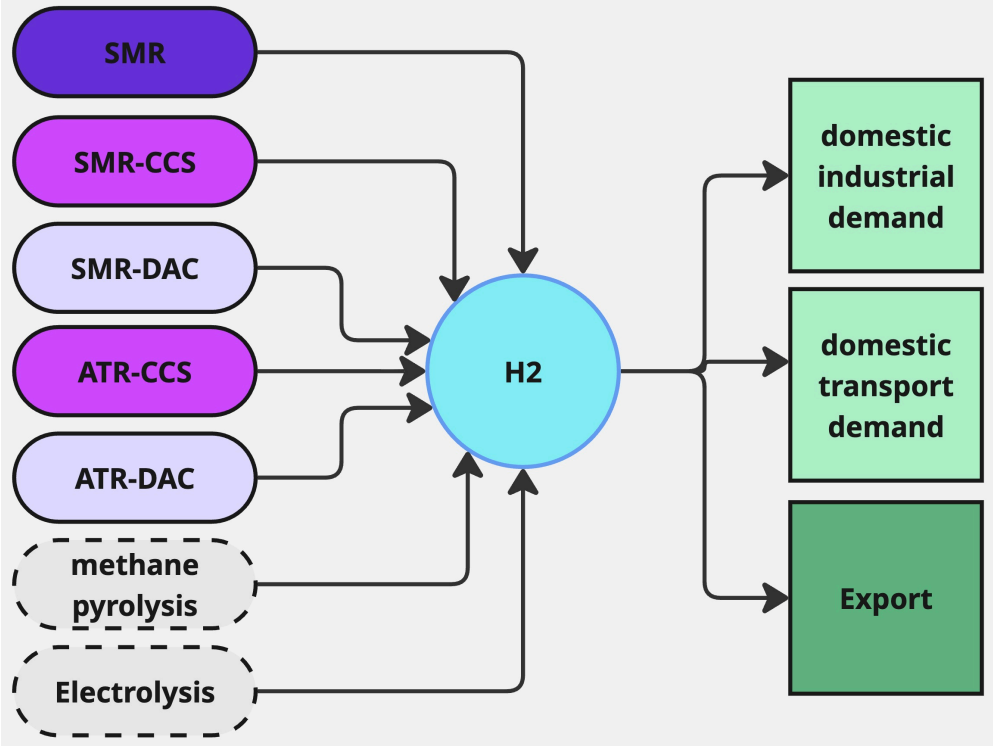


Figure 5.1: Schematic illustration of hydrogen flows within Qatar energy system, assuming that existing installed capacities are utilised to produce hydrogen for both domestic consumption and export markets.

5.2.1.2 Technical Considerations

Another significant consideration in the modelling framework is the internalisation of the export process. Since the model incorporates Qatar's existing LNG production capacity, LNG naturally emerges as the least-cost export pathway, especially when coupled with carbon removal, consistently outperforming hydrogen. To ensure a more equitable assessment of hydrogen competitiveness, the export module is enhanced to internalise both transport-related costs and emissions across the full value chain. Specifically, transport and combustion emissions are accounted for in accordance with the GHG Protocol (2011) Scope 3 Category 4 (upstream transport) and Category 11 (use of sold products). This approach ensures that the model captures not only upstream production costs but also the environmental and logistical externalities associated with export delivery, thereby reflecting a more comprehensive assessment of true system costs.

Emissions associated with the transport of energy commodities are reported in the literature for indicative transport distances between 500 to 20,000 km (de Kleijne et al., 2024) and are converted to align with the input parameters of MUSE-HiQ, as summarised in Table 5.2. At this emission factor, LNG continues to dominate the export market, reflecting its mature and established shipping fleet. However, when combustion-stage emissions are also internalised, consistent with Scope 3 accounting, this provides a more equitable basis for comparison. Under this framing, a critical threshold emerges at which hydrogen and its derivatives become increasingly competitive, as their zero carbon dioxide emissions at the point of use shift the balance of costs and compliance obligations in their favour. Accounting for these emissions impose an added cost on the "low-carbon hydrogen" commodity on demand, which both the exporters and importers must be aware of to ensure compliance and maintain market continuity (IEA, 2024c).

It should be noted that the system-wide emissions results are not discussed in this chapter. The internalisation of transport and combustion emissions, while necessary for assessing export competitiveness, introduces a distortion in the representation of total system emissions. This is because these emissions are external to the domestic energy system boundary, and their inclusion would therefore yield an unrealistic depiction of national emissions performance, offering limited policy insight for domestic decarbonisation planning.

Table 5.2: Emissions associated with transporting LNG, liquid hydrogen, and ammonia. Accounting for combustion emissions elevate the emission factor of LNG only.

Emissions	ktCO2/PJ
LNG	0.004
Liquid hydrogen	0.014
Ammonia	0.328
LNG transport + combustion emissions	53.40

5.2.1.3 Associated Costs

Furthermore, transport costs are explicitly incorporated to capture the learning cost curve associated with hydrogen shipping. Capital investment costs for vessels dedicated to specific energy commodities are drawn from Lee et al. (2022) and subsequently levelised on a per-petajoules basis of transported commodity. The basis of these calculations is listed in Table 5.3.

Table 5.3: Basis for calculating maritime transport costs of LNG, liquid hydrogen, and ammonia

Parameter	LNG	Liquid hydrogen	Ammonia
Ship capex ($/ship)	269,000,000	412,000,000	85,000,000
Capacity (ton/ship)	76,500	11,000	53,000
Operating costs ($/day per ship)	5,550	5,550	5,550

The calculation is based on a discount rate of 4.5%, consistent with the assumptions applied in Chapter 3 and 4, and an assumed equipment lifetime of 25 years (BetterSea, 2025). The capital recovery factor (CRF) is derived using Equation 5.1 which represents the annual equivalent cost of a present value over the economic lifetime of the equipment (Jamil et al, 2020).

Equation 5.1

$$CRF = Discount\,rate \times \frac{(1 + Discount\,rate)^{lifetime}}{(1 + Discount\,rate)^{lifetime} - 1}$$

Thereafter, this value is used in Equation 5.2 to calculate the annualised capital investment cost of equipment, incorporating both the discount rate and the economic life (Jamil et al, 2020).

Equation 5.2

$$Annualised\,CAPEX = CRF \times CAPEX$$

The energy transported per voyage is estimated using Equation 5.3, by multiplying the vessel's payload capacity by the lower heating value (LHV) of the commodity, assuming full vessel capacity.

Equation 5.3

$$Energy\ per\ voyage\ =\ ship\ capacity\ (kg)\ \times\ LHV\ (MJ/kg)$$

The annual transported energy for each export commodity is estimated using Equation 5.4. This formula scales the energy transported per voyage to an annual basis by accounting for the number of voyages conducted each year.

Equation 5.4

$$Annual\ Transported\ Energy = energy\ per\ voyage\ (PJ)\ \times\ voyage\ frquency\ per\ year$$

Finally, the CAPEX cost intensity (MUSD/PJ) is derived by dividing the annualised CAPEX over the annual transported energy, as expressed in Equation 5.5. This metric expresses the capital expenditure per unit of transported energy, thereby providing a consistent basis for comparing the cost efficiency of different export commodities.

Equation 5.5

$$CAPEX\ intensity\ = \frac{Annualised\ CAPEX\ (MUSD/year)}{Annual\ transported\ energy\ (PJ/year)}$$

5.2.1.4 Modelling Constraints

Additionally, to prevent unrealistic early investments in hydrogen, the model constrains hydrogen and ammonia exports until after 2030, when carbon intensity standards are assumed to come into force. From 2035 onwards, exports are permitted at a level equivalent to Qatar's current hydrogen production capacity, capped at 150 PJ. This

capacity is doubled by 2040, after which exports are left unconstrained, reflecting the assumption of a fully matured market, and allowing a retirement window for operational LNG assets. Although both LNG and ammonia already benefit from established global export markets and infrastructure, and LNG has a mature fleet and long-term contractual arrangements, however, ammonia is primarily traded internationally as a fertiliser feedstock. Its challenge lies in repositioning as an energy commodity comparable to LNG, which requires scaling infrastructure, standards, and market acceptance for energy applications.

5.2.2 Hydrogen demand forecast

The uncertainty surrounding future hydrogen demand is partly mitigated by announced pledges and decarbonisation targets (Mendez & Contestabile, 2025). In this study, particular attention is given to countries that have articulated import-oriented hydrogen strategies. Of specific interest to this study are those nations already engaged in long-standing LNG trade relations with Qatar, as illustrated earlier in Chapter 2. Asia, an importer of over 70% of Qatari LNG, represents a strategically viable cohort for hydrogen. Countries such as Japan (METI, 2023), Singapore (MTI, 2022), and South Korea (MTIE, 2022) have already articulated intentions to diversify import chains with low-carbon hydrogen as part of their transition towards a hydrogen economy.

Europe, by contrast, represents a policy-driven demand signal through the European Union's Carbon Border Adjustment Mechanism (CBAM), which imposes a carbon tariff on imported carbon-intensive commodities (European Commission, 2025). Accounting for nearly 24% of Qatar's LNG export value, this market creates a strong incentive for accelerated emissions mitigation in Qatar. This can be achieved; first, by positioning itself as a leading supplier of low-carbon energy, and second, by enhancing competitiveness through alignment of carbon pricing with the European Emissions Trading Scheme (EU ETS), thereby avoiding loss of market share to higher-performing competitors (GIIGNL, 2023; Earthna, 2025; European Commission, 2025).

To construct the demand forecast, it is assumed that future energy markets will remain dual in nature, wherein natural gas continues to serve as a transitional fuel supporting economic stability in gas-producing economies (Safari et al, 2019), while hydrogen progressively emerges as a longer-term enabler of global decarbonisation. Accordingly, the IEA World Energy Outlook (2024) projections for hydrogen are adopted as the benchmark for international energy demand forecasting. The *Stated Policies Scenario* (STEPS) trajectory for Asia is employed to represent the lower demand bound, reflecting a conservative pace of hydrogen uptake, whereas the *Announced Pledges Scenario* (APS) trajectory defines the upper demand bound, reflecting the potential for a global surge in hydrogen demand under more stringent decarbonisation commitments.

Table 5.4 contextualises these demand trajectories against Qatar's current LNG export capacity, as discussed in Chapters 2 and 3. It shows that under the lower demand trajectory, Qatar's existing infrastructure is sufficient to meet international energy demand primarily through LNG exports. However, at the upper demand bound, significant capacity expansion and structural transformation would be required to accommodate a large-scale shift toward hydrogen exports. This framing establishes the analytical foundation for examining the prospective reconfiguration of Qatar's upstream and export system in response to evolving global energy market dynamics.

This approach assumes that Qatar's emerging role in hydrogen markets will parallel its established leadership in LNG exports. Rather than extrapolating from speculative hydrogen import targets, the demand forecast is grounded in the magnitude of Qatar's existing LNG trade and export infrastructure. This assumption also aligns with the simulation methodology, which is descriptive of current assets and production capacity expansion, thereby reinforcing the credibility and realism of the scenario analysis.

Table 5.4: Hydrogen demand forecasts derived from the IEA scenarios and compared with Qatar current LNG capacity

Scenario	Demand Type	2030	2035	2050
Stated Policies	Lower Bound	6363	7074	8236
Announced Pledges	Upper Bound	6358	8520	15383
Current LNG capacity	Forecasted capacity	4435	5804	6542

5.2.3 Scenario assumptions

The scenario design for this analysis formulates three distinct pathways to explore Qatar's prospective energy transition dynamics. The **Baseline Scenario (status quo)** represents an unconstrained pathway in which the model cost optimisation naturally favours LNG, reflecting its entrenched infrastructure, mature export market, and relatively lower production costs in the absence of emissions penalties. In contrast, the **Stated Policies** S**cenario (STEPS)** incorporates the commitments under Qatar Nationally Determined Contribution (NDC) and Qatar National Climate Change Action Plan 2030 (MECC, 2021). Under this pathway, explicit carbon constraints are introduced to reduce system-wide emissions by 25% by 2030 onwards. A third scenario, **Net Zero 2060 (NZ60)**, aligns with the carbon-neutrality timelines of regional peers such as Saudi Arabia and Kuwait, representing a delayed yet comprehensive decarbonisation trajectory that examines the long-term implications of a deep-transition strategy for Qatar.

The comparative scenario design enables the system to endogenously decide between LNG, ammonia, and liquid hydrogen as competing export commodities, thus revealing the trade-offs between cost competitiveness and emissions mitigation. In practice, the absence of a carbon budget perpetuates LNG dominance, whereas the progressive imposition of carbon constraints accelerates investment in lower-carbon energy commodities. Table 5.5 summarises the techno-economic assumptions underpinning these pathways as extracted from references such as QNRES (2024), The Peninsula (2024), The Peninsula (2025), Enerdata (2024), QNA (2022), and QAFCO (2022). It also provides the analytical foundation for interpreting results presented in subsequent sections.

Table 5.5: Synoptic overview of scenarios design for MUSE-HiQ.

Scenarios	Baseline	STEPS	NZ60
Description	Business-as-Usual	Stated Policies	Delayed Net Zero to 2060
Environmental constraint	None	25% emissions reduction by 2030 relative to BAU	Tapered emissions reduction towards zero by 2060
Power mix	Fossil-fuelled turbines	Solar: 4GW by 2030, current 5% to 18% by 2030, QatarEnergy:875MWp in 2024, 2GW in 2030 CCGT: current 80% to 72% in 2030 OCGT: current 4% to 3% in 2030	
CCS uptake	None	2.2 MTPA LNG CCS 11 MTPA 2030	
Blue Ammonia	None	1.2 MTPA blue ammonia by 2026 QAFCO (F)	
Transport electrification	None	EV 10%, EBUS 100% in 2030 onwards	
Water desalination	unconstrained	RO 55% by 2050	

5.3 Results and discussion

This section offers a comprehensive analysis of Qatar potential export pathways in a hydrogen-oriented future. The analysis evaluates LNG, ammonia, and liquid hydrogen under varying demand trajectories to understand the system's economic competitiveness and emissions footprint. The results highlight when it becomes optimal to shift between commodities, how existing infrastructure is utilised or challenged, and what this implies for Qatar ability to sustain its position as a leading energy exporter.

5.3.1 Competing fuels and cost parity

The findings reveal how the relative competitiveness between LNG, hydrogen, and ammonia evolves under varying demand conditions and carbon price trajectories. Generally, LNG remains a strong export commodity under a model-implied carbon price threshold of approximately 90-100 USD/tCO_2. Beyond this switching point, the rising carbon cost steadily erodes LNG's competitive edge, enabling hydrogen to consolidate

its role in exports. Importantly, this threshold represents an endogenous competitiveness breakpoint signalling the level at which policy intervention becomes necessary, particularly following the enforcement of post-2030 carbon budgets. In the absence of such policy signals, structural diversification toward hydrogen may be delayed.

Under the **STEPS** moderate emissions reduction target, hydrogen exports first emerge in 2035, coinciding with the retirement of existing LNG liquefaction plants. This milestone marks an anticipated entry of hydrogen into international markets (IEA News, 2025), with Qatar contributing through its existing hydrogen production capacity ~1.20 MTPA. The transition creates a window for investment in hydrogen production technologies across both lower- and upper-bound demand trajectories.

At the lower energy-demand bound, hydrogen exports are briefly initiated in 2035 at a carbon price of 100 USD/$tCO_{2,}$ continuing only until 2040, in parallel with ongoing LNG exports. During this period, the system temporarily achieves a combined export capacity with hydrogen approximately doubled relative to its current production levels, as defined by the model constraints. Under this demand trajectory, further expansion beyond this level is not economically favoured, leading the model to terminate hydrogen exports and maintain LNG exports supplied through 49% conventional route, and 51% CCS-integrated route, thereby solving for a system configuration that meets the enforced moderate carbon cap.

At the upper energy-demand bound, hydrogen exports are also initiated in 2035, but only at a substantially higher carbon price of 460 USD/tCO_2, occurring mainly toward the end of the modelling horizon. This outcome reflects the continued persistence of LNG, which remains economically resilient and cannot be displaced unless environmental costs rise sharply in tandem with growing global energy demand. Even at a carbon price of 140 USD/tCO_2, LNG retains its competitiveness and cost-efficiency during the early investment periods, reinforcing its persistence as the preferred export commodity under moderate climate targets.

The high carbon price effect is also observed in the IEAGHG Technical Report (2022), where the displacement of grey hydrogen production toward blue hydrogen production is largely subject to carbon prices which in some scenarios reach ~264 USD/tCO2 for the context of Netherlands.

These results indicate that under moderate climate targets and lower international energy demand, LNG retains a strong market advantage. Conversely, under higher demand conditions combined with escalating carbon costs, hydrogen begins to compete with LNG, initially co-existing within the export mix until around 2045, when hydrogen progressively overtakes LNG as both the market and export infrastructure are assumed to have matured. Figure 5.2 illustrates the projected export mix under the STEPS scenario.

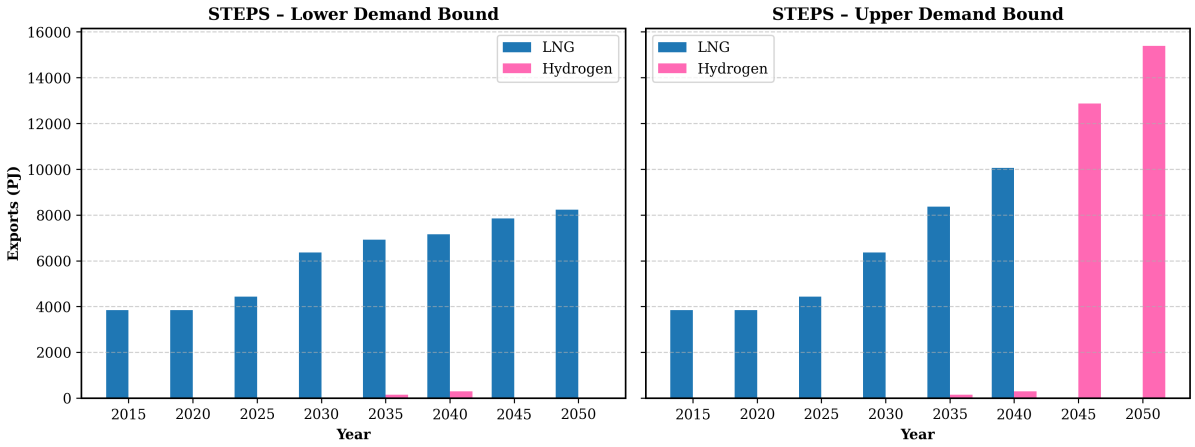


Figure 5.2: Export mix evolution under the STEPS scenario. On the left: STEPS pathway with low global energy demand bound. On the right: STEPS pathway with high global energy demand bound.

Deeper carbon constraints in the **NZ60 pathway** gradually shift the system's balance toward hydrogen. By 2040, a pivotal inflection occurs when LNG emissions are priced, and hydrogen reaches cost parity with LNG at a carbon price of approximately 90 USD/tCO_2 under the lower-demand case and 130 USD/tCO_2 under the higher-demand case. Before this milestone, at around 70 USD/tCO_2, LNG remains the dominant export fuel. However, the existing hydrogen production capacity of ~1.20 MTPA is yet insufficient to establish cost competitiveness prior to 2040, as meaningful export activity materialises only once capacity doubles. This finding underscores the necessity of

upstream capacity expansion as a prerequisite for hydrogen to emerge as a viable energy export commodity under stringent carbon budgets. Hydrogen attains full cost parity in the subsequent timesteps once the binding capacity constraints are relaxed enabling unconstrained investment and large-scale deployment within the system. Figure 5.3 illustrates the projected export mix under the NZ60 scenario showing similar sectoral evolution under upper and lower demand trajectories signifying the prioritised carbon budget lever in this scenario.

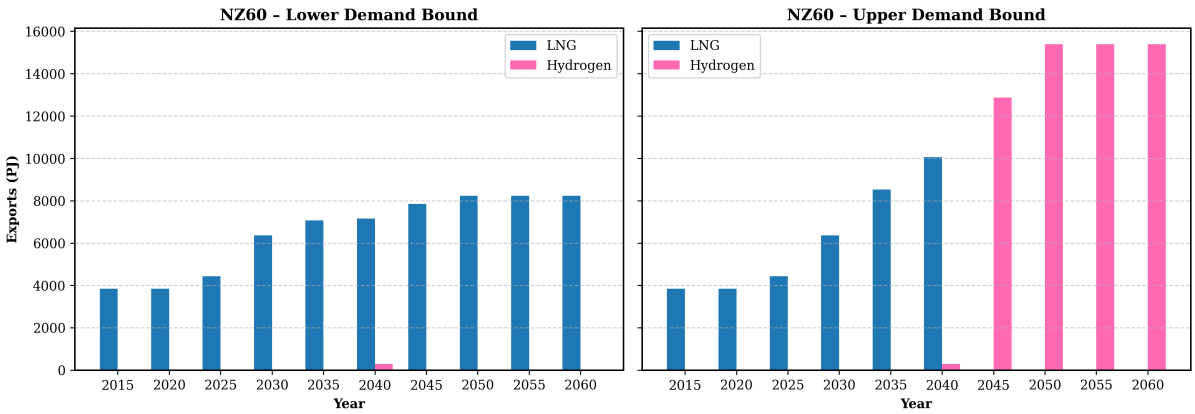


Figure 5.3: Export mix evolution under the NZ60 scenario. On the left: NZ60 pathway with low global energy demand bound. On the right: NZ60 pathway with high global energy demand bound.

Ammonia, by contrast, remains economically uncompetitive even as the reiterative simulation drives the carbon price to extreme levels in the effort to achieve net-zero by 2060. This outcome suggests the structural challenge of repositioning ammonia from its established role in fertiliser markets to that of an energy commodity, as its cost profile prevents it from matching the competitiveness of LNG or hydrogen under stringent decarbonisation policies. A notably different outcome is reported in Okonkwo et al. (2021), whose study indicates that blue ammonia in Qatar can compete as an export commodity with blue hydrogen until the cost of green hydrogen declines sufficiently. These results stem from the assumption that ammonia serves as a fuel in end-use applications such as power plants and maritime transport. Consequently, future

research could expand on this perspective to reassess and challenge prevailing conclusions in the literature.

These carbon price trajectories indicate that, under moderate mitigation conditions, hydrogen deployment requires stronger economic incentives than under the NZ60 pathway. In this context, a relatively steep carbon tax serves as the principal driver of competitiveness, enabling hydrogen to reach cost parity with fossil-based exports. Conversely, under a carbon-neutral framework, the progressively tightening carbon budget drives system-wide deep decarbonisation more collectively and rapidly. This dynamic reduces the need for extremely high carbon prices, as the model endogenously prioritises low-carbon alternatives to meet the emissions cap. Consequently, the persistence of fossil-based technologies diminishes naturally, reflecting a structural transition guided by policy ambition rather than by price escalation alone.

5.3.2 Shifting the production paradigm

In the **STEPS lower-demand bound trajectory**, LNG exports remain the dominant pathway throughout most of the modelling horizon, with only a short-lived window of hydrogen exports between 2035 and 2040. By 2050, within the processing sector, natural gas consumption increases by just 2% relative to the baseline scenario, largely due to integration of CCS in producing low-carbon LNG. Other observed marginal increases in natural gas consumption are linked to internal system decarbonisation measures and are therefore excluded from the analysis of export competitiveness.

In this pathway, hydrogen is supplied exclusively as blue hydrogen derived from autothermal reforming (ATR) with carbon capture and storage (CCS), amounting to 150 PJ in 2035 and 300 PJ in 2040. Its production for market entry is triggered by a feasible LCOE of around 12.0 USD/GJ, which outperforms SMR-CCS at 19.5 USD/GJ and its higher-cost variants whose values increase under carbon price pressures, such as conventional emitting technology, or due to the additional costs associated with direct air capture (DAC) integration. However, beyond 2040, hydrogen exports become

economically stranded and displaced by LNG, which maintains production cost-competitiveness at LCOEs of 8.5 USD/GJ for conventional routes and 7.5 USD/GJ with CCS integration. Figure 5.4 depicts the production routes at the conversion sector of Qatar energy system.

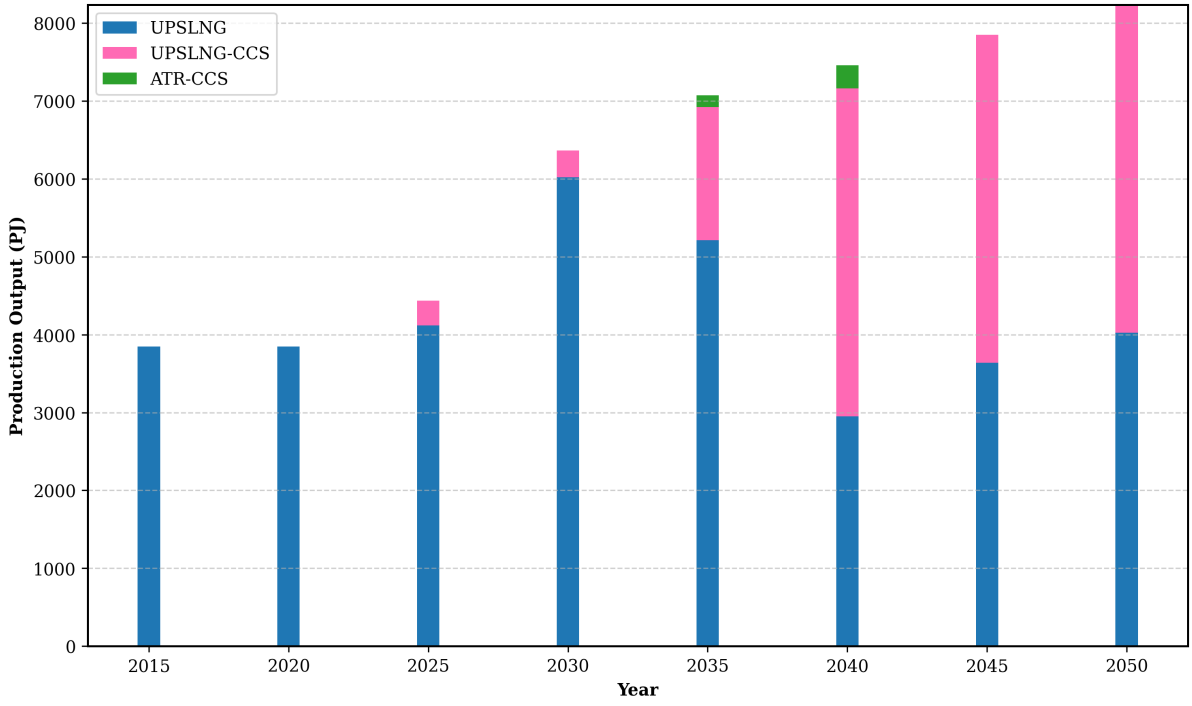


Figure 5.4: Production routes at the conversion sector under the STEPS scenario for the lower energy demand case.

In the **STEPS upper-demand bound trajectory**, hydrogen exports are initiated in the same 2035-2040 window observed in the lower-demand case but continue to expand thereafter, eventually displacing LNG as the dominant export pathway by mid-century. The gradual reduction in LNG exports is offset by rising hydrogen exports, resulting in a 5% decline in natural gas consumption in the processing sector by 2050 relative to the baseline scenario. This reduction translates into savings of approximately 900 PJ of natural gas, which can either be redirect towards domestic decarbonisation measures through powering carbon removal utilities or preserved as reserves.

By 2050, around 84% of the system's total natural gas output is channelled into hydrogen production for export, emphasising the pivotal role of natural gas in enabling a hydrogen-based transition pathway. This shift is driven by the cost competitiveness of ATR-CCS hydrogen production, which achieves an LCOE of ~12.3 USD/GJ, significantly undercutting SMR-CCS at ~20.2 USD/GJ and its higher-cost variants under carbon pricing conditions. These values are comparable to the literature values where low carbon ATR is reported at ~12.7 USD/GJ in the US DOE (2024), and at ~20.2 USD/GJ in the IEAGHG Technical Report (2022), however, these values are highly dependent on carbon prices and calculation assumptions.

These cost dynamics make ATR-CCS the preferred pathway, ensuring hydrogen can progressively replace LNG as Qatar's primary export commodity under moderate emissions cap and high energy demand case. Figure 5.5 depicts the production routes at the conversion sector of Qatar energy system.

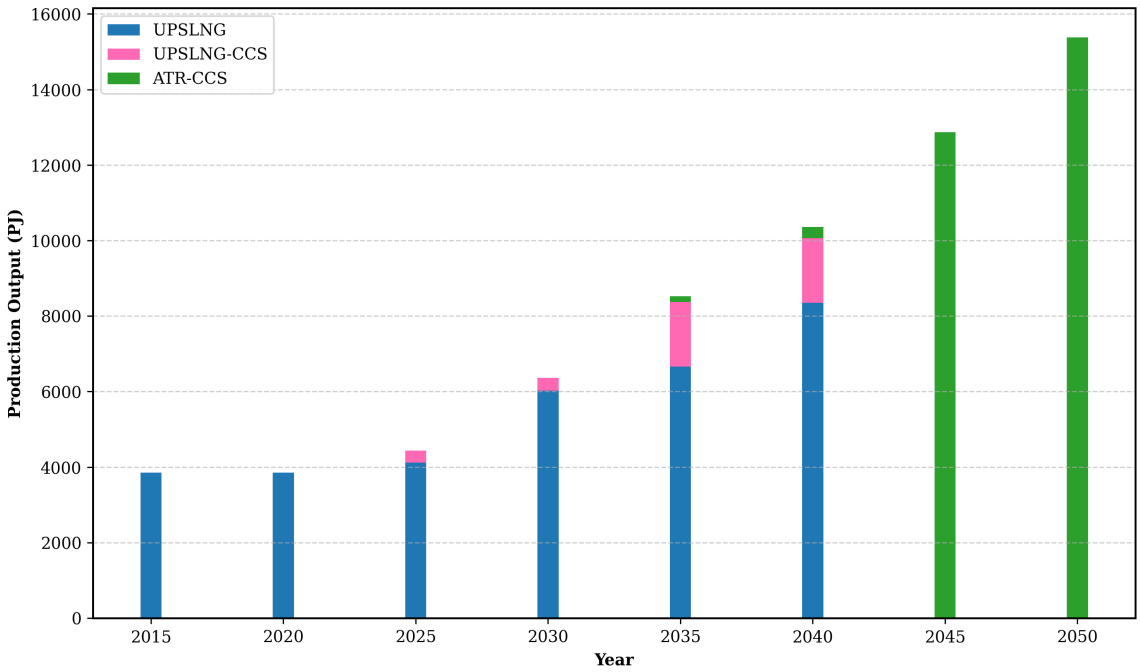


Figure 5.5: Production routes at the conversion sector under the STEPS scenario for the upper energy demand case.

Under the **NZ60 scenario**, LNG with CCS continues to expand progressively until 2040, accounting for 17-24% of total LNG output, at lower- and upper- energy demand trajectories respectively, before being fully phased out as hydrogen emerges as the dominant export commodity by 2045. This transitional trajectory effectively provides a 10-year operational window for QatarEnergy's North Field expansion projects, which is planned for 2030, to operate at scale prior to the structural reconfiguration of the export portfolio away from LNG and toward low-carbon hydrogen exports.

As hydrogen exports begin to materialise later in the time horizon at around 2040, autothermal reforming (ATR) with CCS emerges as the preferred production pathway, achieving an LCOE ~10.0 and 10.1 USD/GJ, and outperforming steam methane reforming (SMR) with CCS, which reaches ~15.0 and 15.5 USD/GJ, under both lower- and higher-demand cases, respectively. Consequently, ATR-CCS supplies the entirety of the hydrogen export load at this stage.

Nevertheless, under the NZ60 lower-demand case, a full transition to hydrogen requires a production capacity expansion of approximately 12% relative to current QatarEnergy LNG expansion plans. In the higher-demand case, however, this requirement multiplies significantly by manifold, with natural gas supply needing to expand by nearly 82% relative to the lower-demand trajectory to sustain hydrogen production.

By 2060, as the carbon budget tightens toward net zero and carbon prices escalate sharply, ATR integrated with direct air capture (DAC) achieves markedly lower LCOE costs of 10.9 USD/GJ in the higher-demand case and 18.6 USD/GJ in the lower-demand case. Nevertheless, this route contributes only a limited share of exports, around 5-9%, constrained by the lock-in effect of previously installed ATR-CCS assets that dominate the system configuration. It also has a negligible impact on natural gas consumption (-2% to 1% variation) relative to baseline scenario. Figures 5.6 and 5.7 illustrate production mix.

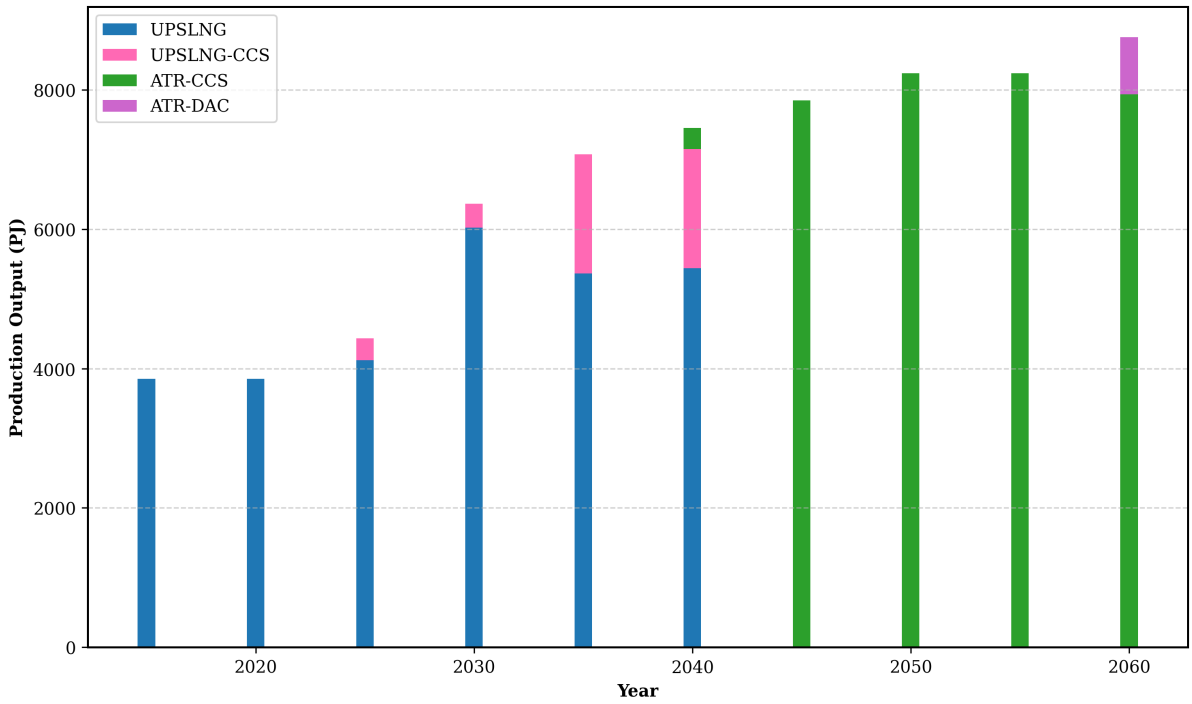


Figure 5.6: Production routes at the conversion sector under the NZ60 scenario for the lower energy demand case.

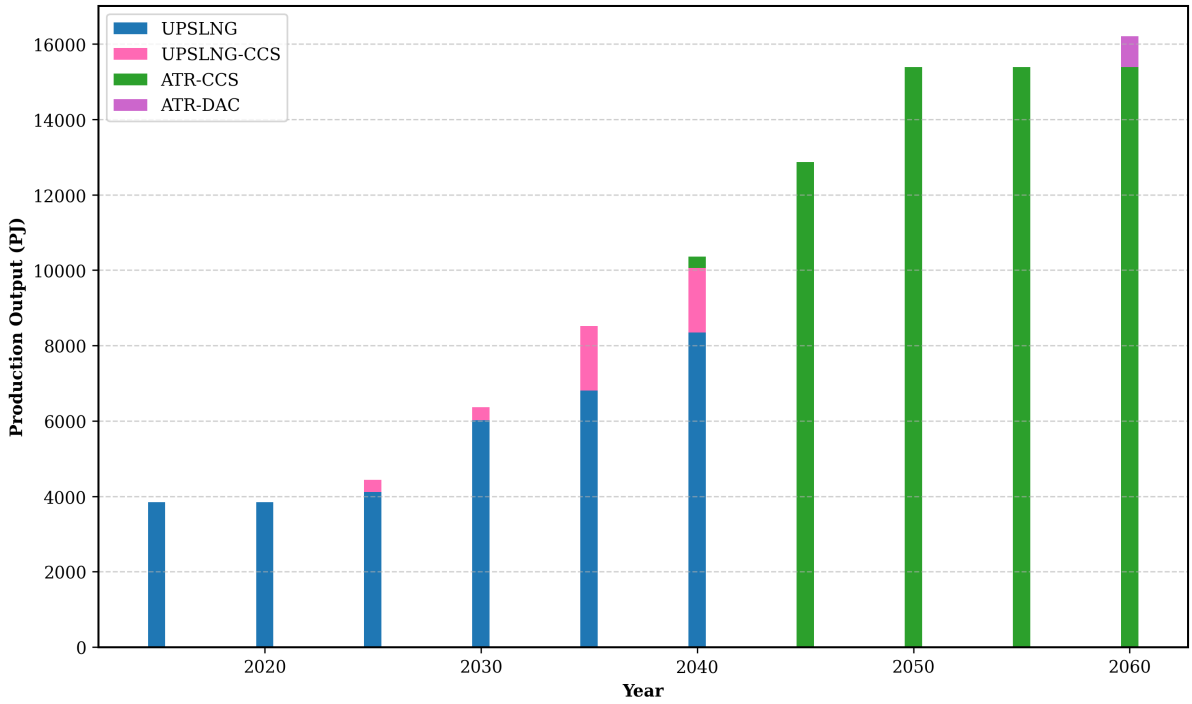


Figure 5.7: Production routes at the conversion sector under the NZ60 scenario for the upper energy demand case.

5.3.3 Future pathways and strategic outlook

Building on the findings from preceding sections, two distinct strategic outlooks emerge for Qatar's energy export future, each shaped by the stringency of emissions constraints and the dynamics of international energy demand trajectories. This modelling sensitivity is exhibited in Chapter 3.

The first outlook is reflected in the STEPS scenario, which aligns with Qatar's current NDC and embodies a moderate emissions-reduction pathway. Under this trajectory, hydrogen assumes only a marginal role within the export portfolio, particularly at demand levels comparable to Qatar's present LNG export capacity. Even as global energy demand rises, LNG retains its dominance and competitiveness well into the 2040s, sustained by its mature infrastructure and established markets. This outcome indicates that stronger policy drivers, more ambitious climate mitigation frameworks, and earlier investment in enabling infrastructure, such as carbon capture, hydrogen transport, and export terminals, would be necessary for hydrogen to make a substantive contribution to Qatar's export mix.

The second, by contrast, is reflected in the carbon neutrality target in the NZ60, which entails a structural transformation of the export portfolio, with hydrogen progressively displacing LNG. Once hydrogen attains economic competitiveness, liquefaction plants are phased out, and natural gas supply is redirected toward hydrogen production through ATR combined with carbon removal. This transition from LNG dominance to hydrogen-centric export mix enables Qatar to diversify its energy products, strengthen system resilience, improve its carbon footprint, and consolidate its position as a long-term supplier of low-carbon hydrogen to key demand hubs in Asia and Europe.

Ultimately, the interaction between demand growth and emissions constraints serves as the defining driver of system reconfiguration. These findings underscore the critical influence of policy design in shaping Qatar's strategic response to global market transformations. Proactive, forward-looking policymaking, coordinated with infrastructure readiness and international market alignment, will determine whether

Qatar transitions smoothly toward a low-carbon export future or remain constrained by its current hydrocarbon trajectory.

5.3.5 Policy and regulation: Trade opportunities

The divergence in the results in the preceding sections underscores the critical importance of closely monitoring global policy signals in shaping Qatar's export outlook. The competitiveness of hydrogen is fundamentally contingent on international carbon pricing schemes, suggesting that the most promising trade opportunities will emerge in jurisdictions with stringent climate policies such as EU Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2025).

Market accessibility is also highly time-sensitive. The findings suggest that Qatar must not only expand its hydrogen production capacity, but also invest in hydrogen-ready export infrastructure. Equally critical is the need to comply with international certification standards for low-carbon hydrogen, such as EU Renewable Energy Directive (REDII) (2023) and Japan Basic Hydrogen Strategy (2023). These conditions are essential if Qatar intends to secure a leading role in the emerging hydrogen market.

However, this strategy carries dual risk as early investment under uncertain demand may result in underutilised infrastructure, while delayed entry risks ceding market share to early movers, notably Saudi Arabia (Shine, 2023). Participation in green corridors and international hydrogen alliances could help Qatar mitigate these risks and capture early-mover advantages.

A set of prioritised near-term enablers are drawn from the findings to mitigate risks pertaining to time and demand uncertainties:

1. **Certification readiness and regulatory alignment**
   Establish a certification system that aligns with international standards such as EU CBAM, RED III, and Japan certification, across oil and gas and industry sectors

with prime stakeholders such as QatarEnergy, QatarEnergy LNG, Qatar Industries, and Ras Laffan, Mesaieed and Dukhan Industrial Cities. Early alignment mitigates carbon-border penalty shocks and sustains export competitiveness.

2. **Hydrogen-ready export infrastructure**

   Establish regulatory guidelines requiring new LNG expansion projects and associated port facilities to incorporate technical adaptability for future hydrogen repurposing. Ensure strategic coordination with QatarEnergy LNG for endorsement and operational feasibility. Asset adaptability will extend the technical lifespan of infrastructure, reduce the risk of premature asset retirement, and preserve investment optionality under progressively tightening climate policy requirements.

3. **CCS scale-up in existing LNG value chains**

   Mandate the progressive scale up of carbon capture capacity in existing oil and gas processing infrastructure, particularly in SMR plants. Mandate the installation of CCS in future technologies such as ATR. Early and sustained deployment would significantly reduce the LNG carbon footprint which can still be exported under the uncertainty of demand scale-up of hydrogen access. This approach will enhance export competitiveness and strengthen the credibility of Qatar energy products, positioning the country as a leading supplier of lower-carbon fossil-based energy commodities during the transition.

4. **Pilot offtake agreements with Asian buyers**

   Secure early pilot offtake agreements and memoranda of understating with key Qatar energy importers, particularly in Asia, to reduce investment risks. This will ensure the dispatch of initial production volumes and will unlock commercial scalability opportunities. Of specific interest, Japan represents a well-suited candidate for Qatari hydrogen evidently in its long-established trade relations with Qatar, and its solid hydrogen outlooks.

5.4 Chapter Summary

This chapter has examined a potential decarbonisation pathway for Qatar energy system that emphasises external drivers shaping its position as a leading energy exporter. The anticipated surge in global hydrogen demand presents Qatar with a strategic opportunity to expand into emerging export market. However, given the considerable uncertainty surrounding the maturation and stability of the hydrogen economy, this study explores the comparative viability of exporting traditional energy commodities, primarily LNG, against hydrogen and its derivatives under varying climate policy scenarios.

This study deploys the recent release of MUSE 1.5.1 to simulate the existing infrastructure of Qatar energy system and to project its evolution under potential decarbonisation pathways. The analysis evaluates the techno-economic dimensions of hydrogen production and export across upper and lower bounds of global demand trajectories. The findings highlight a nuanced export opportunity that not only informs national policy design but also provides a prototype framework for regional energy transition. The results demonstrate that Qatar can pursue local decarbonisation simultaneously positioning itself as a competitive supplier of low-carbon energy commodities to global markets.

The results present a nuanced outlook, shaped primarily by global energy demand trajectories and the stringency of carbon budget constraints. Nevertheless, LNG integrated with carbon capture and storage can sustain its competitiveness and extend its role within the export portfolio under both STEPS and NZ60 scenarios, before being progressively displaced by hydrogen as carbon prices escalate and low-carbon technologies attain market maturity.

These simulated insights are inherently prone to uncertainties rooted in the modelling limitations, input data relevance and learning curves and technology innovation, demand trajectory assumptions. Simplification of the export process represents an area for future development.

Chapter 6

6 Discussion, future work, and conclusion

This discussion chapter consolidates the key findings of the study to critically evaluate decarbonisation strategies and to guide the charting of energy policy. It is grounded in the research questions introduced in Chapter 1, which centre on assessing the transition of Qatar energy system and the robustness of policy measures to support economic stability, environmental sustainability, and system resilience. The rationale underpinning this research lies in its potential to provide evidence-based insights that can inform national policymaking and foster stronger synergies between academic research and policy implementation.

The intricacies of decarbonising a hydrocarbon-intensive system of Qatar stipulates multipronged scrutiny. Model-based analysis in the literature has focused on the optimisation approaches leaving simulation studies unexamined. This thesis bridges this gap by introducing a simulation model for Qatar based on a credible simulation platform of MUSE. To address this challenge, three integrative model-derived policy approaches were examined: Simulation-based scenario analysis; dual-model comparative analysis of simulation and optimisation approaches; and evaluation of potential shift to hydrogen. Layering the insights from this multifaceted approach, draws the conclusion in the following chapter aiming to provide a narrative to signal policy discourse towards sustainable transition.

6.1 Results synthesis and interpretation

This section consolidates key insights from Chapters 3, 4, and 5 to present an integrated discussion of the simulated decarbonisation pathways for Qatar energy system within a scenario-based analytical framework. This discussion delves into the energy system behaviour and responsiveness under varying degrees of decarbonisation ambition,

highlighting how different policy and technology configurations influence transition dynamics. The purpose of this discussion is to outline a strategic pathway for enhancing Qatar's environmental performance while sustaining economic resilience. Strengthening the sustainability of the national energy system will, in turn, enhance Qatar's competitiveness in the global market for low-carbon and cleaner energy products.

The simulation model in Chapter 3 illustrated the performance projectile of the current energy system of Qatar, encompassing the entire supply and demand chain under varying emissions reduction targets. The results reveal that current policy framework, aligned with the NDC target, lacks sufficient momentum to achieve its intended emissions-reduction objective within both the near-term and long-term planning horizon. For example, the current solar power capacity contributes to less than 1 $MtCO_2$ reduction annually, leaving nearly 18.4 $MtCO_2$ of unabated emissions within the system. This gap drives the model to introduce carbon capture and storage (CCS) as a mitigation mechanism to meet the national target.

Investment in CCS, however, is only activated once the carbon price reaches a relatively high threshold of around 210 USD/tCO_2; the point at which the LCOE of carbon-intensive technologies becomes sufficiently elevated to render low-carbon alternatives more economically attractive. These finding highlights both the cost-efficiency and competitiveness of fossil-based technologies in Qatar's energy system, which remain economically viable at lower carbon price levels associated with more relaxed carbon budget under the NDC scenario. Moreover, the persistence of existing installed capacities, which cannot be prematurely decommissioned due to asset lock-in effects, reinforces the continued dominance of these technologies in the short to medium term.

The model indicates that this in investment trigger is only reached once the emissions budget constraint becomes active in 2030, emphasising the critical importance of early policy intervention and the necessity of aligning investment signals with long-term carbon reduction objectives. Early uptake of CCS provides a sustained emissions benefit toward mid-century, as these units operate throughout their full technical lifetimes, offering a financially prudent yet environmentally effective mitigation option.

Under the combined influence of solar energy penetration and carbon removal integration, other decarbonisation levers, such as transport sector electrification, are temporarily deprioritised within the system's transition sequence. This outcome does not imply that the transport is less significant to decarbonise; rather, it reflects a strategic sequencing of priorities, allowing additional time for infrastructure readiness, technological maturation, and social adaptation to large-scale electrification. Within this context, the moderate emissions-reduction target can still be achieved cost-effectively through upstream interventions that deliver immediate and scalable environmental gains.

The analysis also explored system evolution under a more stringent decarbonisation pathway, represented by the NZ50 scenario, the model encounters significant technical challenges, steep investment barriers, and critical trade-offs between emissions reduction and the uptake of costly low-emissions technologies. The steeply tapered carbon budget towards neutrality by mid-century, successfully decarbonises all service demand sectors. This is achieved through full electrification in the transport, residential, and commercial sectors, alongside early scale-up of CCS in industry, oil and gas production, and processing sectors.

However, this progress comes at the expense of substantial investment in direct air capture (DAC) to offset residual emissions from CCS-equipped utilities. The pivot towards DAC occurs under a very high carbon price. Even when the carbon price escalates beyond 920 USD/tCO2, the model achieves only negligible additional emissions reduction, largely due to the persistence of previously commissioned emitting capacities that cannot be retired prematurely.

This behaviour emphasises that enhancement to existing policy framework is essential. Without early, well-aligned measures, the system risks facing radical investment burdens compressed into a limited timeframe. Moreover, despite this radical shift towards carbon removal, DAC routes in the oil and gas processing sector contribute to only ~50% of production or less, leaving petroleum products with improved, yet still costly, carbon

footprint. This raises fundamental questions about the feasibility of upfront capitalisation in DAC technologies, particularly in the context of Qatar's export-oriented energy system. Rather than committing to large-scale DAC deployment at prohibitive costs, the more viable pathway is to invest strategically in pilot projects that accelerate learning curves and technology innovation, while gradually improving the economic viability of carbon removal.

At the same time, Qatar can leverage its comparative advantage in CCS integration by coupling capture technologies with existing refinery, LNG, and GTL infrastructure, thereby supplying the market with cleaner fuels at a lower cost than full-scale DAC. In parallel, fuel switching options, as discussed in Chapter 5, can complement these efforts by diversifying the technology mix and reducing reliance on any single pathway. In this way, Qatar can pursue a balanced and adaptive transition strategy, maintaining competitiveness in global energy markets while building the technological foundation for deeper decarbonisation in the long term.

Furthermore, the comparative scenario analysis between MUSE model and TIMES model in Chapter 4 reveals the modelling formulation underpinnings of the simulation and optimisation paradigms that control investment direction. This analysis validates modelling findings and elucidates areas of discrepancies, offering a more robust synthesised insight into the decarbonisation outlook, and underscoring the importance of methodological choice in shaping investment pathways.

For a harmonised representation of Qatar energy system, both models converge on the limited impact of existing policy-driven strategies in meeting near-term emissions reduction targets under the NDC scenario. By 2030, emissions decline by only 5% relative to baseline, compared to the targeted 25% reduction. This shortfall is primarily driven by modest interventions such as the planned addition of 0.8 GW of solar capacity, in addition to electrification of transport including 10% and 100% penetration rates of electric vehicles and electric buses, respectively.

In response to this gap, both MUSE-QA and QT-TIMES allocate investment towards carbon removal technologies in emissions-intensive sectors, particularly industry and upstream oil and gas. This convergence is underpinned by distinct modelling logics; while TIMES prioritises global optimal capital allocation under perfect foresight, MUSE seeks to minimise marginal environmental costs by favouring technologies with lower LCOE values under imperfect foresight.

The distribution of capture capacity also reflects these structural differences. In MUSE-QA, carbon capture capacity reaches 25 MtCO2 per annum, almost exclusively concentrated in the industrial sector. By contrast, QT-TIMES achieves a similar total capacity of 26 MtCO2, but distributes it more broadly across upstream and industry sectors. This highlights TIMES greater flexibility in retrofitting and reallocating carbon removal across system nodes, while MUSE's agent-based formulation tends to concentrate mitigation in the most cost-effective subsectors.

In the power sector, both models converge on the importance of scaling up solar capacity as a means of reducing the carbon footprint, but they diverge in the magnitude and trajectory of this transition. In MUSE-QA, limited foresight of market dynamics and reliance on LCOE as the primary investment metric drives agents to capitalise on the zero-cost solar energy commodity price relative to natural gas in fossil-fuel power plants. This behaviour gradually expands solar capacity to supply 23% of the power mix by 2050, with an average addition of 2 GW at each timestep. Conversely, QT-TIMES, which operates under perfect foresight and incorporates full knowledge of commodity prices and market evolution, allocates capital more aggressively towards renewables. As a result, solar penetration accelerates to 31% of the power mix, supported by an average increase of 3 GW at each timestep. This reflects TIMES ability to strategically distribute capital across the system to maximise long-term optimisation rather than short-term cost-minimisation.

Under the NZ50 scenario, projections for neutrality by 2050 reveal diverging investment strategies that reflect the fundamental differences between simulation and optimisation paradigms. Carbon capture capacity rises sharply, reaching 209.5 MtCO2 in QT-TIMES

compared to 178.9 MtCO2 in MUSE-QA by 2050. Two key insights emerge from this comparison. First, the path-dependent nature of MUSE prevents the premature phase-out of legacy assets, resulting in residual emissions from CCS-equipped plants that persist in the system. Second, QT-TIMES, through its capacity to optimise allocation, distributes capture more strategically; capturing 180.2 MtCO2 through CCS and 29.3 MtCO2 through DAC, demonstrating how the timing and scale of carbon removal investments critically shape the feasibility of meeting climate targets. This underscores the importance of early adoption of low-carbon alternatives, which reduces the risks associated with stranded assets and alleviates the cost burden of abrupt system transitions.

A substantial portion of captured volumes in both models is concentrated upstream, signalling a structural reallocation of the decarbonisation burden within the energy system. The growing electricity and natural gas demand required to sustain low-carbon supply chains effectively pushes mitigation responsibilities back to the extraction and processing stages of the system. For Qatar, this modelling outcome reinforces its responsibility to decarbonise export commodities, particularly LNG and petroleum derivatives, if it is to maintain market competitiveness in a global landscape increasingly governed by stringent carbon regulations.

These dual-model insights provide deliberative weightings of the trade-offs between environmental ambition and economic considerations, offering a nuanced understanding of investment incentives and system behaviour. While both models validate one another's outcomes, they collectively highlight the underlying drivers of investment decision-making within constrained policy environments. The findings suggest that setting emissions-reduction targets supported by coherent investment strategies can yield significant improvements in the national carbon footprint. However, overly stringent carbon constraints may inadvertently escalate system costs, strain existing infrastructure, and accelerate reliance on nascent technologies such as direct air capture (DAC). This dynamic risks reinforcing lock-in effects, whereby legacy fossil-based capacities remain entrenched, necessitating disproportionate carbon-removal investments to meet aggressive mitigation targets.

For hydrocarbon-dependent economies such as Qatar, these findings demonstrate that transition at the service demand side, such as transport, residential, and commercial sectors, inevitably transfers energy burden to the supply and conversion sectors, intensifying pressure on generation infrastructure and increasing reliance on fossil fuel to manage upstream emissions. The results also highlight Qatar potential role in supplying cleaner export fuels while navigating balanced impact across the energy trilemma of security, affordability, and sustainability.

Building on this foundation, the hydrogen pathway explored in Chapter 5 extends the analysis by evaluating how hydrogen could redefine Qatar's export portfolio under tightening global emissions constraints, offering a forward-looking perspective on sustaining competitiveness in low-carbon energy markets.

The promotion of clean fuels as competitive low-carbon energy commodity in the global market is examined in Chapter 5, which evaluates the implications of a disruptive global shift away from fossil fuels, particularly natural gas, toward hydrogen-based energy systems. The analysis highlights that fossil-derived hydrogen coupled with carbon removal, blue hydrogen, can play a pivotal transitional role in sustaining market supply and supporting gradual decarbonisation. The findings further emphasise the continued viability of LNG within a moderate carbon budget, particularly when integrated with CCS technologies.

The findings demonstrate that hydrogen market entry occurs only at substantially high carbon prices, ranging between 420-460 USD/tCO2, briefly under low-demand conditions, and competes more markedly with LNG in the high-demand case until it fully displaces LNG by 2045, underscoring the persistence of CCS natural gas as both economically viable and its continuity as an effective fuel nearer 2050. This outcome suggests that two critical levers, energy demand growth and the stringency of the carbon budget, collectively drive the timing and scale of the shift toward hydrogen, with both factors heavily influenced by international market signals and export demand trajectories.

This is more pronounced under the net-zero (NZ60) scenario, where the transition accelerates rapidly once hydrogen production capacity doubles, enabling its market at a comparatively moderate carbon price of 90-130 USD/tCO2. Under these conditions, LNG and LNG-CCS production routes remain competitive only if hydrogen production progresses gradually and carbon prices stabilise around 70 USD/tCO2. However, by 2045, as carbon budget tightens further, hydrogen expands at scale, progressively displacing LNG as the dominant export fuel.

Under current scenario assumptions, ammonia does not become competitive with LNG and hydrogen on the basis of production cost efficiency. This finding is challenged by studies such as Okonkwo et al. (2022), who introduce an additional layer of assumptions that render ammonia economically attractive for Qatar export portfolio, particularly when end-use applications are incorporated into the analysis. However, other studies, while recognising ammonia as a potential early enabler of the hydrogen market, do not explicitly model ammonia trade. Instead, they focus on the broader spectrum of hydrogen production pathways that are gaining momentum in the literature (US DOE, 2022) and relevance to fossil-based economies (Qiu et al., 2024). Collectively, these studies highlight the ongoing debate regarding ammonia's long-term role in the hydrogen economy and its competitiveness under evolving market and policy conditions.

These results indicate that Qatar's existing export infrastructure, which remains heavily dependent on LNG, may face structural disruptions arising from market transformations if global carbon constraints are introduced abruptly. This underscores the strategic imperative for early diversification, particularly through investment in hydrogen-ready infrastructure and the development of low-carbon export capabilities, to maintain competitiveness and resilience within a rapidly decarbonised international energy market.

For hydrogen to replace Qatar's current LNG export capacity, a substantial structural scale-up in production, let alone the associated storage, transport, and export infrastructure, will be indispensable. Even under a delayed NZ60 pathway, the transition window remains narrow and technically challenging, requiring significant coordination

across industrial and policy domains. Consequently, continuous monitoring of international market signals will be essential to progressively secure Qatar's export position at its current capacity levels and to expand strategically as the hydrogen market matures. This proactive and adaptive approach will enable Qatar to navigate evolving global market dynamics, mitigate the risks of sudden disruption, and align its export strategy with the emerging low-carbon energy landscape.

6.2 A roadmap

Building upon the converged investment signals observed across the QT-TIMES and MUSE-QA modelling results, a robust basis for a near-term transition roadmap can be established. Over the next 5 to 10 years, priority should be given to actions that simultaneously support cost optimality and reflect market realities under emissions mitigation commitments.

The first five-year phase (2025-2030) should focus on implementing the mitigation measures outlined in the NDC and NDS strategies through the establishment of enabling regulatory frameworks. These include strengthening monitoring, reporting and verification (MRV) systems to track emissions from existing assets, deploying the 1 GW of solar capacity following the inauguration of Al Kharsaah solar power plant, and incentivising or mandating the adoption of low-emissions technologies. Additional near-term actions include the continued electrification of public transport, particularly the transition to fully electric public buses, thereby preparing the existing infrastructure to accommodate progressive decarbonisation measures.

The subsequent five-year phase (2030-2035) should prioritise the large-scale roll-out and integration of mitigation measures across the broader energy system. This includes the deployment and expansion of carbon-capture infrastructure across oil and gas processing and industrial sectors to reach at least 25 $MtCO_2$ of capture capacity, increasing the solar share to at least 19% of the electricity mix, and achieving at least a

10% diffusion rate for private electric vehicles through targeted policy mandates and incentives.

This integrative policy approach ensures that near-term emissions reductions align with NDC targets while simultaneously establishing infrastructure capable of supporting deeper long-term decarbonisation. Such an approach reduces transition risks, and minimises technology lock-in, while maintaining flexibility to respond to potential tightening of domestic mitigation targets or evolving carbon-related pressures in export markets.

6.3 Future direction and policy recommendation

This section outlines a set of strategic insights stemming from key findings of this thesis. The purpose of drawing a comprehensive conclusion is to propose concise policy action that adeptly captures the intricacies of transitioning the hydrocarbon-based system of Qatar in alignment with its accentuated sustainability targets.

Technical: Accelerate early uptake of energy-efficient and low-emitting technologies

A deliberate decommissioning of energy intensive vintage technologies at or about its economic life limit is pivotal to clear space for more efficient technology uptake. The simulation results have shown that existing capacities can delay new technology uptake resulting in total emissions above the targeted borderline and pushing for costly capitalisation in new technologies later in the timeline.

As a progressive step, a mandate must be enacted to shrink vintage capacity at energy and emissions intensive sectors. This would attract technology advancement and accelerate learning curves to compensate for capacity shortcomings, making transition a more economically prudent pathway.

The milestone of 2030 represents a turning point on the system performance which its impact can extend through 2050. As most of the current assets reach its economic limits

by 2030, it represents a golden opportunity for early transition action. The simulation often upscales conventional technology capacity without aggressive efficiency policy. Thus, early improvement to energy efficiency across sectors can yield energy and capital savings on the long run. To effectively implement this, policy must be shaped to strengthen energy efficiency standards for industrial plants, residential and commercial buildings, cooling systems, and deploy energy audits with incentives for retrofits.

Technical: Accelerate renewable energy deployment and electrification

Also, electrifying end-use service demands, particularly in the transport, industry, and water desalination sectors, represents a strategic opportunity to decouple energy consumption from fossil fuel dependence. In the transport sector, this involves electrifying public transport, scaling up electric vehicles penetration, and developing charging infrastructure to displace gasoline and diesel hubs. In industry, electrifying low- to medium- temperature processes can reduce emissions while enhancing energy efficiency. For water desalination, shifting away from thermal processes to electricity-powered technologies like reverse osmosis systems can substantially reduce the sector's energy intensity. To achieve this, regulatory framework is necessary to incentivise transition through coordinated planning to ensure system reliability and readiness.

Thereafter, displacing system energy requirements on the power sector is another opportunity to enhance the environmental footprint and system resilience by reducing fuel dependency and thermal burden. By integrating solar power with storage within the grid, Qatar can benefit from the abundant solar irradiance, can overcome inherent intermittency, reduce peak load, and supply utility scale projects. The simulation results show impetus to ramp up solar share in the system for its low-cost and rapid deployable potential. This step must be taken at a governmental level by commissioning Kahramaa to conduct feasibility studies, to accentuate solar share in the power mix, and to establish pilot projects for various energy service outlets. This approach will effectively reduce energy and emissions intensity of the power sector, augmenting natural gas reserves. Also, by adopting this renewables pathway, Qatar can lead the environmental stewardship in the region and set example for hydrocarbon-dependent economies.

Economic: Introduce a penalty mechanism

The simulation outcomes demonstrated that fossil options remain dominant unless externalities are priced in. Internal carbon pricing can shift investment priorities towards mitigation alternatives. Therefore, in tandem with energy transition as elaborated previously, policy should enforce a carbon price to penalise ongoing carbon-intensive capacities as early as 2030 milestone. By penalising emitting assets and increasing financial barriers for operation continuation of carbon intensive capacities, alternative technologies become more appealing to reduce dependency on costly fuel and to avoid marginal environmental cost.

Emphasising the interplay between operational costs and entailed environmental impact, it is necessary to materialise the financial facet, shaped by considerations including declining efficiency against asset age, fuel input intensity, and fuel type and emissions intensity. For example, capitalising in hydrogen-fuelled trucks would reduce upstream diesel production and consequently reduce both refining and transport emissions, while upscaling new hydrogen production technologies which are less energy intensive compared to vintage capacities.

To implement this, a clear penalty framework should be coordinated with stakeholders such as QatarEnergy, Kahramaa, and other entities. This penalty can be used to support pilot projects for transition, subsidise utility-scale technology adoption, and knowledge transfer and capacity building. Targeting such stakeholders which have direct interfaces to international markets; such as global importers of Qatari LNG and regional electricity buyers through the GCC grid, positions Qatar at the forefront for sustainability leadership, while enhancing the competitiveness and appeal of Qatari energy products in both regional and global markets.

Strategical: Develop a climate policy and align national development strategy with decarbonisation goals

In support of the strategies put forward in this section, a holistic policy discourse is necessary to navigate the transition challenges. A framework must be rigorously composed cascading clear national climate targets and standards, identifying key

objectives and actions, promoting new technology uptake, and heeding towards the substantive emissions effect. Efforts must be galvanised to support energy efficiency at the service demand sectors. This could include energy consumption monitoring, adoption of domestic solar power, informative sessions at schools and universities to address the environmental situation and fostering capacity building through encouraging students to create and innovate solutions at a household and community levels, in addition to encouraging and benefiting from national research base. Targeting the consumer, especially the young generation, will not only improve quality of life, but will also reduce the burden on upstream fuel production and power generation which in turn will sustain the natural gas endowment from aggressively rapid depletion.

By forging integrative policy approach, regular updates and revision are essential to respond to ongoing changes in the energy and climate landscape. Such dynamic approach offers flexibility to adjust and press on the emissions cap over targeted milestones which can ultimately accelerate implementation of climate targets and attract more ambitious goals.

Strategic: Adopt a phased and flexible decarbonisation strategy

The findings of this part of the study suggest that careful planning and thorough understanding of the modelling drivers are central to account for the uncertainty of the future and to avoid the risk of ambitious overplanning. Hence, strategic timing in transitioning to low-carbon investments is more pronounced in the optimised pathway; delayed transition, as depicted in the simulated pathway, could most probably incur higher capital costs towards the end of the modelling horizon undermining smooth progression and prudent economic transition. This must be coupled with a comprehensive framework that dictates capital distribution across the system. The simulation result augments investments in low fuel cost technologies based on LCOE values unlike the optimisation results which shows flexibility in integrating new technologies when it becomes cots effective.

To optimise economic and environmental gains over trade-offs, research efforts must be galvanised to conduct more validation analyses as this one to identify key areas for

effective decarbonisation. This study showed that both models agree that the industry and oil and gas processing are the most cost-effective sectors for early decarbonisation. Therefore, policy must support focused and centralised decarbonisation by incentivising deployment of CCS and electrification of hard-to-abate pipelines through financial incentives, regulatory frameworks and R&D funding.

Further regulatory efforts must be shifted towards enabling infrastructure readiness and receptivity of decarbonisation options in the service demand sectors such as future penetration of electric vehicles and necessary charging stations, penetration of hydrogen trucks and fuelling stations, electrification of water desalination, and ultimately support scaling up of renewables integration with the grid.

Policy should therefore prioritise early low-cost mitigation options while preserving flexibility to integrate future technologies, avoiding premature lock-ins or costly retrofits. It must also avoid overreliance on singular perspective and aim for farsighted equilibrium between emissions reduction and costs.

Strategic: Enhance institutional capacity for adaptive policy design

The foresight assumptions, myopic in simulation modelling and perfect in optimisation modelling signal diverging investment direction. While TIMES lean on progressive carbon removal uptake and gradual solar upscale due to its long-term foresight, MUSE invests in technologies that satisfy the short time step emissions requirement which leads to lock-in effect and large capital investments later on the timeframe. Owing to the complex and uncertain dynamics of system evolution and investment drivers, policymakers should be aware of the inherent uncertainty to avoid over-investing in costly and uncertain technologies by ensuring balanced mitigation portfolios. The contrast in foresight assumption emphasises that policy must adapt dynamically to market reforms by establishing a mechanism for regular review and revision of decarbonisation strategies, including liaison with stakeholders to ensure consistency.

Strategic: Maintain energy security and system reliability while transitioning

Both models underlined the prominent role of natural gas in meeting climate goals. Coupling fossil-based generation with carbon removal emphasises the transitional role

of natural gas while safeguarding system reliability and export competitiveness. Regulations must take place to protect this natural endowment and investigate possible pathways to improve its environmental impact and assert on its energy and environmental potential during the energy shift. By pursuing this, natural gas can become a significant energy commodity for other global systems with reduced carbon footprint at the production level. Also, following the policy recommendations cited earlier, more natural gas will be available for export to support systems to transition from coal and other carbon-intensive fuels.

6.4 Chapter Summary

This research demonstrates that the transition towards a sustainable future is shaped by the complex interplay between existing infrastructure, system configuration, and evolving policy mandates. The findings underscore three critical dimensions of this transition: timing, scale, and distribution. Achieving early emissions reductions is essential to mitigate the steep costs associated with stringent climate targets in later decades and to minimise the risks of premature investment in immature technologies. The role of fossil fuels remains pivotal, not only in operating carbon removal technologies and supporting downstream electrification, but also in enabling the production of cleaner export commodities. In this context, decarbonising domestically strengthens opportunities internationally, highlighting the strategic value of managing the transition effectively.

Looking ahead, Qatar's energy transition will need to be anchored in a coordinated and flexible approach. This entails implementing early policy actions supported by targeted investments in technology innovation, pilot projects, and R&D to accelerate learning curves and reduce costs. In parallel, introducing a robust monitoring framework for industrial emitters, together with financial incentives and subsidies for low-carbon products, can strengthen domestic alignment with international competitiveness.

Overall, this study underscores the importance of employing energy system modelling in shaping coherent policy frameworks that bridges short-term imperatives and long-term objectives. Advancing transition management in this way enables Qatar to fulfil its emissions commitments as well as to consolidate its standing as a frontrunner in low-carbon energy, while contributing valuable international knowledge transfer on sustainable pathways.

Chapter 7

7 Conclusions

This thesis represents a novel approach in modelling decarbonisation pathways for Qatar energy system and delving into derived insights to support energy policy chartings to reduce emissions of the hydrocarbon-dependent system. The study investigated three key questions to address the research gap. Initially, the research conducted a simulation modelling approach by deploying MUSE platform to explore the intricacies of decarbonising a hydrocarbon-dependent system under an NDC emissions target scenario and NZ50 carbon neutrality scenario, to evaluate the impact of policy to change the course of emissions trajectory in a business-as-usual (BAU) scenario. The modelled pathways emphasise the concomitant link between timely planning, strategic policy instruments, and milestone definition to safeguard economic stability while advancing decarbonisation.

The scenario-based simulations in this study outlined two-pronged climate strategies for Qatar energy system. On one hand, the study scrutinised the cross-sectoral impact of exerting a carbon budget to reduce emissions by 25% on 2030 onwards, and on the other, to reduce emissions by 100% through 2050. In both cases, the outcomes manifested as system-wide reconfigurations across supply, conversion, and demand sectors. This framework was essential for evaluating how Qatar's energy system responds to existing emissions policy and for identifying additional measures required to align national decarbonisation strategies with policy ambitions. The results further demonstrated the interplay between supply, conversion, and demand segments, as well as the substantive economic trade-offs inherent in pursuing environmental targets.

Crucially, the findings indicate that current policy efforts, which focus predominantly on the power and transport sectors, are insufficient to achieve the 2030 emissions reduction target and are unlikely to sustain carbon reductions through to 2050. Moreover, delaying policy adjustments under rising carbon constraints risks locking in costlier system configurations by mid-century, amplifying both economic and infrastructural challenges.

This research complemented the scenario-based analysis with a comparative assessment between the MUSE simulation model and the TIMES optimisation model, in order to establish a harmonised framework for evaluating Qatar's energy system transition. The rationale for selecting these two models lies in their international credibility and suitability for modelling hydrocarbon-rich economies, in addition to the author's direct collaboration with the TIMES core team to ensure contextual relevance for the Qatari case. This dual-modelling strategy ensures the study's findings are both methodologically sound and replicable to other contexts in the region.

The comparative analysis revealed both areas of convergence and divergence, particularly under the NDC and the NZ50 emissions targets. Convergence occurs in the prioritisation of decarbonisation in energy- and emissions-intensive sectors, most notably, oil and gas production and processing, as well as the industrial sector. Both models also emphasise the necessity of introducing carbon removal technologies across moderate and stringent climate scenarios. Divergence, however, protrudes in the timing and scale of decarbonisation, reflecting the underlying investment logics of each paradigm. TIMES, grounded in global optimality, distributes capital across sectors flexibly and efficiently, whereas MUSE, governed by cost-minimisation based on LCOE under imperfect foresight, primarily invests in low-emissions technologies to avoid fuel and emissions costs.

These distinctions are further accentuated when the carbon budget tightens beyond the NDC threshold. For example, under the anticipated 10% EV penetration policy, TIMES projects a rapid expansion to nearly 70% EV share by 2050, displacing system emissions onto carbon removal facilities and onto upstream fuel production. By contrast, MUSE accelerates full electrification of road transport, shifting demand onto the power sector and increasing renewable uptake up by manifold. Similarly, TIMES leverages perfect foresight and full knowledge of commodity prices to optimise system cost by electrifying parts of the industrial sector, thereby reducing the burden on fuel refining. MUSE, in contrast, reflect myopic foresight and investors preference that lock in lower-emitting technologies, crowding out alternative options throughout the time horizon.

Together, these findings signal significant lessons, not only the importance of understanding the methodological underpinnings of simulation and optimisation paradigms in shaping transition outcomes, but also the significance of model selection itself. The choice of framework shapes investment direction, sectoral allocation, and the interpretation of policy feasibility. For policymakers, this means model results must be read critically, with attention to how underlying assumptions, such as foresight, decision criteria, and treatment of legacy assets, influence projected pathways.

Lastly, expanding on the analyses of the preceding chapters, this study explored a potential strategic opportunity for Qatar within the rapidly evolving global energy landscape, capitalising in its established expertise in LNG and its emerging capacity in hydrogen production. This chapter delved into the viability of transforming current export infrastructure toward hydrogen exports under both the STEPS and NZ60 delayed neutrality scenarios, which represent contrasting demand trajectories and varying carbon constraints.

The analysis demonstrated that LNG remains a valuable export commodity for Qatar in the near to medium term, yet it may be progressively displaced under conditions of stringent carbon pricing, tightened carbon budgets, and rapid hydrogen market expansion. These findings underscore the importance of closely monitoring global market developments, including carbon adjustment mechanisms, and demand-side signals, to inform a forward-looking regulatory and investment framework. Such a proactive approach is necessary to safeguard Qatar's market position, enhance its economic resilience, and capture emerging opportunities within the global energy transition.

This research has drawn upon diverse data sources and methodological approaches to examine the possible transition pathways for Qatar energy system. The findings generated evidence-based insights that elucidate current policy implications while proposing strategic directions for advancing sustainable energy planning. As this thesis reaches its conclusion, it is essential to integrate the key strategic directives, translate model-based outcomes into actionable policy, and encourage continued exploration of

emerging opportunities within this rapidly evolving field. The subsequent subsection outlines the limitations of the study, providing context for future research and refinements of the modelling framework.

7.1 Meeting the objectives

The research questions set out in Chapter 1 have been addressed as follows:

Research Question 1 was examined in Chapter 3, which introduced a novel simulation model for Qatar energy system. This model enabled the evaluation of alternative decarbonisation pathways and their implications on emissions trajectories and infrastructure configurations. This work was presented at two conferences.

Research Question 2 was considered in Chapter 4, which integrated the modelling framework and inferred insights from Question 1 into a a dual-model comparative analysis. By contrasting optimisation (QT-TIMES) and simulation (MUSE-QA) paradigms, this study highlighted convergences and divergences in system evolution, thereby strengthening the evidence base for policy discourse. This work has been accepted for presentation at the IAEE Conference in Turkey in December 2025.

Research Question 3 was addressed in Chapter 5, extending the analytical framework of Chapter 3 by developing scenario-based pathways for a potential hydrogen future. This analysis evaluated Qatar's energy commodity competitiveness for export under ambitious decarbonisation targets. The outcomes of this work have been accepted as a conference paper at the ICAEE and will be presented in December 2025.

Finally, **Chapter 6** synthesise the findings from Chapters 3,4, and 5, drawing together overarching insights to inform policy charting for Qatar energy transition.

7.2 Limitations

This study provided insightful understanding of the dynamics of existing system configuration and the impact of future energy policies on its evolution under climate targets. Despite its contributions, the study should be interpreted in light of several methodological limitations rooted in factors such as; modelling assumptions, forecast uncertainties, model source code maturity, and input data granularity. Addressing these constraints is necessary to compose a plausible narrative based on available evidence while accounting for risks, and informing the quality of critical decisions, in addition to warranting areas of improvements. Key limitations are discussed considering its implication on the grand scope and specifics of this research.

One general limitation originates from the level of detail of input data. The paucity of locally sourced data and information necessary to frame the context of Qatar pauses a degree of uncertainty. This study has relied on external data sources which are subject to generalisation and estimation. The reference energy system which represents the foundation of the schematic energy flow in this study is based on the IEA data for the energy balance of Qatar. This balance reports broad categorisation and rough aggregated values; for instance, it does not account for some significant industries in Qatar such as aluminium manufacturing which was manufactured by Qatalum and its stock in 2015 was ~0.64 Mt. Also, the IEA emissions balance is limited to energy combustion emissions disregarding process emissions such as that coming from cement production which could affect emissions and emission removal estimations. This highlights the need for locally composed and published energy and emissions balance data set which can enhance accuracy of modelling efforts.

Furthermore, technology portfolio of alternative options is generic and highly dependent on assumptions regarding technological innovation, readiness levels, and cost trajectories. For example, green electrolysis is included in Chapter 3 under a moderate demand trajectory; however, it is omitted in subsequent chapters to concentrate on natural gas assets and technologies that are sufficiently mature to enter the market.

Incorporating such emerging technologies prematurely could result in overly optimistic technology configurations and potentially unrealistic decarbonisation pathways.

Another important limitation stems from the relative maturity of the modelling framework of MUSE. MUSE is a recently developed simulation platform established by a collaborative and evolving research group at Imperial College London. Its readiness to simulate the decarbonisation of a hydrocarbon-based energy system and its nuances, such as that of Qatar, presented unprecedented challenge, particularly since earlier applications of the model were largely confined to a focused aspect of the system representation.

The first modelling phase of this study relied on an early release of MUSE, which required extensive, and time consuming, engagement with the development team to debug code errors, correct LCOE computations, and refine input data structures. This iterative collaboration contributed indirectly to the ongoing enhancement of the model's source code. Nonetheless, several modelling challenges persist. For instance, MUSE currently lacks the capacity to simulate intra-sectoral energy and material circulation, such as the routing of ammonia into urea plants within the same industrial sector, the internal recycling of LPG or refinery gas within refining operations, and the recirculation of CO2 streams from capture facilities into industrial processes.

Moreover, MUSE framework is also limited in constraining emissions as it relies on a predefined set of absolute values which represent an exogenously calculated budget, instead of constraining system or sectoral emissions on a percentage-based reductions. It also remains limited in representing DAC as a system-wide technology capable of mitigating collective system emissions. A further constraint concerns exogenous capacity introductions beyond the base year. For example, recent large-scale solar installations such as Al Kharsaah Solar Power Plant and QatarEnergy's solar initiative could not be introduced as mid-horizon additions within MUSE-QA's discrete timeslice structure. A dditionally, MUSE_QA does not yet distinguish between grey, blue, and green hydrogen. Instead, it represents hydrogen production generically at the upstream level, focusing on ensuring the overall energy balance rather than tracing specific colour

pathways or emissions intensities, again, which can be circumvent through sectoral emissions reduction if this feature is ever available.

As the core objective of this thesis is to gain insights into the evolution of Qatar energy system under decarbonisation targets using a linear simulation platform, it inherently holds the risk of oversimplifying sectoral representation. MUSE natively does not capture export market contractual intricacies nor commodity price change as in optimisation modelling, which can skew results when export revenues or international trade competition are critical drivers in the national energy system. Introducing this layer would require a more sophisticated model configuration and expand the scope and complexity of the modelling exercise. It will also shift the focus away from the scrutinising the existing system towards dependence on the uncertainty of international trade.

Similarly, in this model, the GCC grid connection is excluded. Intra-Gulf electricity trade is primarily intended for grid reliability and emergency support, rather than functioning as a fully integrated wholesale power market. Therefore, in addition to geopolitical disruptions experienced during the 2017 blockade on Qatar, this interconnection is not considered a reliable nor consistent source of electricity supply for meeting long-term demand within the modelling framework.

This study characterises Qatar energy system as a centralised market, overseen by the government and sustained by fiscal revenues. Accordingly, investment decisions are modelled through a single agent framework applying LCOE-based investor metric. While this setup reflects the dominance of state-led planning, it may also result in the accelerated uptake of low-cost, low-carbon technologies, potentially underestimating real-world transition inertia, infrastructure lock-in, and non-economic barriers to technology adoption. Introducing additional agents, each with distinct investment metric preference such as net present value (NPV) or equivalent annual cost (EAC), could provide deeper insights into the economic forces shaping system evolution and broaden the scope for market analysis. However, doing so would increase computational complexity, making it more suitable as a pathway for future research. The use of LCOE as the primary investment metric in this study is therefore justified not only as a means of

representing a centralised market structure but also as a way of optimising the system cost profile by reducing domestic fossil fuel demand, thereby increasing export potential and fiscal returns.

Also, uncertainty in baseline service demand stems from lack of national balances and data scarcity. This is pronounced in the paucity of data regarding temporal electricity consumption translated in cooling and lighting demands. Moreover, the rapid change within a short period in Qatar infrastructure, industrial capacity expansion, expats exodus, tourism floods, and jobs openings, in addition to a wave of geopolitical turbulences, pause an uncertainty towards energy demand projections. Hence, it is based on assumptions that are prone to steep change in course. These assumptions are inferred from sectoral growth indicators.

The inclusion of technology innovations and breakthroughs within the sectoral technology suite without any realised pilot projects suited to Qatar's climatic and operational context, adds an additional layer of uncertainty to the projected system evolution. For example, DAC uptake is upscaled substantially to meet the emissions cap, however, the current few operational DAC plants have a mere 0.01MtCO2 annual capture capacity awaiting research and development and cost curve reduction (IEA, 2025). It also falls under social and political endorsement for choosing to expand costly capitals towards mid-century (The Oxford Institute for Energy Studies, 2023). Moreover, maintenance and retrofitting considerations are not incorporated, potentially leading to an incomplete representation of long-term asset performance and lifecycle costs. This ultimately falls under the limitations of the model to address such adjustments unlike sophisticated models like TIMES.

Despite these limitations, MUSE-QA provides robust insights and address key issues in investigating system behaviour under policy constraints, offering a valuable exploratory platform for studying transition pathways. Nevertheless, these limitations highlight the need for continued model development, refinement of source code, cautious results interpretation, and cross-validation with complementary frameworks such as TIMES, as demonstrated in Chapter 4.

7.3 Future Work

The intricacies and evolving nature of the global energy transition landscape triggers several promising directions for future research. While this study addressed a broad range of system-level interactions, a number of aspects emerged during the modelling process that warrant deeper exploration but were constrained by time, data availability, and computational scope.

Future work should focus on increasing the granularity of input datasets as more detailed data become available. Particular attention should be paid to temporal and behavioural variations in energy consumption, especially within the residential and transport sectors. For instance, incorporating hourly or seasonal demand fluctuations could better capture the reduction in electricity use during daylight hours, increased cooling requirements in the summer months, or traffic intensity during peak commuting periods and seasonal travel such as summer exodus. Similarly, differentiated load-profiles for commercial versus residential users could enable a more accurate depiction of system demand.

The scope of the model can be expanded to include additional sectors currently excluded from MUSE-QA, such as agriculture, non-energy uses of hydrocarbons like petrochemical feedstocks, and the associated process-based emissions. Integrating these sectors would provide a more comprehensive view of the national energy-emissions nexus and allow for cross-sectoral mitigation analysis.

As Qatar's energy system continues to diversify, future versions of the model could incorporate a wider set of agents representing different stakeholder categories, such as national energy companies, private investors, joint ventures, and foreign partners, each with distinct investment priorities and behavioural parameters. Moreover, social and behavioural agents could be introduced to reflect public preferences and adoption rates for new technologies, such as electric vehicles, public transport usage, or domestic rooftop solar deployment. This agent-based dimension would enhance the realism of investment and technology-adoption decisions within the model.

In line with UN NDC (n.d.) guidelines, which require updates every five years, and Qatar's QNRES (2024), which is reviewed on a three-year cycle, the MUSE-QA model should also be updated periodically. Such periodic revisions would capture changes in energy demand, new policy instruments, updated technology cost curves, and inaugurated capacities such as solar power plants and CCS units. Regular updates would therefore ensure that the model remains an up-to-date and credible decision-support tool for national policy evaluation.

Future comparative work could expand beyond the TIMES model to include internationally recognised modelling frameworks, thereby improving cross-validation and robustness of insights for policymakers. Collaboration with regional modelling efforts, particularly within the Gulf Cooperation Council (GCC), could enable comparative analysis, enhance knowledge transfer, and support coordinated regional energy transition strategies.

Future research is needed to address the uncertainties surrounding future hydrogen markets. This includes assessing potential demand trajectories, export infrastructure requirements, terminal designs, regasification capacities, and the readiness of transport systems for alternative fuels. These aspects are critical for Qatar, whose long-term export strategy will depend heavily on hydrogen's role in global decarbonisation pathways.

Lastly, given the interdependence of Qatar's energy system with global markets, future studies should also explore system-wide coupling and knowledge exchange mechanisms. Lessons from other successful transition models could inform policy design, improve modelling methodologies, and strengthen Qatar's institutional capacity to manage the full value-chain transformation towards a sustainable, low-carbon energy future.

7.3.1 Proposed future direction

Building on the previous, this subsection itemises the next steps in order to provide coherent and succinct future direction for energy policymaking to support realising national emissions targets:

- **Expanding modelling representation of the export chain:** the modelling framework can be extended to explicitly represent the full energy export chain, including shipping, conditioning, storage, and terminal operations, parametrised using Qatar-specific techno-economic data where available. This export chain can be modelled as an intermediate sector positioned between gas processing sector and the final export demand sector, thereby capturing the operational and costs dynamics. Incorporating these elements would enable the model to reflect more accurately the economic cost of exports that needs to be taken into account when strategizing transition pathways.
- **Sensitivity and uncertainty analysis:** updating the model every 2-5 years is essential to maintain data accuracy and continued relevance for long-term strategic planning. This process should incorporate revisions to key parameters including technology learning curves to reflect investment feasibility and commercial scalability, fuel price trajectories to capture operational viability, and evolving carbon pricing regimes to evaluate export competitiveness and overall system resilience. Such iterative updates will enhance the model's significance to support evidence-based policymaking and enables its integration into future revisions of Qatar NDC and NDS frameworks.
- **Scope 3 accounting framework:** developing a carbon auditing framework that explicitly distinguishes between domestic (Scope 1 and 2) and value-chain (Scope 3) emissions would enable clearer identification of mitigation levers that are directly influenced by Qatar local policy control against those driven by external market dynamics, particularly energy export-related activities. Such separation enhances transparency in emissions reporting and supports targeted policy interventions.

- **Green hydrogen as a comparative case:** extending the modelling framework to incorporate green electrolytic hydrogen would broaden the analysis to reflect emerging international demand for non-fossil hydrogen. Incorporating this option enables a comparative assessment of fossil-based against renewable-based hydrogen routes, emphasising the transitional role of hydrocarbons in the medium term while identifying long-term transition pathways. This extension also reveals potential investment opportunities in electrolysis and renewable energy deployment, including both solar and wind. It also provides a basis for institutional collaboration with key stakeholders such as Kahramaa and QatarEnergy to support data sharing and development.
- **MRV and certification modelling:** establishing a structured emissions monitoring, reporting, and verification (MRV) framework within the modelling environment would enhance data accuracy and facilitate alignment with international certification standards. Integration with frameworks such as the EU Emissions Trading System (EU-ETS) and Japan's ClassNK Accreditation would enhance the credibility and marketability of Qatar energy export products as lower-carbon commodities. This approach can support coordinated implementation through national institutions, including the Ministry of Environment and Climate Change (MoECC), QatarEnergy, and Industries Qatar (IQ) enabling effective compliance with evolving international market requirements.

7.4 Conclusions

This research indicates that, although Qatar has taken commendable steps towards emissions reduction, its high emissions baseline necessitates more ambitious and timely policy measures to stay on track with its climate goals. The 2030 short-term goal represents a pivotal milestone to reduce and maintain improved emissions trajectory towards mid-century. The analysis highlights two key considerations about the climate

target: the supporting policy package, and the timeline. Current policies lag in delivering targeted emissions cuts underscoring the urgency of policy enhancement. At a moderate transition scenario, further to current policies, the study shows necessary emissions reduction at centralised segments of the system. However, the extreme decarbonisation target reveals challenging transformation hurdles which potentially risks the co-benefit of economic-environmental goals. For example, the results veer towards 100% penetration rate of EV in the transport sector irrespective of infrastructure strain prioritising climate reduction targets. Therefore, tailored mitigation pathway for Qatar energy system collating sectoral and a system-wide analysis is necessary.

While the modelling provides valuable insights, its findings are sensitive to assumptions and inherent uncertainties. Therefore, moving forward, Qatar must carefully garner research-derived energy policy recommendations targeting cost effective pathways with regular updates to incorporate technological advancement with learning curves. Qatar should also promote cross-sectoral energy efficiency transformation and incentivise new technology uptake through mandates and subsidies. At a regional level, Qatar should lead the example of setting a framework for a sustainable yet prospering energy system without compromising its economic power to its fossil-rich neighbouring countries, through capacity building and knowledge transfer which can be fortified by model-based analyses. This research forms the basis for guiding energy policy drafts which can effectively implement climate targets at the short term and improve environmental footprint towards mid-century.

Building upon the insights from this research, this study can actively contribute to reviewing Qatar National Development Strategy (NDS) beyond its third edition, to guide Qatar towards meeting its announced climate targets and claiming environmental stewardship as a hydrocarbon exporting country, in addition to empowering women's indispensable input in this national development as articulated in the NDS (2021).

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Appendix A: Simulation Model

Table A.3: Technology naming convention

Sector	Technology	Technology Description
UPSTREAM	MINNG	Mining.Natural_Gas.
	MINNG-CCS	Mining.Natural_Gas.Carbon_Capture_and_Storage.
	MINNG-DAC	Mining.Natural_Gas.Direct_Air_Capture.
	MINCRD	Mining.Crude_Oil.
	MINCRD-CCS	Mining.Crude_Oil.Carbon_Capture_and_Storage.
	MINCRD-DAC	Mining.Crude_Oil.Direct_Air_Capture.
	MINNGL	Mining.Natural_Gas_Liquids.
	MINNGL-CCS	Mining.Natural_Gas_Liquids.Carbon_Capture_and_Storage.
	MINNGL-DAC	Mining.Natural_Gas_Liquids.Direct_Air_Capture.
GTLREFINERIES	OILREF	Oil_Refiney.
	OILREF-CCS	Oil_Refinery.Carbon_Capture_and_Storage.
	OILREF-DAC	Oil_Refinery.Direct_Air_Capture.
	GTL	Gas_to_Liquid_Plants.
	GTL-CCS	Gas_to_Liquid_Plants.Carbon_Capture_and_Storage.
	GTL-DAC	Gas_to_Liquid_Plants.Direct_Air_Capture.
	UPSLNG	Natural_Gas_Liquefaction_Plants.
	UPSLNG-CCS	Natural_Gas_Liquefaction_Plants.Carbon_Capture_and_Storage.
	UPSLNG-DAC	Natural_Gas_Liquefaction_Plants.Direct_Air_Capture.
	GREEN-H2-ELECTROLYSIS	Electrolysis_Process_for_Green_Hydrogen_Production.
	SMR	Steam_Methane_Reformer.
	SMR-CCS	Steam_Methane_Reformer.Carbon_Capture_and_Storage.
	SMR-DAC	Steam_Methane_Reformer.Direct_Air_Capture.
POWER	OCGT	Open_Cycle_Gas_Turbine.
	CCGT	Combined_ Cycle_Gas_Turbine.
	CCGT-CCS	Combined_ Cycle_Gas_Turbine.Carbon_Capture_and_Storage.
	CCGT-DAC	Combined_ Cycle_Gas_Turbine.Direct_Air_Capture.
	ESOLPV	Solar_Power.PV.
	ESOLPV-ES	Solar_Power.PV.Storage.
	WIND-ONSHORE	Wind_Power.Onshore.
	WIND-OFFSHORE	Wind_Power.Offshore.
INDUSTRY	IISDRELCAF	Industry.Iron_and_Steel.DRI. Electric_Arc_Furnace.
	IISDRELCAF-CCS	Industry.Iron_and_Steel.DRI. Electric_Arc_Furnace.Carbon_Capture_and_Storage.
	IISDRELCAF-100H2	Industry.Iron_and_Steel.DRI. Electric_Arc_Furnace.
	IIPCPROD	Industry.Portland_Cement_Production.
	IIPCPROD-CCS-POST	Industry.Portland_Cement_Production.Carbon_Capture_and_Storage.Post_Combustion.
	IIPCSPROD-CCS-OXY	Industry.Portland_Cement_Production.Carbon_Capture_and_Storage.Oxy_Fuel.
	IIPCPROD-H2	Industry.Portland_Cement_Production.Hydrogen_Fuel.
	IANH3PROD	Industry.Chemical.Ammonia_Production.
	IANH3PROD-CCS	Industry.Chemical.Ammonia_Production.Carbon_Capture_and_Storage.
	IANH3PROD-DAC	Industry.Chemical.Ammonia_Production.Direct_Air_Capture.
	IANH3PROD-GREEN	Industry.Chemical.Ammonia_Production.Green_Process.
	IUPROD	Industry.Chemical.Urea_Production.
	IUPROD-CCS	Industry.Chemical.Urea_Production.Carbon_Capture_and_Storage.
	IUPROD-DAC	Industry.Chemical.Urea_Production.Direct_Air_Capture.
	PETRO-ETH-CRACKER	Industry.Petrochemical.Ethane_Cracker.
	IOTRLTH	Industry.Other_Industrial_Products.
	IOTRLTH-CCS	Industry.Other_Industrial_Products.Carbon_Capture_and_Storage.
	IOTRLTH-DAC	Industry.Other_Industrial_Products.Direct_Air_Capture.
TRANSPORT	TCARGASOL	Transport.Passenger_Cars.Gasoline_Fuel.
	EV	Transport.Passenger_Cars.Electric_Vehicle.
	TTWGASOL	Transport.Two_Wheelers.Gasoline_Fuel.
	TTWELC	Transport.Two_Wheelers.Electric.
	TBUS	Transport.Public_Bus.Compressed_Natural_Gas.
	EBUS	Transport.Public_Bus.Electric.
	TTDSL	Transport.Heavy_Truck.Diesel_Fuel.
	TTH2	Transport.Heavy_Truck.Hydrogen_Fuel.
	TAIJET	Transport.Air_Transport.Aviation_Fuel_JetA.
WATERDESAL	MSF	Water_Desalination.Multi_Stage_Flash.
	MED	Water_Desalination.Multi_Effect_Distillation.
	SWRO	Water_Desalination.Seawater_Reverse_Osmosis.
RESIDENTIAL	RCSAC	Residential.Space_Cooling.Air_Conditioners.
	RCSDC	Residential.Space_Cooling.District_Cooling.
	SH ELECTRIC HEATING	Residential.Space_Heating.Electric_Heaters.
	RCWTR	Residential.Water_Cooling.Electric.
	RHWTR	Residential.Water_Heating.Electric.
	RHWTRSOLAR	Residential.Water_Heating.Solar.
	RLCON	Residential.Lighting.Conventional.
	RLLED	Residential.Lighting.LED.
	RCOKELC	Residential.Cooking.Electric.
	RCOKLPG	Residential.Cooking.LPG.
SERVICE	SCDC	Service.Space_Cooling.District_Cooling.

	SCSAC	Service.Space_Cooling.Air_Conditioners.
	SEAP	Service.Appliances.Electric.
	SELC	Service.Electricity_Consumption.
EXPORT	EX-GAS	Export.Natural_Gas.
	EX-OIL	Export.Crude_Oil.
	EX-NGL	Export.Natural_Gas_Liquids.
	EX-LPG	Export.LPG
	EX-GASOL	Export.Gasoline.
	EX-JET	Export.Jet_Fuel.
	EX-DSL	Export.Diesel.
	EX-FO	Export.Fuel_Oil.
	EX-NAPHTHA	Export.Naphtha.
	EX-LNG	Export.Liquified_Natural_Gas.

Appendix B: MUSE-QA Global Commodities

Table A.4: *Global commodities naming and general properties*

Commodity	Commodity Type	Commodity Name	Commodity Emission Factor_CO2	Heat Rate	Unit
UPSTREAM total resources including in-ground natural gas burnt off during extraction of gas, oil and ngl	Energy	resources	0	1	PJ
UPSTREAM gas ready for SMR and other gas processing	Energy	upsng	56.1	1	PJ
UPSTREAM refined oil for export	Energy	upsoil	73	1	PJ
UPSTREAM processed natural gas liquids	Energy	upsngl	63	1	PJ
UPSTREAM hydrogen from SMR	Energy	hydrogen	0	1	PJ
CO2 fuel combustion	Environmental	CO2f	0	1	kt
UPSTREAM refined LPG	Energy	lpg	0	1	PJ
UPSTREAM refined gasoline	Energy	gasoline	0	1	PJ
UPSTREAM refined kerosene	Energy	jet	0	1	PJ
UPSTREAM refined diesel	Energy	dsl	0	1	PJ
UPSTREAM refined fuel oil	Energy	fo	0	1	PJ
UPSTREAM refined naptha	Energy	nph	0	1	PJ
UPSTREAM refined refinery gas	Energy	refgas	0	1	PJ
UPSTREAM refined other oil products	Energy	otroil	0	1	PJ
UPSTREAM refined ethane from TRANSFERS (GTL)	Energy	ethane	0	1	PJ
UPSTREAM GTL gas to liquid	Energy	upsgtl	0	1	PJ
UPSTREAM LNG liquified natural gas	Energy	lng	0	1	PJ
UPSTREAM other hydrocarbon from GTL process	Energy	otrhyd	0	1	PJ
USTREAM GTL syngas generation	Energy	syngas	0	1	PJ
POWER electricity	Energy	elc	0	1	PJ
POWER solar PV	Energy	solar	0	1	PJ
POWER wind power	Energy	wind	0	1	PJ
POWER heat from CHP	Energy	heat	0	1	PJ
WATERDESAL water desalination	Energy	wtr	0	1	Mm3
RESIDENTIAL space cooling	Energy	rcs	0	1	PJ
RESIDENTIAL space heating	Energy	space heating	0	1	PJ
RESIDENTIAL water cooling	Energy	rcw	0	1	PJ
RESIDENTIAL water heating	Energy	rhw	0	1	PJ
RESIDENTIAL lighting	Energy	rlight	0	1	PJ
RESIDENTIAL appliances	Energy	reap	0	1	PJ
RESIDENTIAL cooking	Energy	rco	0	1	PJ
TRANSPORT car	Energy	tra	0	1	kvkt
TRANSPORT two wheelers	Energy	ttw	0	1	kvkt
TRANSPORT bus	Energy	tbus	0	1	kvkt
TRANSPORT heavy truck	Energy	tt	0	1	kvkt
TRANSPORT aviation passenger	Energy	tai	0	1	bn-pass-miles
INDUSTRY iron and steel	Energy	iis	0	1	Mt
INDUSTRY cement	Energy	ipc	0	1	Mt
INDUSTRY ammonia	Energy	amn	0	1	Mt
INDUSTRY urea	Energy	iurea	0	1	Mt
INDUSTRY methanol	Energy	methanol	0	1	Mt
INDUSTRY ethylene from ethane cracker	Energy	ethylene	0	1	Mt
INDUSTRY aluminium	Energy	ial	0	1	Mt
INDUSTRY refgas	Energy	irefgas	0	1	PJ
INDUSTRY otroil	Energy	iotroil	0	1	PJ
INDUSTRY otroilproducts coming from industry not elsewhere specified	Energy	otrindproducts	0	1	PJ

EXPORT gas	Energy	expng	0	1	PJ
EXPORT oil	Energy	expoil	0	1	PJ
EXPORT ngl	Energy	expngl	0	1	PJ
EXPORT lpg	Energy	explpg	0	1	PJ
EXPORT gasoline	Energy	expgasoline	0	1	PJ
EXPORT kerosene	Energy	expjet	0	1	PJ
EXPORT diesel	Energy	expdsl	0	1	PJ
EXPORT fuel oil	Energy	expfo	0	1	PJ
EXPORT napththa	Energy	expnph	0	1	PJ
EXPORT LNG	Energy	explng	0	1	PJ
EXPORT GTL	Energy	expgtl	0	1	PJ
SERVICE space cooling	Energy	scs	0	1	PJ
SERVICE appliances	Energy	sap	0	1	PJ
SERVICE electricity consumption not elsewhere specified	Energy	selc	0	1	PJ
DAC sequestered CO2 Direct Air Capture	Energy	seqCO2	0	1	kt

Appendix C: Transport Calculations

Table A.3: car ownership and saturation level

	2015	2016	2017	2018	2019	2020
Population	2,404,776	2,617,634	2,724,606	2,760,170	2,799,202	2,833,679
Number of registered cars	1,233,147	1,047,444	1,091,235	1,128,116	1,165,890	
Saturation level: cars per 1000 people	513	400	401	409	417	

Table A.4: Transport calculations: Average Annual Distance Travelled (AADT) as calculated from FAHES data

Vehicle type	AADT (km) in 2015
bus	53003
cars	26549
heavy equipment	50413
motorcycles	30397
trucks	72227

Table A.5: Fuel economy calculation for gasoline vehicles

WOQOD annual report (2015)

Fuel sales	Reported (million litres)	Calculated (PJ)
Regular gasoline	975	31.2
Super gasoline	1338	42.82
diesel	2843	90.98

Conversion factors

1 Litre gasoline =	32 MJ
1 Litre diesel =	36 MJ

Table A.6: Fuel consumption per type

	IEA gasoline (PJ)	WOQOD gasoline (PJ)
cars	63.46	73.82
Two-wheelers	0.2	0.2
Sum of gasoline	*63.66*	*74.02*
Buses	80.99	65.15
Trucks	32.11	25.83
Sum of diesel	113.09	90.98

Table A.7: Fuel Economy calculations – gasoline

	Sum of gasoline (L)	Sum of gasoline (PJ)	PJ/kvkt	Litres/kvkt	kmpl
WOQOD	2313	74.02	0.0053	0.1658	6.0298
IEA	1989.4	63.66	0.0045	0.1426	7.0107

Table A.8: Fuel Economy calculations – diesel

	Total diesel (L)	Total diesel (PJ)	PJ/kvkt	Litres/kvkt	kmpl
WOQOD	2843	90.98	0.0173	0.5419	1.8453
IEA	3534.36	113.09	0.0215	0.6737	1.4843

Air transport costs calculation

Table A.9: Capital cost for passenger and cargo air service demand (MUSD/bn-pass(ton)-miles)

	Avergae capital cost of one passenger (cargo) aircraft (MUSD)	Average number of passengers (cargo tonnage) per year	Average flight distance per year (bn-miles)	Cap_par
Passenger	25.48	22.35	5.74	75.94
cargo	28.33	2.7m	0.24	4.23

Appendix D: IPCC emissions factors

Table A.10: emissions factors

Energy commodity	Emissions factor ($ktCO_2/PJ$)
Natural gas	56.10
Crude oil	73.30
Natural gas liquid (ngl)	63.00
gasoline	69.00
Compressed natural gas (cng)	56.10
diesel	74.00
Jet	72.22
Liquified petroleum gas (Lpg)	63.10
Refgas	57.60
ethane	61.10
hydrogen	00.00
electricity	00.00

Appendix E: Solar Utilisation Factor

Table A.11: solar utilisation factor

Timeslices [Renewable Ninja]

(kW)		winter	spring	summer	autumn	
		DJF	**MAM**	**JJA**	**SON**	
Date		15/01/2019	15/04/2019	15/07/2019	15/10/2019	
daily mean		0.190	0.240	0.19	0.210	
start	5:00 am	0	0.008	0.029	0	
lowest>>	6:00 am	0.021	0.149	0.123	0.077	
	7:00 am	0.189	0.358	0.247	0.286	
	8:00 am	0.383	0.537	0.394	0.47	
	9:00 am	0.616	0.678	0.524	0.594	morning
	10:00 am	0.7	0.748	0.585	0.675	
highest>>	11:00 am	0.723	0.772	0.608	0.708	
	12:00 pm	0.684	0.752	0.605	0.686	afternoon
	1:00 pm	0.594	0.681	0.549	0.626	
	2:00 pm	0.446	0.56	0.446	0.511	
	3:00 pm	0.241	0.388	0.31	0.342	evening
end	4:00 pm	0.042	0.183	0.16	0.134	
	5:00 pm	0	0.015	0.042	0.000	night
time in use		10 hrs	12 hrs	12 hrs	10 hrs	