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Identifying Qatar's Potential for Carbon Sequestration

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A thesis submitted to Swansea University in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

[redacted] ……………. Date 18 DEC 2022

This work is the result of my own independent study/investigation, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Acknowledgment

It is generally accepted that pursuing a PhD is a journey full of ups and downs. It involves challenges related to finding the right topic, collecting and analysing data and making a contribution to knowledge. These are the concerns of a typical PhD student; however, who would have thought that a global pandemic that caused chaos worldwide and disrupted every aspect of life would be added to these challenges. For me, COVID-19 not only disrupted my daily activities, such as buying groceries and taking my children to the park, but also disconnected me from my family back home and added an additional layer of stress and worry about the wellbeing of my loved ones. Furthermore, COVID-19 added complexity to completing my PhD by making it challenging to collect the data I had initially planned to gather.

While completing my PhD during COVID-19 was indeed an unprecedented challenge, I was able to get through it and reach the end with the help of my supervisor, family and friends, who all encouraged me to believe in myself and always see the light at the end of the tunnel. Therefore, I would like to express my sincere gratitude to my supervisor Dr Andrew Barron for his continuous support throughout my PhD journey. He was kind, understanding and a fountain of wisdom when it came to addressing the difficulties I faced. Without his tremendous support, it would have been impossible for me to complete my study.

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Even though completing my PhD marks the end of my journey, it also opens a new chapter in my life. I am looking forward to transferring the knowledge I have gained at the University of Swansea and from the Energy Safety Research Institute back home to Qatar and thereby contributing to the social and economic development of my country and its achievement of the 2030 national vision.

Abstract

The following research collects data on the current dissemination of carbon sequestration and storage and utility (CCSU) globally, analyses the challenges of CO_2 management in the long-term, as well as locates the opportunities of such technologies for the context of specific countries, in this case being Qatar. The author first defines different types of CO_2 sequestration technology, measures their global advancement and other key characteristics. The study primarily utilises a systematic review methodology to identify the latest trends in CCSU, as well as analysing current technological, socio-economic, and political conditions using publicly available sources. Then, highlight findings from the literature review are compiled into a survey, aimed at specifically targeted specialist professionals in the CCSU industry who can provide input about the applicability of said CCSU solutions to Qatar. This triangulated methodology is taken forward to a deeper analysis chapter which combines desktop and survey information for a pragmatic unionisation of the study topics. This analysis includes specific suitability analysis of technologies for Qatar, current initiatives, as well as providing insight on how identified systems can be integrated for an infrastructure level carbon sequestration system. In the fifth Discussion chapter, analysis findings are critically examined for feasibility in relation to their economic feasibility in comparison to current environmental socioeconomic drivers, i.e., the vital economic output of the country’s dependence on the oil and gas sector, political threats from international relations and global climate change, as well as the lack of sustainable food and water sources in Qatar.

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Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
BIGCC	Biomass Integrated Gasification Combined Cycle
CaLC	Calcium-Looping Carbon Capture
CAPEX	Capital Expense
CCA	Cost of CO_2 Emissions Avoided
CCGT	Combined Cycle Gas Turbine
CCL	Coal-based Chemical Looping Combustion
CCS	Carbon Capture and Storage
CCSU	Carbon Capture, Storage and Utilisation
CCT	Carbon Capture Technology
CCU	Carbon Capture and Utilisation
CEO	Chief Executive Officer
CHP	Combined Heat and Power
CMEM	Coal-based Membrane Separations
CNFCC	Carbon Nanofibre Combined Cycle
COXY	Coal-based Oxyfuel Combustion
CS	Carbon Sequestration
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DEA	Data Envelopment Analysis
DEFRA	Department for Environment, Food and Rural Affairs
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EPA	Environment Protection Agency
EPSA	Exploration and Production Sharing Agreement
EU	European Union
FC	Fuel Cell
GCC	Gulf Cooperation Council

GHG	Greenhouse Gas
GTL	Gas-to-Liquid
IEAGHG	International Energy Agency Greenhouse Gas
IGCC	Integrated Gasification Combined Cycle
IOC	International Oil Company
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LNG	Liquid Natural Gas
MAC	Marginal Abatement Cost
MILP	Mixed Integer Linear Programming
MIT	Massachusetts Institute of Technology
MOEA	Ministry of Economic Affairs
MSF	Multistage Flash
NGCC	Natural Gas Combined Cycle
NPS	Non-Point Source
OCGT	Open Cycle Gas Turbine
OPEX	Operating Expense
PV	Photovoltaic
QCCSRC	Qatar Carbonates and Carbon Storage Research Centre
QESMAT	Qatar Energy System Model and Analysis Tool
QP	Qatar Petroleum
QUCCCM	Qatar University Culture Collection of Cyanobacteria and Microalgae
RGI	Resource Governance Index
SCPC	Supercritical Pulverised Coal
SFP	Sahara Forest Project
SOE	State Owned Enterprises
SWRO	Seawater Reverse Osmosis
TFC	Total Final Consumption
TRL	Technical Readiness Level

UNFCCC	United Nations Framework Convention on Climate Change
VAR	Vector Auto-Regression
WGC	World Gas Conference

1. Introduction

1.1 Problem Statement

1.1.1 The Threat of Climate Change

The threat of climate change is having a significant impact on the ways in which energy is sourced and used across the planet. Increasing pressure from international agreements such as the recent 2016 Paris Agreement - the mission to attain the 2030 United Nations Sustainable Development Goals – is moving countries towards minimising their carbon footprint and a cleaner method of satisfying their industrial and domestic needs. The rising danger of a calamitous global change in environment, as well as other environmental mismanagement aspects, have resulted in several concerns about economic development outpacing the capacity with which the Earth can sustain it.

As a result, researchers have recommended the need to have a transformation in the industrial landscape so that the environmental objectives of different governments are accomplished alongside positive economic development. Most developed countries and international organisations have come up with different initiatives and ideas, including:

- green industrial policy;
- sustainable transformation;
- green structural transformation;
- green transformation; and
- green growth (Lütkenhorst, et al., 2014).

Generally, green transformation can be described as the processes within companies and/or industries which result in a decreased impact on environmental change. Over the last few decades, many initiatives and policies have been put forward and enacted by governments and firms across the world with the aim of ensuring this change. However companies, particularly those generating higher levels of pollution, have been shown to spend a considerable number of resources to water down, slow, or completely block measures focused on safeguarding the environment. Nevertheless, not all of these organisations act in this manner, as certain authors have reported. The aim of this Introduction is to carry out a literature review on the role of government, as well as the firms themselves, in the management of industrial pollution emitted by companies.

Over the last few years, the impacts inflicted by corporate organisations have attracted increasing attention, and GHG emissions have been at the centre of this. Alongside rising societal issues, business enterprises have also been faced with increasing pressure from environmental policy from governments. Lobbying of firms has been indicated to be one of the most effective methods that can be used to accomplish environmental protection, by ensuring an increase in the market share they possess in order to enhance an organisation's returns from going green. As a result, this distortion suggests that welfare is increased. Arguably, protecting the ozone layer was the leading environmental concern during the 1980s. Policymakers since then, have attempted to maintain the world's regulations with the goal of limiting the production of ozone-depleting CFCs and encouraging cleaner alternatives investments. For much of this time, particularly prior to 1988, the key ozone-polluting companies resisted environmental protection utilising their influence on limiting the ozone layer protections put forward. A clear example of such a firm that lobbied against the implementation of these policies is DuPont, the largest CFC producer in the US. This firm, however, suddenly changed its stance and is no longer opposed to the rule, even wanting a global CFC production phase-out. According to Grey (2018), the political support of firms may be very crucial for governments trying to ensure companies within their countries safeguard the environment. The researcher states that this change of viewpoints by firms like DuPont is aimed at stealing market share from their competitors. Building on this, Grey (2018) develops a model where higher polluting firms make significant investments in clean technology and thereafter successfully and strongly lobby for protection of the environment, as doing so will ensure that their market share shifts away from competing companies that have either been unwilling or unable to significantly invest in clean technologies.

The narrative through which environmental action is framed in this research is the concept of ‘carbon sequestration’. Carbon sequestration (CS) includes Carbon Capture, Storage and Utilisation (CCSU) - carbon storage can be defined as “the long-term storage of carbon in plants, soils, geologic formations, and the ocean” (Selin, 2009). It can include any type of natural or technological ‘carbon sinking’ activity which can remove carbon from anthropocentric activities and safely store it away from the atmosphere to mitigate its climate-changing impact. CS technologies are highly dependent on regional climate, industrial, and economic conditions, and hence, in order to achieve strategic utility from these innovations, it is important to consider their use specifically and separately for different countries and economic regions.

1.1.2 Climate Change and GHG Emissions in Qatar

Qatar is shown to have the highest level of GHG emissions per capita of any country on the planet by a large margin - almost triple that of the United States (World Bank, 2014). Rapid and successful development in Qatar has, for the most part, been fuelled by its vast oil and gas reserves. This trend is common amongst countries of the Gulf region, with most regional economies being based on the petroleum industry. Qatar has the 3rd largest proven reserve of natural gas out of all countries (Alsheyab, 2017) and has experienced rich GDP growth due to the export of oil and gas, allowing rapid construction of a sophisticated infrastructure in the last half century.

Qatar is faced with both great opportunities and challenges in becoming a world leader in energy innovation and tackling of environmental impact – there is availability of vast potential for solar energy in its barren deserts, however the provision of 99% of its domestic water needs come from the desalination of water from the Persian Gulf (Darwish & Mohtar, 2013), As shown below using MIT’s Atlas of Economic Complexity, the oil and gas industry dominates Qatar’s national exports by sector, making up $52.3 billion in revenue, while also being responsible for a vast majority of the country’s GHG emissions.

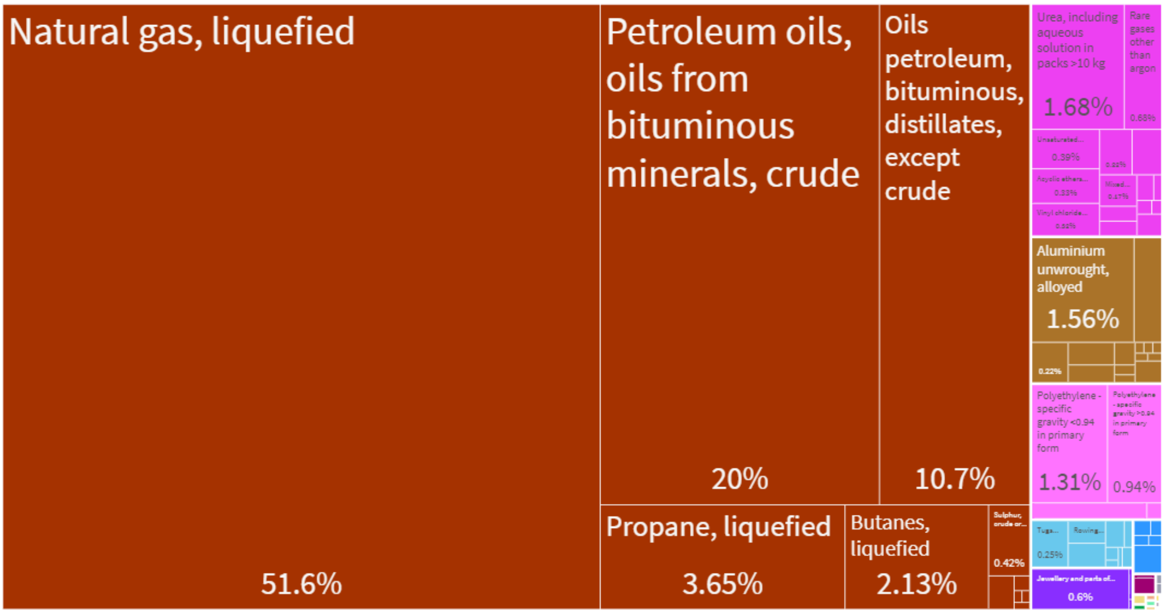


Figure 1- A Schematic Representation of Qatar's Exports by Product Types (OEC, 2019).

Qatar’s energy consumption is mostly based on its industrial sector, with residential, commercial and public services making up a significantly smaller proportion. Non-energy use and transportation are also noteworthy contributors, but not as significant as industry.

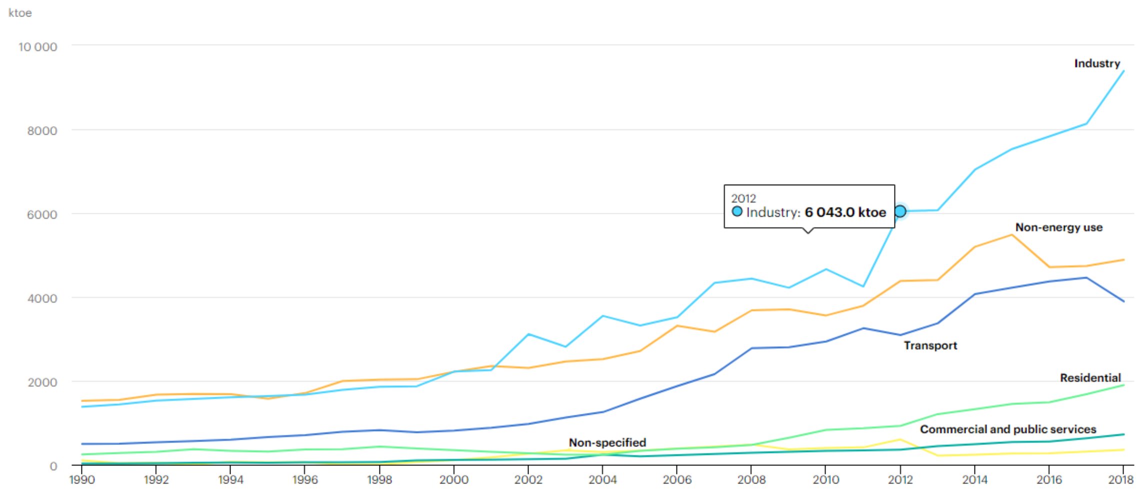


Figure 2 - Plot of Total Final Consumption (TFC) from All Energy Sources by Sector, Qatar 1990-2018 (IEA, 2018).

A critical environmental issue is that of water and food; there are no surface water sources in the country, and the level of rainfall is already at an extremely low 8 cm per annum, which also leads to little groundwater collection. Furthermore, desalination technology is incredibly inefficient, leading to a loss of 30% of its production processes’ output (Baalousha & Ouda, 2017). This environmental impact is likely to lead to further desertification due to the loss of moisture from the land, which will put further pressure on the provision of water demands from desalination. There are also significant risks for the country due to the rise of sea levels induced by climate change and the vulnerability of the country’s coastal infrastructure to extreme weather events such as natural disasters. On top of this, the loss of coastal marine biology, serious threats to the ecosystem and reduced chance of rainfall, all lead to a dire need for swift action towards sustainable development (Alsheyab, 2017). Accordingly, Qatar presents a valuable example of how an economically-active nation with a relatively small population, high executive ability and high GHG emissions can embark on a mission to lower its impact on the environment using the latest technology.

1.2 Research Question

The main research questions required for this study include:

- What are the current trends in CO_2 emissions and their reduction across industries – where does the potential for most control exist, and what technologies are available and/or being researched further to fulfil this?
- Using a case study, how can these identified trends be tackled and processes implemented into a country's national mission, and what are the measures of success for their environmental and economic impact?

1.3 Aims and Objectives

The overall aim of this study is to paint a holistic picture of the current capacity and future potential of CCSU technologies for Qatar. Research in this area for Qatar is sparse and prior to this study there has been little attempt to synthesise currently available information. The literature lacks a more structured assessment of the "incentive gap" between scenarios with substantive CCSU deployment and existing policy enablers to effectuate CCSU deployment. This study aims to present to stake holders and academic researchers with a developed understanding of the gaps in literature and painting a realistic view of CCSU dissemination, based on recent cutting edge research and direct professional input, and provide a series of recommendations and prioritisation for future research and in the private and public sector,

Further research is required to build on the overview of technologies presented in this introductory chapter, and how the specific climate of Qatar can aid in the utility of different CCSU innovations offered across the planet today, especially those that relate most closely to the conditions of hot, arid countries with few biologically active or vegetated areas. Accordingly, to meet this aim, the author must satisfy the following objectives in this research:

- Understand the current environmental shortcomings and sustainability-related resilience-building strategies required for Qatar, as a model case for regional countries;
- Identify a pragmatic overview of CS technologies available today, analyse their applicability in Qatar alongside current approaches to sequestration or re-use to determine potential changes to current processes;
- Build qualitative analysis through data from current technology to determine the emissions reduction as a function of economic cost per unit of CO_2 emissions - this will provide a performance versus cost prediction of various proposed processes – and interviews conducted with key stakeholders to determine needs and drivers;
- Provide key policy routes for Qatar to lower CO_2 emissions based on data and present findings in terms of a novel and up-to-date picture of CCSU application in the country as a national road map to meet energy, waste, and critical infrastructure-related demands in the country.

1.4 Thesis Layout

After the Introduction section, the research will explore literature on the various type of CCSU technology, as well as their socioeconomic drivers before summarising preliminary findings. Then, a methodology is outlined to guide the further data collection strategies through survey design - a subsequent Analysis chapter will combine detailed desktop and survey-based research to demonstrate the capacities of Carbon Capture and Storage (CCS) technologies in Qatar. Findings are then reviewed in the Discussion section for their whole lifecycle assessment, to assess economic feasibility and additional key conditions that are necessary for converting these results into national policies. Finally, the paper findings are summarised in the Conclusion section, and Recommendations are presented for future work.

2. Literature Review – Carbon Sequestration: Types & Drivers

2.1 Types of CS Technology

The following sub-chapter aims to systematically explore the types of sequestration technologies that are available or being explored today, based on: their country availability; extent of commercialisation; capture capacity and challenges; industry; feedstock; capture method; need for transportation; storage type; and cost.

CS represents all technologies and industrial strategies aimed at minimising the GHG emissions of carbon-producing processes by capturing and storing them at different stages of industrial lifecycles. Starting from the production of carbon in the petroleum industry and the generation of electricity from the combustion of fossil fuels, to the capture and condensation of carbon from the air and storage in depleted oil and gas reservoirs, CS technology represents a wide range of sectors, industries and life cycle stages. The categorisation is predominantly based on and most commonly associated with means of capture at power plants and its chronological relationship with combustion (pre & post, and adsorption & absorption), while other secondary innovations such as Direct Air Capture (DAC), Fuel Cells (FCs), and advances in nanotechnology are also explored. Utilising reference to real examples, findings present a pragmatic and detailed overview of the overall CS technologies that are worth pursuing today, abbreviated as CCSU technologies.

Recent concerns about climate change have led to CS becoming a growing global business sector. The Carbon Capture and Sequestration - Global Market Outlook (2017-2026) forecasts that the CCSU market will move beyond its 2017 valuation of $4.88 billion to $16.90 billion by 2026. Whilst industrial, agricultural, and other applications present opportunities in CCSU, Enhanced Oil Recovery (EOR) (whereby carbon dioxide is injected into the well once primary and secondary techniques have already been employed, to increase the recovery of crude oil by reducing viscosity, swelling crude oil, and lowering interfacial tension), has been reported as the leading prospect (Cooney et al., 2015). Such projects need to be evaluated in terms of their net present values (NPVs), which are calculated using their revenues and costs, as the financial aspect is one of the major factors for coupled EOR and sequestration projects, these (Jahangiri and Zhang, 2011). EOR not only enhances well efficiency, but also sequesters CO_2 in the process with potential climate benefits (Dai et al., 2014). Although CO_2 for EOR can be sourced from many anthropogenic sources, including natural gas processing and ammonia production, the greatest near-term opportunity for CO_2 capture from power plants is post combustion capture (Cooney et al., 2015). Though the report has detailed coverage of CCSU in Qatar, the full report is inaccessible behind a paywall, and hence not usable for this research (Statistics Market Research Consulting Pvt Ltd, 2019).

There is a wide range of processes and storage options available, alongside considerations for reuse of both input and waste materials, available from CCSU, which vary in their effectiveness as well as value for time and money. Optimising the use of CO_2 as a feedstock has the potential to increase the effectiveness of chemical conversion processes, producing economically valuable products (Al-Yaeesh et al., 2018), therefore utilizing CO_2 in current procedures and technologies to open up new business potential for Qatar. A study was conducted by Jarvis and Samsatli (2019) providing a detailed summary of a number of these currently available technologies, as shown in Figure 3:

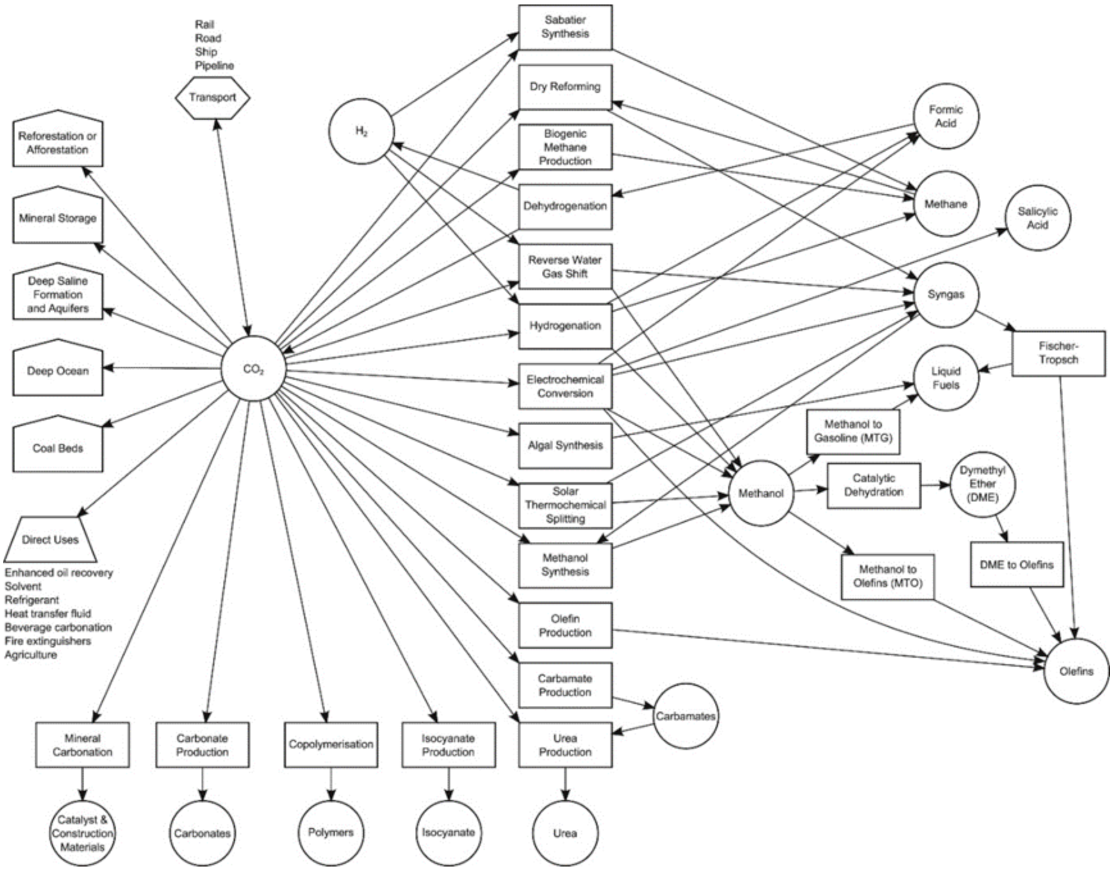


Figure 3 - Schematic of an Integrated Carbon Value Chain including Utility and Storage Options (Jarvis and Samsatli, 2019)

As a generalisation, to give direction to the study, it can be assumed that industries with the highest level of waste (in the form of released carbon) should be prioritised for the most effective utilisation of CCSU. Meanwhile, waste carbon can also be categorised as that which is already produced, and which is yet to be emitted through industrial production processes, allowing us to also account for existing GHG emissions as a form of waste. This literature review uses several main recent studies which have classified many of the existing CCSU technologies available today, before using other more specified studies to report on various characteristics of the technologies which may not be available in wider literature reviews. For example, a major study lists 27 CCSU technologies which serve as a valuable resource for identifying the most feasible existing CS techniques (Cuéllar-Franca & Azapagic, 2015). The study breaks down technologies according to absorption & adsorption by various materials, and separation via membranes, cryogenic processes, or separation of oxygen from air. Another major review lists carbon capture projects, including those with physical and chemical solvents in the pre- and post-combustion capture option, as well as the date of their operation commencement and a number of other characteristics which have been added to the tabulated data (Mumford, Wu, Smith, & Steven, 2015, p. 126). Another technique for capturing carbon from oxy-fuel combustion also exists which works by separating the oxygen from air and diluting with recycled flue-gas from the combustion, leading to a purer mix of resultant CO_2 and water.

An overall framework of this categorisation method is shown in figure 4, taken from the major study mentioned above.

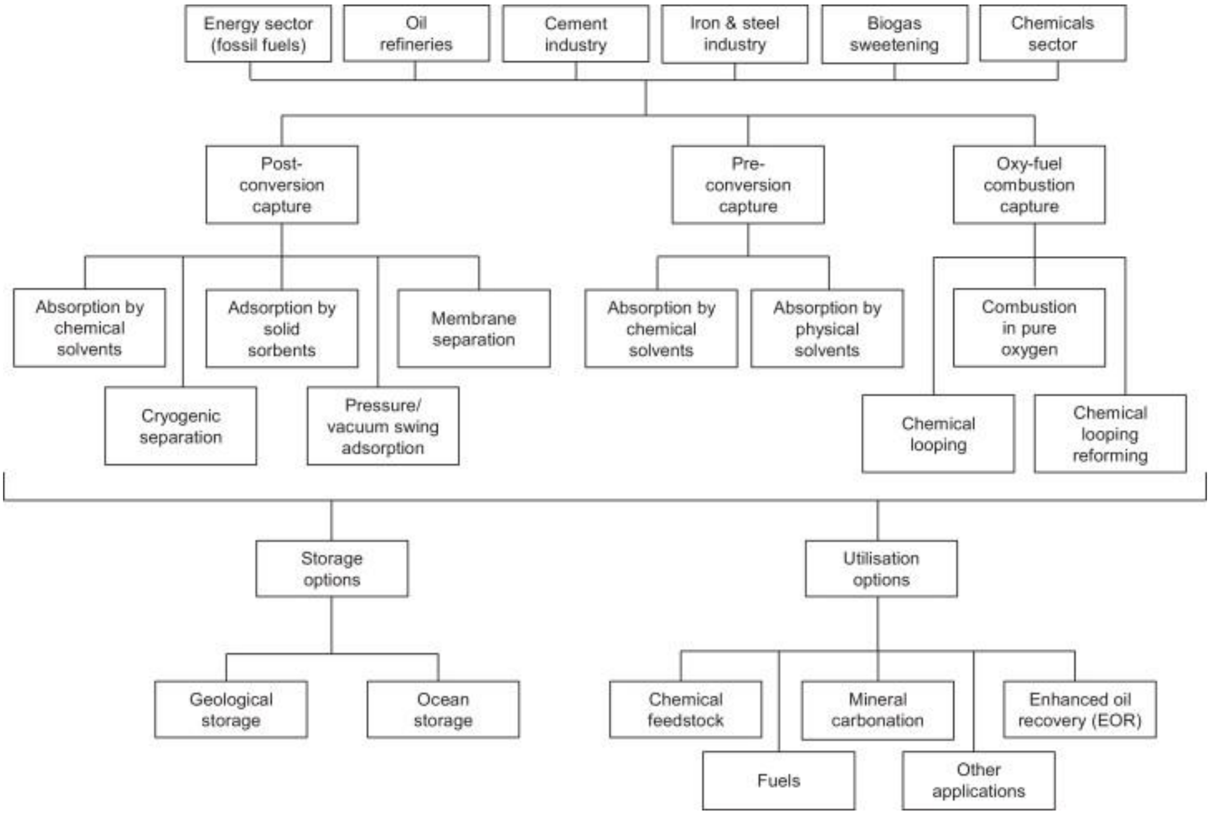


Figure 4 - Schematic Representation of Different CCSU Methods (Cuéllar-Franca & Azapagic, 2015).

This categorisation also helps to understand the difference in options at different stages of the process, including capture, storage (geological and oceanic) and utilisation (chemical feedstock, mineral carbonation, enhanced oil recovery, fuels, and other applications). More detailed accounts of each technology's costs, sequestration capacity and other data will be presented in an accompanying table. Recent estimates from the IEA (2021) of the levelised cost of CO_2 capture by sector and initial CO_2 concentration is also summarised in Figure 5.

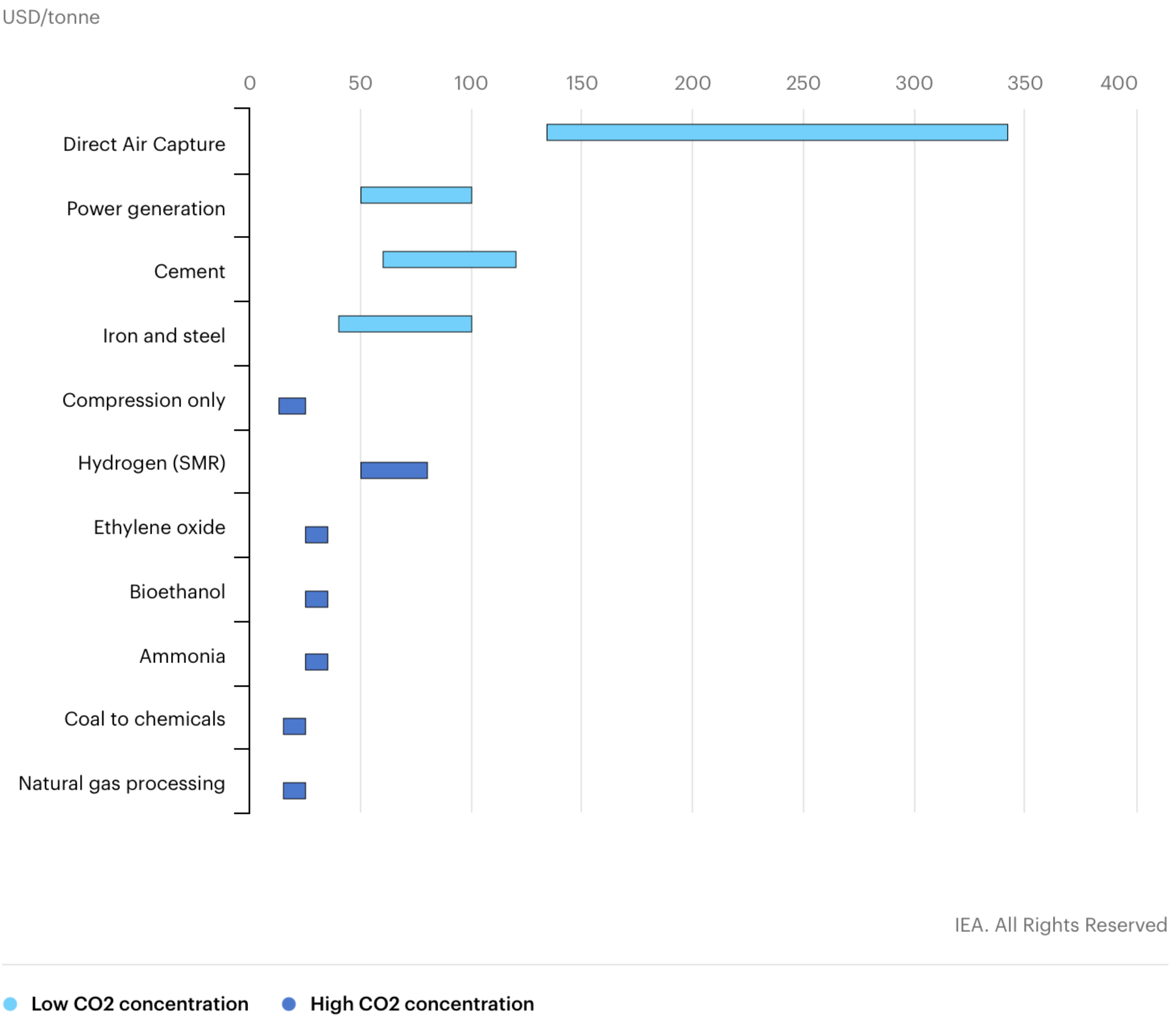


Figure 5 - Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019 (IEA 2021)

2.1.1 Capture at Power Plants

Globally, the majority of global carbon and GHG emissions come from energy generation (72%), including electricity & heat (31%), other fuel combustion (8.4%) manufacturing & construction (12.4%), transportation (15%) and fugitive emissions (5.2%), as well as other emissions caused from industrial processes (6%) (C2ES, 2017). The details of this can be seen in figure 6:

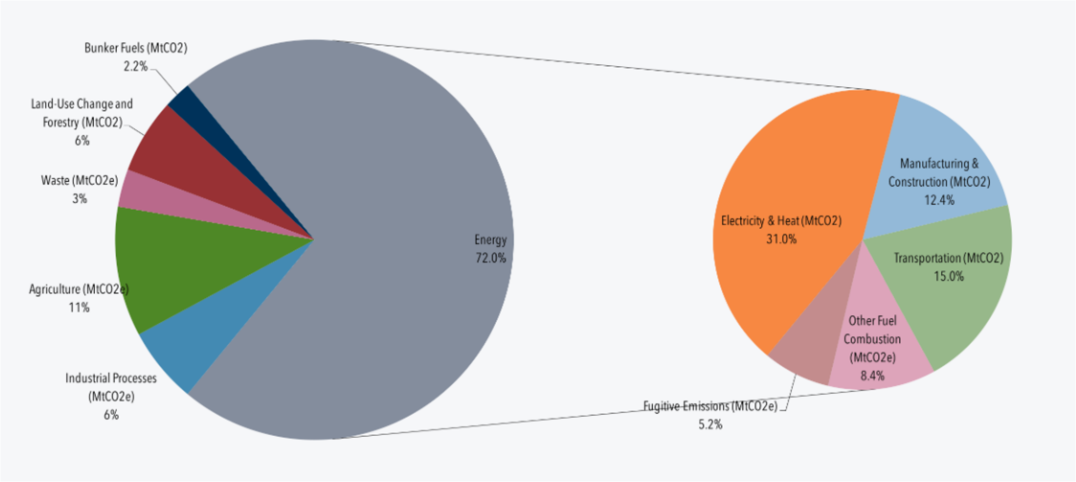


Figure 6 - Pie chart of the Global Carbon Emissions by Industry with the Energy Sector Separately Displayed (World Resources Institute, 2017).

Depending on the profile of natural resources, these emissions differ between countries, fluctuating in intensity. For example, in the UK, transportation had the highest GHG emissions in 2018, followed by energy supply from power stations, residential energy use, other energy supplies, businesses, etc. (UK Government, 2018).

Industrial carbon emissions can be divided into two categories:

a) combustion of carbon (coal) or hydrocarbon fuels for the generation of electricity or heat,

b) inherent carbon emissions from chemical reactions, such as cement production (EPA, 2017).

2.1.1.1 Pre-Combustion

The way in which pre-combustion differs is that carbon is captured before fuel combustion, therefore it can only be applied to a more limited selection of chemical and power plants currently. Pre-combustion plants initially separate oxygen from air in a chamber, and mix this with fuel to produce gasified syngas. Heat is generated in a third section when mixed with steam, and the CO_2 is finally separated for capture through various processes in a shift reactor, i.e., absorption and adsorption. Additional by-product capture from this system includes hydrogen, which can in turn be used for various industries, including gas turbines and chemical processes.

Pre-Combustion has high capture capacity, with a medium level of energy dedication from the power plant's total capacity. Nevertheless, its high capital investment limits its applicability and, as it usually must be built into the facility originally and cannot be retrofitted, it is difficult to apply to existing infrastructure (Blomen, Hendriks, & Neele, 2009).

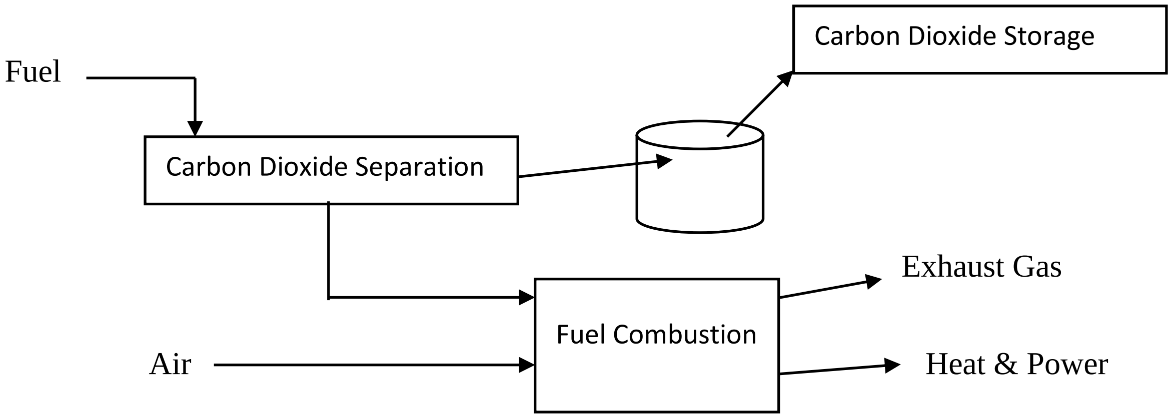


Figure 7 - Schematic of a Typical Process Flow Diagram of Pre-combustion Carbon Capture. Adapted from Theo, Lim, Hashim, Mustaffa, & Ho (2016).

2.1.1.1.1 Absorption

2.1.1.1.1.1 Selexol / Rectisol

Representing the solid domain of absorbents, Selexol and Rectisol are processes used to remove CO_2 from syngas before combustion. This is achieved by by dissolving acid gases through increased pressure in the chamber and releasing them when pressure is decreased and temperature rises. When used in Integrated Gasification combined cycles, the energy penalty for the process drops to 7-8%, which is superior to some post-combustion technologies. The process involves a two-step removal task which includes:

- the absorption of H_2S and separation of sulphur as a sellable by-product; and
- removal of CO_2, leading to the regeneration of the solvent and production of clean hydrogen-rich syngas for combustion (Global CSS Institute, 2019).

Absorption capture using Recitsol presents remarkably high electricity costs of 145 €/MWh but at an extremely high CO_2 purity of nearly 99.5%. Comparatively, Selexol requires €/MWh 20 less and produces at a slightly lower CO_2 purity of 98% (Porter, et al.).

2.1.1.1.1.2 Amine-Based Solvent

Whilst similar to the process of physical absorption, solvent-induced pre-combustion processes use gasification through the two-stage H_2S and CO_2 separation process by adding MDEA solvents to an IGCC plant. Studies of this usage show that a capture of 87% is possible with a net energy penalty of 9.5%, however the study does not offer any cost considerations (Moioli, et al., 2014).

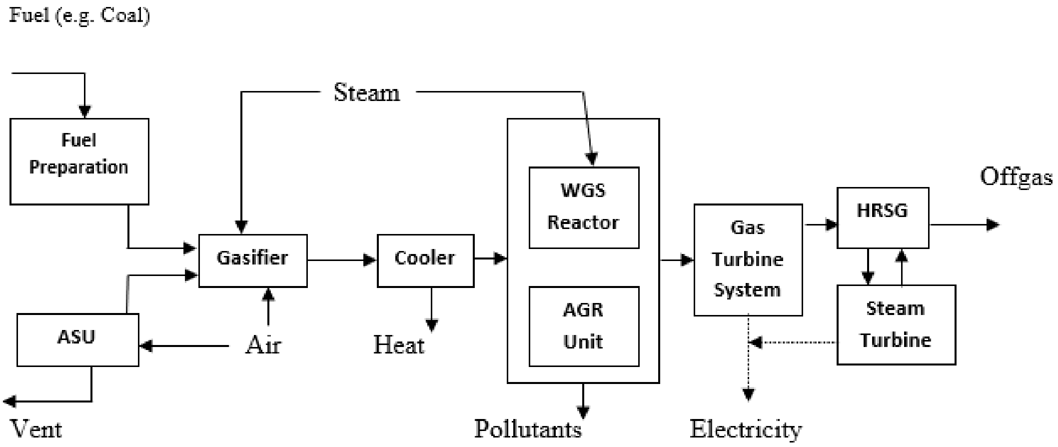


Figure 8 – Schematic of an IGCC process: Integrating Gasification with Combined Cycle Technology. Adapted from Sorgenfrei (2016).

2.1.1.1.2 Adsorption

2.1.1.1.2.1 Microscopic Polymeric Membranes

While most membrane technologies are applied in the post-combustion power facilities, recent data is looking towards utilising them before the combustion process as a means of significantly increasing the energy efficiency of such systems. Such an innovation that can meet both the permeability and selectivity of gases as required in the gasification process can have major impacts on world energy use, as distillation and purification processes account for a significant portion of world GHG emissions.

Research into such membranes includes: thermally rearranged polymers; intrinsic micro-porosity; covalent organic frameworks; porous organic frameworks; and more, each of which have their own shortcomings or challenges. While still in the experimental lab research level of viability, the porous organic frameworks show promising results to achieve H_2 / CO_2 separation at the temperature and pressure conditions of a gasification chamber. However, lack of stability, ultrathin character and vulnerability, and decreased performance in the presence of water are some challenges accompanying this innovation (Shan, et al., 2018).

2.1.1.2 Post-Combustion

One of the most common methods of separating CO_2 from other flume gases in power stations, petrochemical and heavy industry sectors is chemical absorption, especially using solvents - typically amines and ammonia. Post-combustion is applicable to all industries and, due to the ease of retrofitting it to any factory type, it provides an easily managed installation and management process. In this technology, fuel is combusted to generate heat or electricity, before the CO_2 gas is mixed with a solvent in a separate absorber chamber to liquify. The CO_2 is separated from the solvent in a stripper chamber, producing reusable solvents and pure capturable CO_2. Some of the barriers to implementation include: high capital investment; increased cost; and decreased level of electricity output due to process energy intensiveness.

2.1.1.2.1 Absorption

2.1.1.2.1.1 Amine-Based Solvents

Aqueous amine capture has been found to be a valuable method for application to Natural Gas Carbon Capture plants. Despite the medium 49.5-51.8% level of capture, the ease of their integration, technological maturity, and ease of access has made them a popular choice for commercialisation (Subramanian, et al., 2017). The disadvantages of amine-based solvents include: high vapor pressure; corrosiveness' and high-energy input for regeneration (Babamohammadi, et al., 2015).

Amines are also volatile and diluted in water, the latter of which leads to excess energy consumption in each heating and condensation process. Pressure conditions set apart pre- and post-combustion processes, leading to the requirement of tuneable or suitable sorbents. Volatility is a major issue for solvent retention in high temperature processes and liquid solvent-based procedures require high selectivity and affinity for carbon dioxide capture (Liang, et al., 2015). Many Amine-based plants have been identified - one of significant interest is the Shidongkou power plant in Shanghai, China, which is reported to capture 120,000 tCO_2 /year at a total cost of US$24 M, providing one of the most cost-effective major scale examples of this technology. In comparison, the US$ 668M AEP Mountaineer facility in West Virginia, USA reports a capacity of 100,000 tCO_2 /year (Oko, Wang, & Joel, 2017; MIT, 2016). Amine absorption has been found to be the best current technology for capturing CO_2, according to a study by the Carbon Capture Project (Makertihartha, et al., 2017).

2.1.1.2.1.2 Alkaline Solvents

While overall research and applicability within the industries is limited on Alkaline Solvents (Wu, et al., 2014), compared to amine and ammonia solutions, some research shows that the base absorption efficiency level of alkaline solvents is higher at 92%, compared to the formers' 61% and 78% base efficiency. At the same time, the alkaline nature of such solvents means that they are highly corrosive which leads to higher operating costs. Such discrepancies also pave the way for experiments with a blend of different solvents to achieve an optimal level of suitability (Peng, et al., 2012).

2.1.1.2.1.3 Ionic Liquids

Ionic liquids present unprecedented opportunities for a new absorption material with the potential for higher stability and easier workability to be introduced into carbon capture. While as many as 10,000 ionic liquids exist, recent research in various countries is leading towards the identification of the most robust selections for this application through database creation, cost modelling and more (Zhao, et al., 2016). Some recent examples include the identification of 100% pure liquid salts with extremely low volatility and corrosiveness, with an easy process for extraction of captured CO_2 (Maginn, 2014).

2.1.1.2.1.4 Carbonic Anhydrase Enzyme

Recent innovations by countries which are aiming to make these technologies commercial include CO2 Solutions Inc's first commercial project, which utilises a unique enzyme-enabled carbon capture mechanism inspired by the respiration process of CO_2 exhalation in human lungs. The company's system is being deployed for a 30-tonne per day capture capacity, with the aim of commercially selling carbon in the next year (CO2 Solutions Inc, 2018). While the company boasts:

- 90% post-combustion emissions capture'
- major cost reductions of 35-60% compared to other technologies on the market;
- a 99.95% purification rate;
- high tolerance to other gases;
- reduced pre-treatment;
- low operating temperatures;
- waste-less technology; and
- low corrosivity

this is yet to be witnessed in action, as the 30-tonne per day amounts to 0.01 Mt CO_2 per annum and its cost effectiveness will be determined once operational (CO_2 Solutions Inc, 2019). Nevertheless, there is some evidence in academic research that a high pH, exposure to nitrate, nitrite, sulphates or sulphites, and stability at high temperatures may affect its performance and resilience (Yong, et al., 2017).

2.1.1.2.2 Adsorption

Adsorption is an industrial process through which a gas or liquid becomes accumulated on the surface of a liquid or solid material It is a mechanism for capturing materials after various processes to separate the required chemicals or elements, in this case being carbon (Nowicki & Nowicki, 2016). Accordingly, different Carbon Capture Technologies (CCTs) use different liquid and solid materials to achieve this aim - these are presented below.

2.1.1.2.2.1 Amine-Based Solid Sorbents

While the application of amines was presented for absorption purposes in both pre- and post-combustion, the energy intensiveness of regeneration as well as corrosion issues of these processes can be countered through chemical adsorption of CO_2 using porous supports to which amines are attached. Such materials include a blend of amine sources and support materials, including mesoporous silica and polymers with different content and capacity arrangements.

Large scale use of this technology has not yet been achieved, and more research is required to increase its molecular stability, capacity, cycle lifetime and durability, amongst other factors (Monkul, et al.2017). Some solid research on the topic has been carried out by Cornell University through the development of “nanosponges” which allow for the amine to become chemically bound to the sorbent, hence reducing amine loss over time. This “nano-scaffolding” technique also helps to save costs by ensuring that amines are retained in the processes (Qi, Fu, & Giannelis, 2014).

2.1.1.2.2.2 Alkali Earth Metal-Based Solid Sorbents

Considering the above difficulties in achieving a solid sorbent which meets the requirements of stability needed in the adsorption process, other mechanisms to promote this behaviour have included the promotion of alkali and alkaline-earth metals in conjunction to improve the adsorption properties of sorbents such as magnesium oxide, with Lithium, Calcium, and

Strontium. Such studies are at a computational level and yet to even turn into pilot plant prototypes, hence they only present potential means of improving the use of metal-based solid sorbents in both post-and-pre-combustion (Kim, et al., 2014).

2.1.1.2.2.3 Zeolites

Zeolites are natural volcanic minerals which are formed when erupted volcanic ash interacts with salt from the sea - the material has great benefits for the removal of toxins, heavy metals and maintaining alkalinity (Zeolite, 2014). Due to their volcanic origin and embedded resistance to heat, zeolites present significant potential as a membrane for adsorption of CO_2 in post-combustion, in addition thanks to their unique sorption-diffusion separation capacity. The main obstacle towards widespread use of zeolites is their high price as they can only be sourced from places near volcanic activity, hence why in industrial examples, many are seeking to mix it with polymers for membrane creation (Makertihartha, et al., 2017).

2.1.1.2.2.4 Activated Carbon

Activated Carbon technologies include the development of a microporous carbon material with enormous internal surfaces which allow specific components from gas streams passing through the filter mechanism to be adsorbed. The efficiency of this process is dependent on several variables, including: pressure; temperature; air humidity; and type of pollutant that is being removed - it can reach 98% yield for concentrations of up to 2000 ppm.

Activated Carbon feedstock can be sourced from many organic waste products including wood, coal, peat, coconut shells and other agricultural products which are transformed into biochar. Some advantages to the technology include high efficiency, ease of maintenance and placement, while some of its disadvantages include lack of suitability for wet flue gases, complications with dust, malfunction with component mixtures and risk of spontaneous combustion (EMIS, 2019).

2.1.1.2.2.5 Microporous Copper-silicate

There are numerous other experimental materials which may eventually hold the answer to breakthrough in carbon capture. An example is a copper silicate crystal which is devised for DAC and flue gas systems, due to its ability to adsorb CO_2 and water in different sites within it making it resistant to humidity. The stability of the material, also known as SGU-29, presents great potential for cost saving through the removal of the water & CO_2 separation process, should it be proven for scalable commercialisation in the coming future (Datta, Khumnoon, & Lee, 2015).

2.1.1.2.3 Membrane Separation

Membrane systems represent methods of using ‘sponge-like’ materials to capture CO_2 from emission sources in a high flux, cost-effective and efficient method. The difficulty in separation of molecules in flume gas, including CO_2, is that often these molecules are of a similar size and thermal profile, making capture and separation a difficult process which is highly dependent on the material used as membrane and the chemical profile of flume gases being developed. A great barrier to various membrane separation processes includes the need for tall distillation columns which require energy-intensive and high-cost capital for plant construction and separation processes.

2.1.1.2.3.1 Polymeric Membranes

One category of polymers which are of use in polymeric membranes include ethylene, which can be captured and recycled from a large variety of polymer products that are produced in different industries today, i.e., plastic bags. Nevertheless, polymeric membranes do not have great efficiency for high CO_2 capture rates, being found to be around 34.9 -46.2% (Subramanian, et al., 2017).

2.1.1.2.3.2 Inorganic/Hybrid Membranes

The previously-mentioned material known as Zeolite is also promising for use in membranes for post-combustion CO_2 separation and capture - they are considered as a favourable industrial material due to their thermal and chemical stability, tight control, sorption-diffusion separation mechanism, micro-porosity, and more. Meanwhile, the industrial level of utility of the material is not yet feasible due to the relatively higher price - to meet this challenge, researchers have proposed its potential to be used as a hybrid membrane which is mixed with polymers (Makertihartha, et al., 2017).

2.1.1.2.4 Cryogenic Separation

Used as a method of separation in oxy-fuel processes, cryogenic separation presents a method of refrigeration through a nitrogen removal unit. This process allows the capture of CO_2 in various forms, with some recent research proposing liquid CO_2 as an effective mechanism with potential for capture of 83.7% of CO_2 produced with 99.17% purity (Knapik, et al., 2018) as well as ease of transport compared to condensed gas. While cryogenic separation is used in facilities with high CO_2 concentration such as oxy-fuels, it is not yet a common process for more dilute systems. Other barriers for this technology include the energy required for the cumbersome refrigeration process, as well as difficulties with water separation technology (CO_2 Capture Project, 2008).

2.1.1.2.5 Microalgae Bio Fixation

Considering not all CO_2 is produced just from power plants, there can be applications for capturing CO_2 from other natural and anthropogenic processes, including forest fires, volcanic eruptions, decomposing organic matters and automobiles. The use of specific strains of microalgae holds potential for many of these non-industrial and industrial processes, by producing biofuels which can be used in place of petroleum products. This process turns CO_2 into lipids, and it is dependent on CO_2 concentration, light intensity, temperature and nutrition, which includes nitrogen and phosphorous. As biological processes make use of photosynthesis, they require a relatively environmentally friendly and low-intensive CO_2 fixation procedure which can be a beneficial method instead of heavy industrial processes. The use of photobioreactors at emission source allows for the application of microalgae for carbon capture without the need for transportation (Mondal, et al., 2017).

The process and use of natural materials also has relevance when considering the formation of biochar - a material like charcoal which is produced when organic waste is burned in oxygen-free chambers in a process known as pyrolysis. The biochar is then buried into the soil in a manner that can allow it to capture carbon safely for thousands of years.

This process heats organic waste to the point that it becomes like charcoal but it is not entirely burnt, and can be carried out next to existing syngas and oil production. While the evidence for biochar is divided, a study by Cornell University claims that sustainably obtained biochar which does not impact food and soil production can reduce global gas emissions by 12% from the stabilisation of decaying organic material; which naturally emit carbon dioxide (Levitan, 2010). Not much practical research in the form of pilot studies have been identified by the author, nevertheless over 4400 academic studies have included all the three keywords of "pyrolysis" "carbon sequestration" "biochar" since 2015 (Google Scholar, 2019), showing the vast interest of the scientific community in pursuing the technology and realising its potential.

2.1.1.3 Oxygen-Fuel Combustion

2.1.1.3.1 Oxy-Fuel Process

As oxygen is the main ingredient in air, which is required for combustion, separating it from the regular atmospheric air allows for a cleaner burn, and an easier process of separating carbon after combustion. This is because the flue gas produced in this instance produces only CO_2 and water which is easily separated through a condensation process. The technology can remove other dangerous chemicals from the process, including nitrogen oxides, and it does not need the energy and resource intensive chemical processes of most other mainstream solutions. The lack of chemical processing also allows for a more efficient capture of CO_2. However, the separation of oxygen from air is not yet commercially viable, leading to extremely high capacity costs, energy intensity and difficulty retrofitting into existing plants.

2.1.1.3.2 Chemical Looping Combustion

Chemical Looping Combustion utilises a reversible combustion mechanism through which metal oxide systems reverse chemical reactions. Using metal oxide particles as carriers of oxygen, combustion in the two-chamber format allows for reduction of energy penalties. While energy produced in the first chamber leads to the development of a metal oxide, this is turned into syngas and metal in the second chamber, allowing the metal to be reused for the process while the syngas is taken forward. This conversion of fuel into syngas without oxygen purification has substantial economic benefits and it has also been dubbed as a ‘flameless combustion’. This is at odds with the intuitive view that processes require 700-900 °C temperature conditions for effective use of the metal compounds and the engineering ingenuity are to reach such levels without producing flames (Global CSS Institute, 2019). Meanwhile, the idea has not yet become commercially viable, but examples such as the 120 kW chemical looping pilot rig in the Vienna University of Technology show some of its applications, barriers, limitations, and successes as one of the first operating facilities in this field (Kolbitsch, et al., 2009).

2.1.1.3.3 Chemical Looping Reforming

Chemical Looping Reforming is a mechanism for reusing various liquid forms of fuels in a closed circuit to make the most out of its potential for energy production. This process can include sources such as kerosene, ethanol, sunflower oil, biomass tars, waste liquid fuels and waste cooking oils, as these fuel types mostly represent complex structures which may not combust as easily or cleanly as petroleum. Furthermore, the formation of syngas through the oxygen-fuel combustion process allows for numerous levels of “reforming” to remove organic contaminants until a desirable molecule size is achieved and used to produce clean H_2 (Ryden, 2015).

For the example of a post-combustion GTL CCS system, the Figure 8 shows how GTL flue gas is used through heat recovery to achieve 98% CO_2 capture.

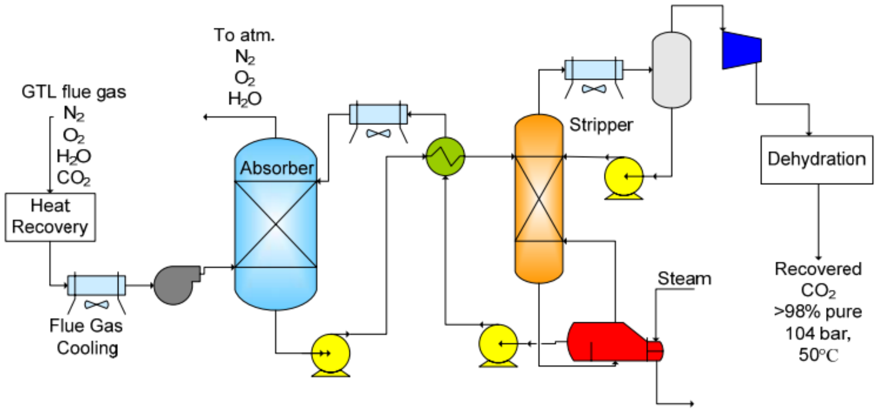


Figure 9 - Post Combustion Process for GTL Carbon capture (Heimel & Lowe, 2008; p. 4042).

The oxy-fuel combustion process differs in the sense that flue gas from the GTL process is recycled and combined with 95% pure oxygen and fed into the system again, while nitrogen is removed at later stages. This is shown in Figure 9:

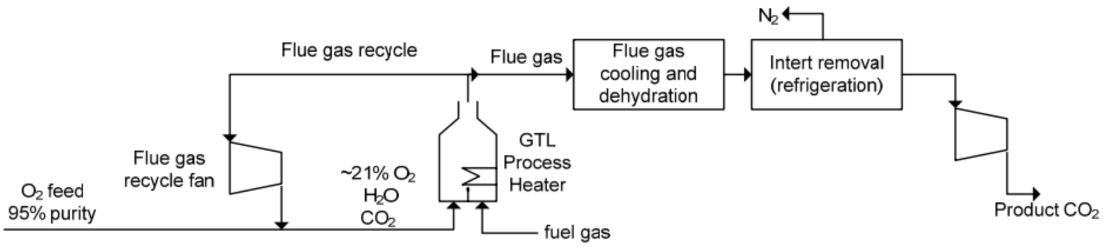


Figure 10- Oxy-Fuel Capture in GTL Plants (Heimel & Lowe, 2008; p. 4043).

While the lack of availability of reliable techno-economic analysis for this technology was mentioned, the potential for post-combustion was most recognised in the answers, followed by oxy-fuel which is more limited in its scope of application to a GTL process (heaters and burners). Pre-combustion may be applicable to the syngas generation process.

Nevertheless, in-depth analysis of different GTL plants is required for this means, which requires an in-depth plant-based study in Qatar and thus is outside the scope of this study.

2.1.2 Direct Air Capture (DAC)

The numerous attempts at directly capturing CO_2 from the atmosphere and transforming it into manageable collections of carbon has been referred to as mechanisms of “direct air capture”. Several companies, including ClimeWorks have moved towards commercialisation, readily selling their systems to customers in a range of industries (ClimeWorks, 2019). The modular system is customisable with a choice of the number of individual CO_2 collectors that it uses, as well as additional equipment including cooler and heater modules, post processing modules, including a gas buffer, CO_2 conditioning and storage. Other DAC technologies often differ in the means of their capture and storage into a biproduct - the air-to-fuels technology recycles the captured CO_2 into forms of liquid fuel that can be used instead of crude oil. The company behind the technology boasts the competitive rate of $1 per litre for this fuel type when scaled up which is compatible with prices from the oil industry (Carbon Engineering, 2019).

Direct air carbon capture and geological carbon storage mechanisms are viable according to numerous variables which affect it - fuels created from atmospheric CO_2 have a significantly lower life-cycle carbon intensity than those created from geologically-stored CO_2, and due to differences in revenue streams and costs, the scale of application varies between them (Carbon Engineering, 2013).

The main shortcoming with DAC technologies is that the amount of CO_2 as a percentage of chemicals present in the average ambient air conditions is not concentrated enough to make this technology commercially viable; however, it may present a valuable solution in extremely polluted microclimates such as congested cities. Nevertheless, the feasibility of DAC technologies is an ongoing academic question which does not have a solid answer, yet progress is being made within the field (Tollefson, 2018).

2.1.3 Bioenergy with Carbon Capture and Storage (BECCS)

Recent research by the Royal Society of Chemistry has found that BECCS technology can have a wide range of positive and negative consequences, depending on numerous nuances of the technology. These include sources of energy loss, i.e. biomass conversion, transportation, drying and farming, power plant efficiency, vehicular fuel efficiency, transport distance, moisture content, etc. The technology is also highlighted for its simultaneous capacity to produce electricity and remove carbon, with the two sides of this balance affecting its return-on-investment potential (Fajardyab & Dowell, 2018, p. 1592).

2.2 Types of Carbon Storage, Utility & Other Factors

As one of the most established forms of carbon storage and utility, many experiments have been carried out on the commercialisation of capture and permanent storage in the earth's subsurface (Page et al., 2019; GCCSI, 2021). Regardless of the capture mechanism, geological storing allows for the storage of carbon in kilometres-deep geological formations, including gas and oil fields from where they were originally taken from. These can include coal beds (mined, drained or unmineable), deep saline ground water in porous rocks, volcanic rock formation in basalt (CarbFix) or altered mafic reservoirs. This released carbon into the substrates is stabilised through various processes which either ensure safe trapping of the carbon in structural formations, or alteration through chemical reactions with the surrounding environment which can include rocks, saline water, and other carbon compounds. In the case of the leading example of this technology, the CarbFix team (constituting a collaboration between ClimeWorks, University of Iceland and other partners, including EU funding), has been successful with the Hellisheidi power plant in Iceland by reducing 40% of the plant's emissions, storing it into the subsurface and proving its transformation into stable rocks in just two years (CarbFix, 2019). Utilising MIT's now-defunct CCSU project database, examples of this can be found; i.e. the case of Citronelle, a capture and storage project linked with the Plant Barry power plant in Alabama, connected with a 10-mile pipeline, at a total project cost of $111.413 million, utilised storage in a deep underground saline reservoir, with a capacity of 0.24 M tons of carbon storage in its 2.5 years of operation (MIT, 2016).

Storage can also occur in deep off-shore saline aquafers as seen in the case of Korea's carbon storage projects. This project aims at capturing carbon from coal through IGCC and oxy-fuel processes, while surveying, researching and successfully storing carbon dioxide in several deep saline reservoirs, and capturing an aimed 3 Mt / year (Wang, Kim, & Lee, 2016). Another storage site type is depleted gas reservoirs which have already been mined - this has been executed in Algeria’s In Salah oil field, where 1-1.2 Mt/yr were pumped into the reservoir from 2004 to 2011, before operations were eventually stopped as concerns about leakages became substantial enough to become a potential threat. Up to now, advanced monitoring mechanisms are used to make sure that no leakages occur, such a project and its uncertainties highlight the difficulty in assessing such novel technologies, understanding their long-term effects on the environment, and determining their potential for man-made natural disasters (Ringrose, et al., 2013). Yet in spite of such complications, CCS continues to make significant progress around the world as demonstrated in the 2021 Global Status of CCS report, which reveals that global storage capacity has increased 32% in the last year alone. There are now 135 commercial CCS facilities in the project pipeline (27 are fully operational) from a diverse range of sectors including cement, steel, hydrogen, power generation and direct air capture.

2.2.1 Carbon Nanofiber Combined Cycle (CC CNF)

As a means of increasing the efficiency of natural gas energy plants and mitigate its production of CO_2 into the atmosphere, certain technologies are attempting to feed this source of pollution back into the system and capture in a valuable format. One instance of this is the conversion of CO_2 into carbon nanotubes; a highly valuable carbon product with a 10000-fold value compared to the $30 tax costs per ton as a government incentive in the United States (Lau, Dey, & Licht, 2016).

2.2.3 Fuel Cells

While the concept of FC energy has been around since the 19th century when a scientist realised that reactions between hydrogen and oxygen can generate electricity and water. Since then, numerous efforts to turn FCs into a valuable technology have been thwarted by cost, durability and security of hydrogen supply, and the promise of the technology has significantly let down green energy enthusiasts, only to raise their hopes again. Current studies at the Barry Plant between FuelCell Energy and ExxonMobil include the development of a FC technology which can capture up to 9000 metric tons per day to 95% purity, however, the technology requires significant electrical needs which is currently provided by natural gases and presents a counter-intuitive case of requiring more fossil fuels to generate energy for its fossil fuel management (Eisler, 2018). Other research also presents potential for carious FC technologies to be quite high. Namely Nouman (2019) found the post-combustion retrofitted Molten Carbon FC carbon capture mechanisms to capture hydrogen, generate electricity and allow for avoidance of up to 94% CO_2. Similarly, a recent study based in Qatar by Al-Khori & Mohammed (2020) investigated the potential of Solid Oxide FCs in natural gas processing plants. These devices can turn chemical energy directly into electricity without the need for combustion and they can be integrated into various parts of a plant system, namely boiler, flare unit and PV systems. This system was found to bring significant emissions reductions, less use of fuel for electivity, annual savings of 200,000 tonnes of CO_2 equivalent in the total system, and lower levelized costs of electricity. Overall, the field of FCs is an exciting and novel prospect which must be inquired in further depth.

2.2.4 Transportation

The transportation process involved in CCSU depends on the type of capture and storage facilities required for each specific situation and, accordingly, it cannot be generalised easily. Some methods of transportation include using pipelines for relatively close capture to storage facilities, while longer distances can be covered by a mix of road, rail and shipping mechanisms. Transportation represents a major contribution to GHGs,, therefore it has been proposed that some of the less environmentally-demanding and less-energy intensive processes include those that are developed near infrastructure clusters where it can be utilised or stored quickly (Mander & Miller, 2018, p. 5). Regardless of distance, gas CO_2 must be compressed to almost the same density as a liquid to be transported in a cost-efficient means that can easily be injected or turned into a utility - in such a process, the gas compresses by over 99% to liquid form (CSS Browser, 2019).

2.3 Energy Penalties Estimates from Carbon Capture technology

The energy required to run a capture process is known as the energy penalty (EP) (Jenni et al., 2013; Vasudevan et al., 2016), and can be formally defined as: "*The energy required to capture a ton of CO_2 divided by the electrical energy generated by the power plant per ton of CO_2 emitted*" (Bhown and Freeman, 2011). The EP therefore gives an estimation of the amount of energy that needs to be expended for carbon capture in relation to the energy generated by the plant (Vasudevan et al., 2016). Or simply put, it is the relative increase in energy input or the relative decrease in electric power output of a power plant with capture compared to the same power plant without any carbon capture technology installed.

EP provides stakeholders with an objective value or measure they can use when considering whether to implement a proposed capture technology in conjunction with the footprint and capital costs of the capture plant. Work by Vasudevan et al., (2016) considers the energy penalty related to CO_2 capture from coal, natural gas and fuel oil-based power plants. Their study evaluates the minimum thermodynamic work for CO_2 capture, and considers all the three modes of capture-combustion: pre-combustion, post-combustion, and oxy combustion. Their findings revealed that natural gas-based power plants achieve the highest capture energy per ton of CO_2. However, pre-combustion capture in natural gas-based power plants achieved the lowest energy penalty of 10% (versus 17% for coal-based power plants). The highest energy penalty of about 20% is found for oxy combustion capture from coal-based power plants (Fig 10). In general, pre-combustion capture seems to provide the lowest energy penalties.

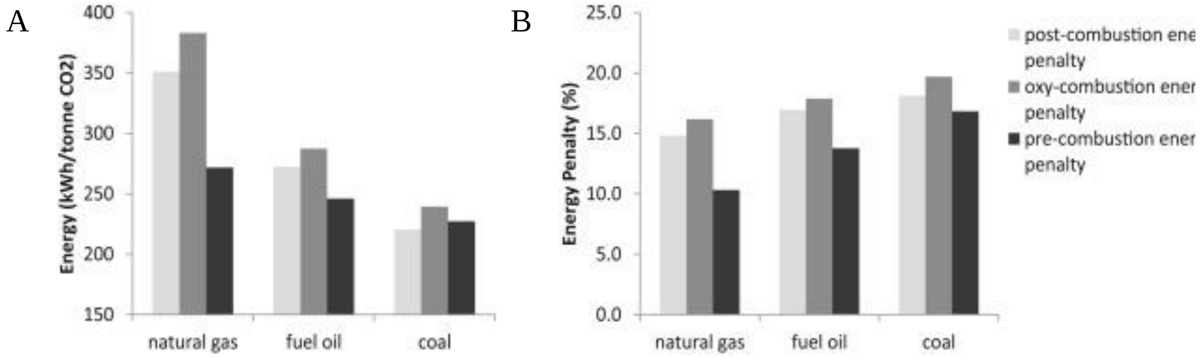


Figure 11- A) Energy cost for different methods for CO2 capture, B) Target energy penalties for different methods of CO2 capture (Adapted from: Vasudevan et al., 2016)

From this it can be surmised that the best option for new power plants would be to utilize natural gas with pre-combustion capture. For existing plants, where there would be additional capital costs associated with retrofitting for pre-combustion, oxy or post-combustion capture will likely take precedent. Of the former two, post-combustion seems to be the more attractive option associated with lower energy penalties (Vasudevan et al., 2016).

2.4 Life Cycle Assessment

The potential benefits of CCS technology need to be assessed using a Life-cycle assessment (LCA), also known as life-cycle analysis prior to their implementation. LCA is a primary tool used to account for the environmental impacts of a product or service throughout its entire life cycle and is used to support decision-making for sustainable development (Muller et al., 2020). The process involves careful consideration the entire life cycle of a product from cradle to grave; from selection of raw-materials, transportation and packaging, to the products end use, maintenance, and its eventual disposal or recycling. In the 1990s the international standardization organization (ISO) standardized in the LCA methodology with ISO 14040/14044 which is still regularly updated (most recently in May 2018). ISO 14040 describes the ”principles and framework for LCA”, while the ISO 14044 “specifies requirements and provides guidelines” for LCA (European Committee for Standardisation, 2009, 2018).

According to the ISO standard, a LCA study is sub-divided in four phases (Figure 11):

1. Goal and Scope definition

2. Life cycle inventory analysis

3. Life cycle impact assessment

4. Interpretation.

However, even though LCA is a standardized method, practice differs widely in methodological choices (e.g. selecting the system boundaries, or functional unit -the product, service, or system whose impacts are calculated by a life-cycle assessment). The resulting LCA studies show large variability even for identical technologies because different processes are selected for the production of feedstocks or utilities., which limits their value for decision support (Muller et al., 2020).

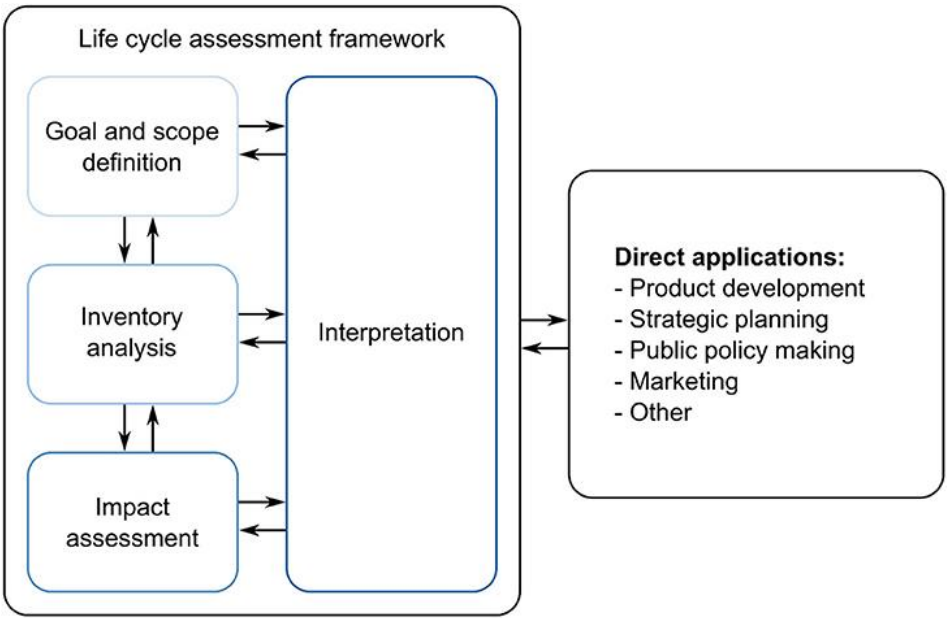


Figure 12 - General framework for life cycle assessment (European Committee for Standardisation, 2009; Muller et al., 2020).

2.5 Business Models

For the implementation of CCSU technologies, the business model for arguing the case to utilise CCS technologies must be taken into consideration. The CAPEX and OPEX of these projects, as well as the risks, opportunities and revenue streams of these ventures must all be taken into account when considering whether it is viable to install these systems within an economy.

Amongst other nations, a lot of drive comes from agreements made internationally to meet targets, which if missed can result in large fines, therefore presenting a large risk or expense to not implementing technologies in the first place. In areas such as Europe and North America there are also the technical skills available to be invested in to further develop these technologies, consequently reducing their costs and improving their perfomance and efficiency.

The Qatari government do not have so many of these drivers, though have demonstrated some ambition to meet the needs of other nations by committing to increasing their carbon capture by 2030. This allows them to show they are willing and determined to meet international agreements, however their capabilities fall short of those in other continents. Whilst there is plenty of capability in the scientific areas to develop these technologies, it is not a priority in their research and so there is an increased reliance on knowledge from other nations in order to supply the necessary solutions.

Fortunately, many of these nations have interest in investing in the area due to the natural resources being supplied – additionally, this can be seen as a measure taken by these nations to counter their use of the resources from the region, which lead to higher levels of CO_2 in the atmosphere.

A business model can also be created around carbon storage, where a revenue stream is generated by other nations looking for store their carbon emissions in available solutions, and will pay for the privilege. This benefits nations which have natural geological storage solutions.

Qatar is one of these, both through saline aquifers which cover a large portion of the nation, as well as the hydrocarbon fields from which the oil and gas is obtained – these have demonstrated their capability for storage by holding the oil and gas for many centuries. However, whilst the country can take advantage of this, they are in more of a position where they need to use these stores for themselves, due to their CO_2 outlay from extracting the resources and their large scale construction projects. This provides less of an income stream. It must also be considered how the CO_2 from other nations is transported to the country, and whether this is economically and environmentally viable for those that want to use these storage options.

Both of these issues require more drive from the government to encourage utilisation of this model, and potentially provide some investment to ensure it is employed. However, the government have more interest in investing in their infrastructure and improving the country's standard of living, reducing the likelihood that this business model will be used. Whereas these models can be easily implemented in areas such as Europe and North America due to the technology, skills and investment available, it is not a solution that is as straightforward for Qatar and nations in the surrounding region. This is a consideration that must be made for applying CCSU technologies to the area.

2.6 Socio-Economic & Sustainable Drivers

Literature concerning the political economy factors on environmental regulation effectiveness, despite being young, has encountered speedy growth. Madhoo (2013) empirically investigates environmental regulation politics in relation to proactive lobbying at various public environmental management levels, such as legislation enactment and policy implementation. Environmental regulations effectiveness in the proposed models is captured by: the achievement of different goals on environmental performance; the degree of enforcement; and environmental regulations stringency level. From cross-country regressions, the study's findings supported the capture theory in which it was established that at the legislation level, greater resources availability and small size render Small Island Developing States industrial groups powerful. Unlike Grey (2018) who indicated innovation as the driving factor to lobbying, Madhoo (2013) found that industrial lobbies' rent-seeking behaviour seemed to be channelled through corruption. However, they are limited by better rule of law, improved governance measures, and high reliance of SIDS on international trade. The author found that both agriculture and industry were proactive about noncompliance to environmental legislation at the implementation level, and this caused significant damage to the environment. At the legislative level, agricultural lobbies were found to be weak and could have resulted from extensive support that governments provide to agriculture, which acts to nullify or dampen any farmers' cost borne due to stringent environmental laws. On the other hand, the tourism lobby's impact on the performance of the environment is yet to be concluded. In SIDS, tourism lobbies maintain certain environmental quality level, and even after controlling for their association with different variables (governance effectiveness, rule of law, and corruption), these lobbies do not severely and adversely impact the implementation phase.

Even though lobbying, especially after the development of cleaner technologies by respective firms, has been shown to facilitate environmental protection and increase market share (Grey 2018), there has been an enormous amount of discussions as to whether the environmental policy has the capacity to improve the competitiveness of organisations for more than two decades. Consequently, Lundgren and Zhou (2017) carried out an investigation to shed light on this debate by investigating the associations between three aspects of companies' performance, such as environmental performance, energy efficiency, and productivity by particularly paying attention to the obligation they have towards the management of the environmental management. In relation to the study performed by Lundgren and Zhou (2017), environmental management was defined as those investments that aimed at reducing the impacts on the environment, and that could additionally impact the competitiveness of firms in terms of productivity change and incentivize more (or less) efficient energy use.

To investigate the causal and dynamic link between the environment investment and the three firm performance dimensions as well as to determine the Malmquist firm performance indexes, the study applied two techniques, a panel Vector Auto-Regression (VAR) technique and data envelopment analysis (DEA) methodology, respectively. The findings revealed that the environmental performance and energy efficiency are integrated, and that productivity and energy efficiency reinforce one another positively, suggesting the cost-saving behaviour of more efficient energy use (Wang & Zhang, 2013). Therefore, as several modern day's energy policies advocate, increasing the efficiency of energy could possibly provide several benefits to companies. The findings additionally established that improving environmental investments and performance has the ability to oblige next period productivity, an outcome which contrasts the strategic corporate social responsibility and Porter hypothesis, which underline and convey the perception that directing efforts and supporting environmental management may significantly improve a firm's competitiveness and productivity.

According to Gupta and Innes (2014), corporate environmentalism has recently been used by most companies to manage the environment. In particular, as a way of promoting environmental objectives, the utilisation of private political tools and activism has been rising, and this was evident from the number of continuing animal rights and environmental boycotts of organisations and companies that increased from 27-43 between 1990 and 2011. In addition, voluntary approaches to pollution management have recently increased, and private sector organisations have increasingly and voluntarily embraced environmental management practices the authorities do not require from them (Segerson 2013), and these approaches can only be effective if designed carefully alongside a good political climate in which the approach is enacted. In studying the effects and determinants of private political actions and considering impacts on the environment protocol and environmental management systems adoption, Gupta and Innes (2014) found that private political actions significantly influence an organisation's environmental management decisions. In fact, firms considered as "receptive targets" with a reputation for social responsibility have greater probabilities to experience such actions.

While most studies that have been analysed so far have majorly focused on environmental protection approaches from the individual firm perspective, some have given emphasis on the important role played by global environmental standards as a strategy to combat industrial pollution. These standards, as asserted by Angel, Hamilton, and Huber (2007), arose during the 1970s as a healthier approach to state-centred environmental regulatory systems among OECD nations and were believed to have a multifaceted genealogy, arising from two factors, namely public health and ecological analysis as well as taking into consideration the regulatory process efficiency and the intervention equity to deal with competing social priorities, including economic growth and environmental protection. The authors note that three factors contributed to the interest to adopt global standards: the increasing force of what could be included under global ethics networks, the challenges of complex global production networks management between countries with different regulations, and concerns over the emergence of a regulatory deficit arising between global economic flows and country-based regulation. As firms, NGOs, and policymakers saw global environmental standards as a platform for intrafirm innovation and learning and to facilitate trade and manage complex global production networks, the rationale to adopt environmental standards have become more complex. According to Angel, et al. (2007), the predominant architecture that underlies today’s global environmental standards is networked and not of global territorial coverage. The authors also indicate that many hybrid forms distinguished by authority structures, drivers, and standard content exist within this wider category. Angel et al. (2007)’s industry global environmental standards review fits within broader debates concerning the environmental policy reinvention through new forms of global and environmental governance. Although a discussion over the benefits and costs of the shift to governance from government continues, studies on governance are somewhat unified behind the claim that different stakeholders at various scales are presently emerging together with the previous regulatory standards that were mainly used by the state.

To achieve economic and environmental goals of their respective governments, policymakers across the globe select a wide variety of regulatory and policy instruments. In industrialized countries, direct regulation has significantly delivered environmental improvements and has been extensively used in situations in which a regulatory outcome certainty is desired, as a way of preventing 'free-loaders' in which it is necessary for stakeholders to quickly adopt measures and to have a secured confidence in the public when combined with a system of ensuring it is implemented. Conversely, as noted by Taylor, et al. (2018), direct regulation has the problem to potentially hinder international competitiveness and innovation, and this has compelled governments to look for other options and to get regulation through approaches based on risk. Practically, instruments rarely function independently; rather, they form a complementary mix influencing behaviours across multiple actors and through various levels. In addition, the origin of regulations might dictate the approach to be taken may necessitate a 'command and control' approach.

On the other hand, only the treasury of the state can introduce some economic instruments, including taxes. In their semi-structured interviews with the UK's Department for Environment, Food and Rural Affairs (Defra) policymakers, Taylor, et al. (2018) intended to examine the utilisation of various regulatory instruments and various risk levels across eighteen separately named risks and fourteen policy domains. From the framing analysis, the study found mixed views, although noticeably positive for economic instruments, such as the provision of information, fiscal instruments, and taxation. In contrast, an overlap analysis investigated the mapping of public environmental risks of officials to types of instruments that are appropriate to their management. The findings demonstrated that despite the disadvantages associated with ‘command and control’ approaches, it is still the most preferred by policy officials when an outcome certainty is sought, and those other ways are sought in situations where risks are low. Although the scope of this study was modest, it seems policymakers have a sound grounding in the concepts of economy and generic risk, probably through cost-benefit analysis and formal policy appraisal training within the government.

Likewise, the officials’ understanding of conventional regulatory instruments is effectively furnished and well-grounded with occasional examples of other options, namely voluntary agreements, information-driven instruments, and economic instruments. Nevertheless, it is important to understand other aspects affecting instrument selection and enhance the relationship between the character and significance of risks with instrument choice beyond the general need to reduce risk using ‘command and control’ (Taylor, et al. 2018), and this should apply to the Government department that sponsors policy development as well as other departments within the government through engagement. This is what Tsai and Chou (2004) explored when they reported the cooperation between the Ministry of Economic Affairs (MOEA) and Taiwan’s Environmental Protection Administration (EPA), and the mandate the focus they had on promotion programs and the regulatory system for pollution prevention and industrial waste reuse. The authors noted that combined efforts directed at industrial waste minimization have made significant developments toward the promotion to reuse/reduce industrial waste over the last decade. The progress resulting from industrial waste minimization is beneficial in various aspects since, through Industrial Waste Exchange Information Service Center, it not only offers financial incentives and technical assistance, but it also provides and enhances the conservation and reuse of resources. Due to these measures, Taiwan was able to realize great benefits in terms of improving productivity and saving disposal/treatment-related costs.

Specifically relating to Qatar, a report by Meltzer, Hultman & Langley (2014) highlighted the fragmentation of current CCS policies, as well as the need for moving towards a National Programmes, including: a national storage mapping initiative; a legal and regulatory framework for environmental liability planning and risk management; and a global reporting of CSS projects and challenges associated with them.

For these initiatives, this will require:

- identification of all saline aquifers, geological formations and mature oil fields where CCSU can take place.
- management of carbon pricing and how such an international effort could potentially affect the price of gas as an export product.
- regional collaboration for reporting, taking into account political challenges, with the aim of generating national income via global technological export and consultancy - this can be organised through various international forums, including the Global CCS Institute and UNFCCC.

Cooperation, as many researchers have proposed, is normally faced with difficulties, especially when dealing with many air pollutants, such as persistent organics, mercury, particulate matter, ozone, and acids, due to their regional nature. These pollutants move beyond regional and national boundaries to scales that are sufficiently large to cross-continental, national, provincial, and state borders. As such Bergin, et al. (2005) suggest that responsible authorities should first overcome cultural, economic, and political differences to establish cooperation between several jurisdictions when managing these regional pollutants. The management also requires recognition of the connections between pollutants and their effects at various geographic spheres. Therefore, Bergin, et al. (2005) discuss the pollutants' regional dynamics, individually looking at them; however, they propose collaborative efforts in characterizing and managing regional pollution to successfully achieve transboundary pollution control.

Elnaboulsi, Daher, and Saglam (2018) focus on emissions taxes, which is one market-based instrument that is widely utilised and experienced to address environmental policies. The objective of environmental taxation is to achieve structural changes in the ecological and economic behaviour of firms, households, and individuals through the adjustment of price signals in an environmentally positive way. There has been growing interest in environmental taxes analysis under uncertainties of information since Weitzman's seminal work "Prices vs. Quantities" (Elnaboulsi, et al. 2018; Stavins, and Whitehead 1992). Since optimal ex-ante environmental taxes fail to achieve the optimal solution under asymmetric information, it is important to professionally design the taxes, which considerably relies upon regulatory context alongside other informational distortions. Although studies have continued to refine the understanding of environmental taxation and its performance implementation, and the role it performs under various informational uncertainties, Elnaboulsi, et al. (2018) find that from a policy perspective, disclosure with verifiable reports can be helpful to the public, as it not only ensures greater market transparency but also enhances efficiency. Access to publicly disclosed information improves the regulator's ability to levy environmental taxes specific to the firm and allows the tax rules to be fine-tuned toward given environmental situations. However, firms must be careful since exogenously disclosed information may be a double-edged sword, as it might facilitate collusive behaviour (Elnaboulsi, et al. 2018), thereby producing anti-competitive effects. However, interfirm information sharing can take place thus resulting in a better outcome regarding industry emissions and output, undermining the performance of environmental policy.

So far, a wide range of traditional approaches to industrial pollution control has been extensively discussed. However, non-point-source (NPS) pollution, in which neither the specific emissions size nor the emissions source may be identified or observed with an adequate amount of accuracy may be extremely difficult to manage using conventional environmental policy instruments, including tradable quotas and emissions, due to stochastic effects and information asymmetries (Xepapadeas 2011). The pollutants' ambient concentration linked to the individually unobserved emission is primarily observed in NPS pollution. Pollution resulting from NPSs because of agricultural runoff is the main source of hypoxia, eutrophication, and water pollution. Practically, input-based instruments appear to be mostly used; nevertheless, rising technology developments might enhance monitoring of individual discharges contributing to NPS solution. Using monitoring technologies can result in an efficient means to regulate NPS pollution; however, the evolution of individual emissions monitoring costs determines this efficiency, as high costs of monitoring might result in problems of enforcement and acceptability (Xepapadeas 2011). Thus, a lot relies upon the advancement of individual emissions low-cost monitoring technologies which make contributions to NPS pollution.

To conclude, industrial pollution continues to be a major concern in today's world. Its disastrous effects have compelled policymakers, governments, international organisations, firms, and many third parties to put in place policies aimed at addressing this environmental concern. However, the type of approach adopted depends on the type of pollution that is being experienced. It is, therefore, necessary for responsible firms and authorities to engage in extensive consultations before adopting any approach to ensure its effectiveness.

2.7 A European Case study: Sweden

2.7.1 Overview

Sweden and the wider Nordic region have endorsed ambitious climate targets for the next 30 years, which could be realised with the help of CCUS (in addition to other strategies) (IOGP, 2019). The highest industrial sources of CO2 emissions in the Nordic region are found in Sweden (fig. 13) and Finland; the composition of which has remained mostly unchanged since the 2000’s (SEA, 2010; Garðarsdóttir et al., 2018). Sweden in particular has a significant proportion of solid biomass fuels in their total energy consumption, which indicates that using bio-CCS to capture carbon dioxide (CO_2) from the burning of biomass might be a practical and affordable way to reach net-zero emissions by 2050 (Lefvert et al., 2022; Nurdiawata et al., 2022).

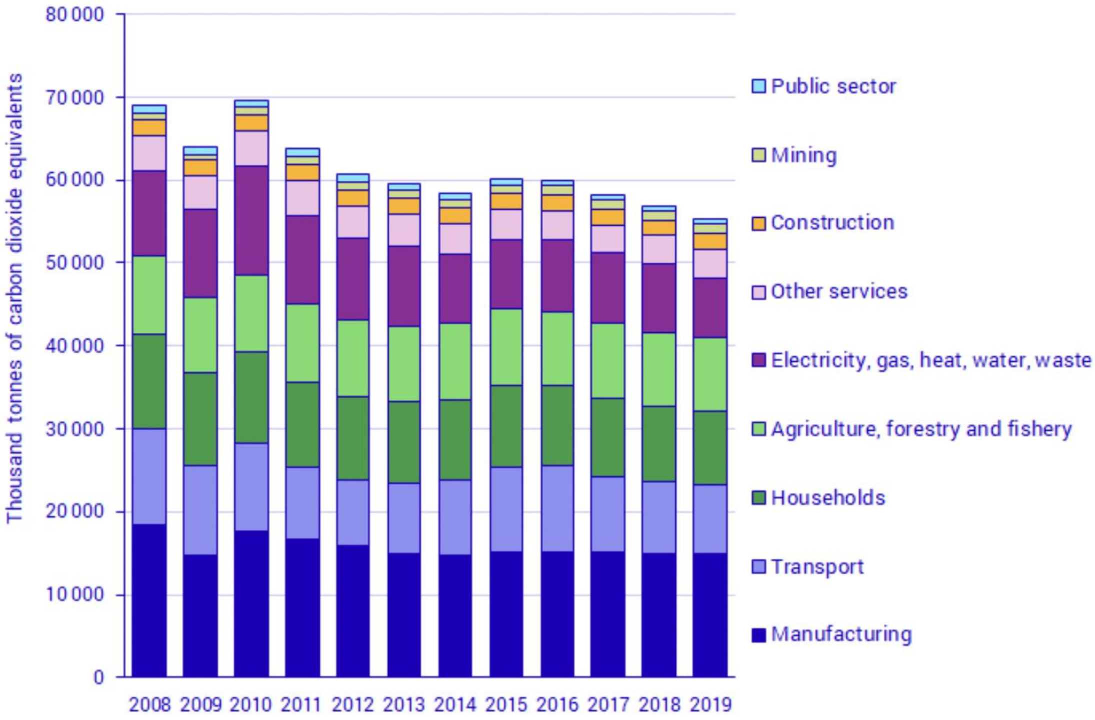


Figure 13 - Greenhouse gas emissions from the Swedish economy, 2008-2019, per aggregated industry (SNI 2007), thousand tonnes carbon dioxide equivalents (Source: Statistics Sweden, Environmental accounts)

However, few CCUS initiatives are currently up and running in Sweden, despite the fact the technology has existed since the 1980's (Evar et al., 2012). The costs have remained expensive, additional technological development is required for widespread adoption, and there are also several regulatory obstacles to contend with (Lefvert et al., 2022). Additionally, the development and application of these technologies is a convoluted process that may be hampered by path dependence and lock-in (Nurdiawati et al., 2022).

2.7.2 Emissions and Targets in Sweden

In 2016, average global emissions were calculated at around 5 tonnes CO2/capita (Global Carbon Atlas, 2018), however the distribution of carbon emissions across the globe is far from equal (Faure et al., 2019). Looking emissions levels for individual countries; Qatar takes the lead with around 46 tonnes CO2 per capita, whereas Sweden ranks 87th on this list with 4.3 tonnes CO2 per capita (Ibid.) In terms of consumption-based emissions Qatar again was one of the highest (2nd behind Luxembourg) with 33 tCO_2/person in 2016, while Sweden was placed 43rd in this list (Ibid.).

In 2019, Ninety-five process industries and energy utilities in Sweden reported a combined 49.2 million tonnes of CO_2 (MtCO2) in the European Pollutant Release and Transfer Register (E-PRTR), 68% of which came from biogenic CO_2 emissions (Lefvert et al., 2022; EEA, 2021). Sweden's long-term emission goal, as stated in the national energy and climate plan (NECP), is to reach zero net emissions of GHG by 2045 (Brown et al., 2020; Fridahl et al., 2020). In order to achieve this objective, the emissions from Sweden must be at least 85% lower in 2045 than they relative to 1990 (Brown et al., 2020). Once this level is reached, the remaining emissions (predominantly methane and nitrous oxide) can be offset by "additional measures" such carbon storage in forests and land or BECCS (Fig. 14). Such measures could offset a maximum of 8% in 2030 and 15% in 2045 (Brown et al., 2020), yet, Sweden’s NECP does not currently outline any CCS-specific goals (Fridahl et al., 2020).

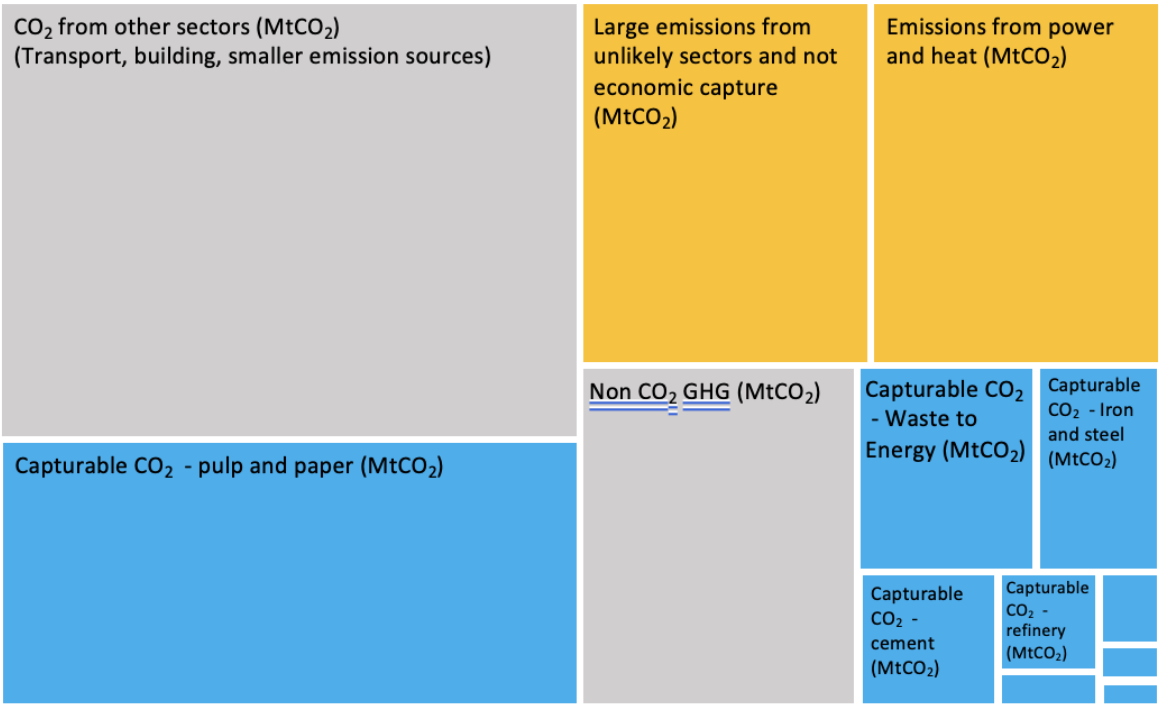


Figure 14 Overview of GHG emissions and CCS Potential - 2017 Data – Sweden In grey GHG emissions that cannot be reduced with CCS – in blue: capturable CO2 – in orange: remaining emissions Both fossil and biomass CO2 are represented on this figure. Adapted from: Eurostat

2.7.3 CCS/BECCS Plans and Policies

CCS of fossil CO_2 emissions and BECCS are the likely next phase of evolution in the Swedish energy system, which has been on-going since the 1970's due to the oil crisis and subsequent change in energy policy in the early 80's favouring the use of biomass (SEA, 2020; Werner, 2017). However, much of the local geology is ill-suited to underground storage of carbon, and no large scale onshore storage of CO_2 is allowed in Sweden (Onarheim et al., 2015). The most recent Swedish official report on a strategy for negative emissions concluded that Sweden should instead export it's captured carbon for storage in another country (Norway or the North Sea). The same report identified BECCS as an essential supplementary measure to attain negative emissions. The countries high volume of biomass production and consumption permits substantial use of BECCs (Brown et al., 2020). The strategy explains that because of the lengthy lead periods, the first plants must be operational by 2030 if BECCS is to play a substantial role in climate policy in 2045 (Swedish Government, 2020). The plan consequently demands that the Swedish government take action right away (Brown et al., 2020).

Sweden’s government has developed and implemented several financing mechanisms for CCS-related projects through the Swedish Energy Agency. Most notably the Industriklivet initiative, which in 2019, allocated SEK 100 million to research and innovation projects aimed at accelerating the deployment of CCS and BECCS. The support is planned to continue with SEK 50 million awarded annually until 2027. Yet though there are policy measures in place, such as investment support, they have not yet been determined to be adequate for the realisation of large-scale projects. Recently, the Swedish government made the decision to approve the London Protocol modification, which allows for cross border transportation of CO2 for sub-seabed storage (Garrett and McCoym 2013; Lefvert et al., 2022). The NECP identified this as a step that must be taken in order for the country to advance CCS.

Table 1 - Summary of information for Sweden

CCS is part of the national plan	Yes
Possibility to store in country	No
Low capturable volume (MtCO2/y)	7
High capturable volume (MtCO2/y)	11
National support mechanisms in place for CCS	Energiklivet initiative, support of SEK, 100 mill. towards negative emissions including bio-CCS
CCS deployment timeline	Unknown
Government position towards CCS	Are favourable to CCS, have the intention of supporting it financially

Public acceptance for CCS	No recent study on the topic
Overall significance of CCS	High

2.7.4 Roadmap to CCS/BECCS in Sweden

Analysis from Lefvert et al., (2022) suggests that Sweden is on a transitional pathway towards deploying CCS alongside other mitigation measures, with a focus on BECCS in particular. However, they also highlight the potential for this transformation to be disrupted by various potential landscape pressures or other factors such as public acceptance, changes to the bioeconomy, national and international policies, industry investment cycles, and bottlenecks in storage capacity.

Zetterberg et al., (2021) propose five different models for incentivising and financing BECCS in Sweden (Fig. X), but ultimately conclude that the successful deployment of BECCS will likely involve a combination of the proposed models applied in a sequential manner.

Model 1, in which, the government guarantees purchasing BECCS outcomes, is offered as a short term solution to help establish BECCS. Over time, it seems likely that models 2 (quota obligation on selected sectors to acquire BECCS outcomes) and 3 (allowing BECCS credits to compensate for hard-to-abate emissions within a carbon pricing regime) will become increasingly important once BECCs has become conventional. Models 4 and 5 (voluntary markets and state buyers) may play a role in BECCS deployment in the long run, but they are unlikely to do so in the short term due to the significant levels of uncertainty they are associated with regarding the timing and volume of predicted negative emissions.

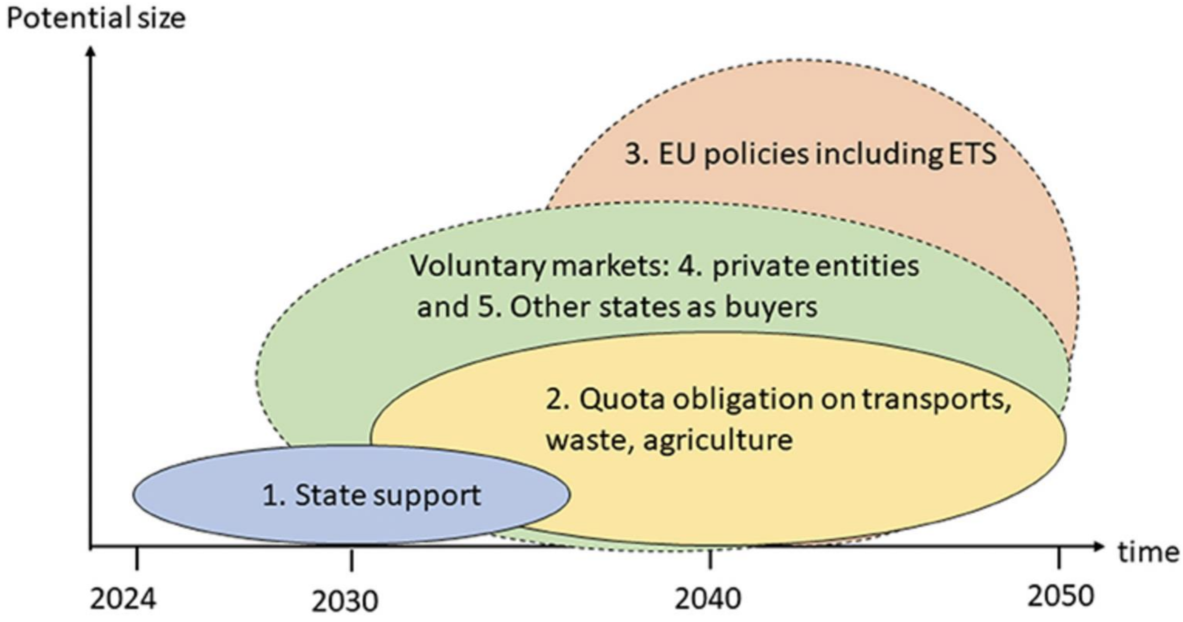


Figure 15 - Schematic illustration of the timing of the five Policy Models (Zetterberg et al., 2021). The volume levels are indicated only in relation to each other.

2.7.5 Comparison with Qatar

When comparing current strategies for the deployment of CCUS, Qatar and Sweden have very different starting points in terms of politics, economies, even the local geology. Qatar's vast oil and gas fields offer unique opportunities for the combined use of CCUS for EOR, which has the added benefit of reducing the cost of oil production (Zhang, 2021). Due to geological constraints Sweden must instead depend on to storage under the Barents Sea or in neighbouring countries Norway.

Analysis of the legal and regulatory measures governing CCUS in Sweden and Qatar reveals different challenges including regulatory clarity on key aspects governing CCUS, integration of CCUS in the portfolio of climate mitigation strategy and ensuring consistency with international law. In contrast to Sweden, Qatar has not ratified the London Protocol which suggests that the relationship with international law as a means of regime coordination and cooperation is extremely limited, and the lack of common regulatory grounds creates a barrier for exporting and receiving CO_2 (Zhang, 2021). However, framework established by the Kuwait Convention in 1978 provides a viable solution to accommodate regional cooperation for CCUS development.

2.8 Summary of CS Technologies

Having identified a large scope of current initiatives in the CCSU industries findings from the previous chapter have been compiled and further improved upon in terms of technical details, including cost of capture, capture options, feedstock, capture type, transportation requirements, geographic application, and extent of availability. This information has been tabulated and presented for later ease of access, as well as a key systematic review outcome of the current study.

Table 2 - Summary of Identified CCSU Technologies.

Tec type	Extent of Availability	Country if Available	CO_2 Capture Capacity (Mtpa)	Industry	Feedstock	Capture type	Capture Option	Transport type	Transport length (km)	Primary storage type	Cost	Ref
KOH Sorbent & Calcium Caustic Recovery Loop	Commercial	United States	1	Energy	Atmospheric Air	Direct Air Capture	Fan-based Towers	Pipeline	-	Silo	94-232 $\$/tCO_2$	Keith, Holmes, St. Angelo & Heidel (2018)
Biochar	Research	Global	1800-4800	Agriculture / Biowaste	Biomass	Biomass Collection	Pyrolysis	-	-	Soil	-	
BECCS	Commercial / Research	UK	10GtCO_2/yr	Agriculture / Biowaste	Biomass	Direct Air Capture	Multi	Pellet / Bale	Variable	Gas / Liquid	60 – 250 $\$/tCO_2$	Royal Society (2018); Fajardyab & Dowell (2018); Kember (2016)
CC CNF	Research	United States	Unknown	Energy	Gas	Absorption	Combustion	On Site	-	Nanofibres	Offset by nanofibres sale	Lau, et al. (2016)
CarbFix	Commercial	Iceland	10000 (globally)	Energy	Air CO_2 / Emission Source	Geological Storage	Combustion	On Site	-	Rock Formation	24.8 $\$/tCO_2$	CarbFix (2019)
ClimeWorks	Commercial	Switzerland / Int	49.3 - 1795.8 (per plant)	Multi-Sectoral	Air CO_2	Direct Air Capture	Fan-based Towers	On Site	-	Liquid	$\$600/tCO_2$	ClimeWorks (2019)
Air to Fuels	Commercial	Global	2	Energy	Air CO_2	Direct Air Capture	Fan-based Towers	On Site	-	Liquid	Unknown	Carbon Engineering (2019); Gunther (2011)
Amine-Based Solvents	Mature Technology	Global	0.12 (best case per plant)	Energy	Power plants; iron and steel industry; cement industry; oil refineries	Absorption	Post-combustion	On Site	-	Gas / Liquid	Variable	Cuéllar-Franca & Azapagic (2015); Mumford, Wu, Smith & Stevens (2015)
Alkaline Solvents		-	Unknown	Energy				On Site	-	Gas / Liquid	High	Peng, Zhao, & Li (2012)
Ionic Liquids		-	Variable	Energy				On Site	-	Gas / Liquid	Type-dependant	Maginn (2014)
Amine-Based Solid Sorbents	Research	US	Unknown	Energy	Emission Source	Adsorption		On Site	-	Unknown	Unknown	Qi, Fu, & Giannelis (2014)

Alkali Earth Metal-Based Solid Sorbents		-	Unknown					On Site	-	Unknown		(Kim, Han, Lee, & Lee, 2014)
Porous Organic Frameworks – Polymers		-	Unknown	Energy				On Site	-	Unknown		(Shan, et al., 2018)
Polymeric Membranes	Commercial	-	34.9-46.2%	Powerplants; natural gas sweetening		Membrane separation		On Site	-	Gas / Liquid	Medium	(Subramanian, Jordal, Anantharaman, Hagen, & Roussanaly, 2017)
Inorganic membranes	Research	-	Unknown					On Site	-	Gas / Liquid	High	(Makertihartha, Dharmawijaya, Zunita, & Wenten, 2017)
Hybrid Membranes	Research	Lawrence Berkeley National Laboratory	Unknown					On Site	-	Gas / Liquid	High	(Makertihartha, Dharmawijaya, Zunita, & Wenten, 2017)
Cryogenic Separation	Research	-	83.70%	Energy	Power plants	Cryogenic separation		On Site	-	Freezing / Liquid	High	(Knapik, Kosowski, & Stopa, 2018)
Zeolites	Commercial	Near to Volcanic Areas	High	Energy	Power plants; iron & steel	Adsorption - Pressure/Vacuum Swing		On Site	-	Mixed	High	(Makertihartha I. G., Dharmawijaya, Zunita, & Wenten, 2017).
Activated Carbon	Commercial	Global	98%	Energy				On Site	-	Mixed	Unknown	(EMIS, 2019).
Microporous Copper Silicate	Research	-	Unknown	Energy	Air CO2/ Emission Source	Direct Air Capture		On Site	-	Crystal storage	High	(Datta, Khumnoon, & Lee, 2015).
Micro algal bio fixation	Commercial	-	Unknown	Agriculture / Energy	Biomass & Emission Source	Mixed		On Site	-	Bio	Varied	(Mondal, et al., 2017).
Carbonic Anhydrase Enzyme	Soon to be Commercial	Canada	0.01	Energy	Emission Source	Absorption	Post-combustion	On Site	-	Gas / Liquid	Not Feasible Yet	CO2 Solutions Inc (2019)
Selexol	Commercial	Texas & Wyoming, USA	0.3-8.4	Energy	Fertiliser Production (pre) / Natural Gas	Absorption	Pre-combustion	On Site	-	EOR	83-86 M€/yr	(Porter, et al.)
Rectisol	Commercial	Alberta, Canada	1.2 - 1.4	Energy	IGCC	Absorption		On Site	-	EOR	98 M€/yr	(Porter, et al.)

Amine-Based Solvent	Demonstration Plant	Mitsubishi Heavy Industries	87%	Ammonia & Coal	IGCC	Absorption		On Site	-	Gas / Liquid	Unknown	(Moioli, et al., 2014)
Porous Organic Frameworks Membranes	Research	-	-	Gas separations	Fuels / Air	Adsorption		On Site	-	-	Unknown	(Shan, et al., 2018).
Oxy-Fuel Process	Both	UK	426	Mixed	Power plants; iron, steel & cement	Separation of oxygen from air	Oxygen-fuel combustion	On Site	-	Mixed	102-104 M€/yr	MIT (2016)
Chemical Looping Combustion	Research	Vienna, Austria	120kW	Energy	MetalOxide			On Site	-	Mixed	Unknown	(Kolbitsch, Pröll, Bolhar-Nordenkampf, & Hofbauer, 2009).
Chemical Looping Reforming	Research	-	-	Plants; syngas & upgrade				On Site	-	Mixed	Unknown	(Ryden, 2015).
Plant Barry / Citronelle	Project Completed	Alabama, USA	0.24	Energy	Coal	Absorption	Post-combustion	Pipeline	16	Geological	>$300 million	Southern Energy / SECARB / Denbury
Plant Barry	Operational Research	Alabama, USA	9000 /day	Energy	Coal	Absorption	Fuel Cell	Pipeline	16	Mixed	>>> Coal	MIT (2016)

3. Methodology

3.1 Introduction

3.2 Research Method

The following research is an exploratory study which utilises an inductive approach to find data on the topic of CCSU in Qatar and gather data from a variety of primary and secondary sources to arrive at a conclusive summary on the topic. Accordingly, the author gathers data both through relevant journal articles, reports from industrial and academic leaders, national and international agencies, as well as carrying out primary survey-based research about CCSU technologies and their application in Qatar. This view of the study which combines the systematic review process with original interview-based information from professionals in the field is to be presented as a policy recommendation document, one that can be addressed towards the government officials of Qatar, for use in funding for technological research and development and furthering the industrial knowledge on the topic.

The research has been conducted by the author using the “Research Onion” method (Saunders et al, 2007). Working through the layers, the paper is an ontological study using a positivism philosophy. An inductive approach was taken using, as suggested with the focus on Qatar, a case study strategy to gather the findings. A cross sectional time horizon has been assumed, with both primary and secondary data collected for the study.

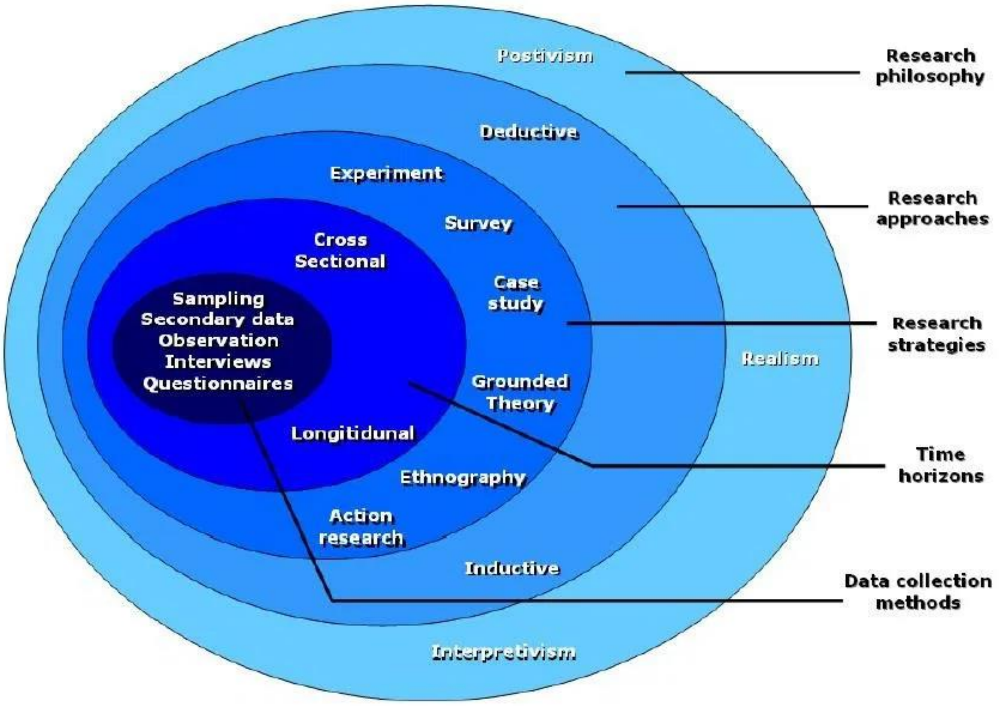


Figure 16 - Research Onion (Saunders et al, 2007)

The philosophy that forms the underpinning of the methodology for this research will be in the form of post-positivism. As this research permeates various variables of technological and social factors, it is partially based on scientific reality of a logical positivist philosophy through the collection of quantitative data, empirical evidence, deductive reasoning and systematic reviews. The main hypothesis for this paper is that climate change projections are in fact a real threat and require significant national and international levels of intervention. This hypothesis, in fact, does not require testing in this study, but it forms the scientific theory and basis that arguments will be based on. However, subjective experience of specialists in the field also forms a qualitative dataset, based on the concept of interpretivism, especially when interviewing a sample group of survey respondents whose subjective opinions will require further testing and compliance with the overarching scientific backbone of this study.

To produce successful research, the research philosophy must be aligned with relevant ontology, epistemology, meaning conditions, sources, structure, limitations objectivity and justifications (Steup, 2005), and data collection methods (Bracken, 2010). Accordingly, the study must choose an objective position, and pursue information based on impartiality. If subjective ideations about the topic are presented then they must be challenged, rebuked, or proven according to scientific data (Gray, n.d.). The general research method to be applied to data collection will be through 'grounded theory' - inductive approaches are used to generate themes and common contexts from the data, ‘grounding’ a theory which will be explored in greater detail. The realist ontology has been chosen, defined as a perception of the nature of reality, and is grounded in scientific basis and natural laws of standard reality.

3.3 Data Collection

Data collection is carried out using a combination of secondary and primary sources. Based on the preliminary research in Chapter 1, and subsequently in the literature review of Chapter 2 and analyses in the following chapters, data is accessed via previous academic research, official statistics by world organisations and private research bodies, mass media products including news pieces and documentary reports, official government reports, historical data and information, as well as other potential useful web information, newspapers, independent research companies and think tank whitepapers.

3.3.1 Literature Review

For the literature review and desktop-based investigations of this study, the main method of inquiry is utilising online databases to navigate data and arrive at valuable information on the topic; journal articles from the topic are chosen and limited to relevant research identified through a Google Scholar (2019) search for a combination of the terms, "carbon sequestration", "Qatar" and "capture". Where possible, the author has utilised the most recent studies in order to reduce the chance of duplicated insights.

3.3.2 Survey Design

The following survey is designed as a means of accessing primary research about the potential for CCSU in Qatar. The objectives of this research include:

- Acquiring insights about influential feasibility factors from a range of industrial stakeholders.
- Arriving at a quantifiable metric which determines emission reduction as a function of economic cost per unit of CO_2, i.e. £/tCO_2, to be used for modelling performance and cost-related analysis.

Accordingly, 10 questions have been devised to reflect these requirements. Survey respondents are then chosen to reflect a wide range of expertise across the CCS fields, including specifically-targeted academics, professionals, and industry players. Direct information about Qatar is also sought from sources within the UK who have experience or business interests in Qatari development (i.e., the QCCSRC lab at Imperial, or other non-Qatari international authors whose literature has been identified in the bibliography).

3.3.2.1 Survey Demographic

The author aims to gather information from a variety of stakeholders which represent the numerous key industries and points of view. Participants were targeted for their expertise within in the groups outlined below, and filtered based upon experience/length of time in the role and their seniority within their industry. Accordingly, it is suggested that a sample of size of at least 10 respondents are chosen, representing the following groups:

Table 3 – Chosen Respondent Types for Survey Research.

Stakeholders	**Significance**	**Sample Size**
Environmental Economists	Estimates of £/mt CO2	2
EOR Professionals	BECCS & CO_2-related Data	2
GTL Professionals	Gas Industry CS&C £/mt CO_2 Potential	2
Academia	Relevant CCS Authors in this Study	2
CCS Professionals	Aquifer & Geological Formation Identification	2

Interviews are to be carried out as written or voice-recorded surveys with ample encouragement for long-form responses. Considerations must be made ethical data collection and analysis, as well as ensuring the privacy and security of the data. Respondents must be notified of the potential of the author to get back in touch with them for further details if necessary. If possible, increasing the number of respondents will significantly increase the chance of accuracy and overall value of study.

3.4 Data Analysis

The two above methods of sourcing information will provide useful yet diverse means of inquiring about the topic. To construct a discussion that is applicable to both, a dual method of analysis - will be used. Using separate analysis of primary and secondary sources, a summary is produced for each of these sections and these are then compared to find similarities, differences, and any possible anomalies in the data sets.

3.5 Limitations

While the author attempted to contact stakeholders in Qatar for responses about the proposed survey, next to no interest was identified. This was due to the lack of openness and willingness of domestic industry actors to engage in academic dialogue, with reasons not entirely clear.

This is demonstrated in the response from Qatar’s Energy Minister who responded with the following when asked about when the country’s plans will be announced:

“Talking too much about something, hyping what you want to do, is not useful for anybody. If you are going to do it, go do it, work on it and deliver. And when you have delivered, then you talk about it” (Mees, 2019).

Due to Qatar's recent political clashes with other regional countries, the opportunity to interview CCSU stakeholders in neighbouring countries was also limited for the author and, accordingly, survey research had to be limited to respondents from other locations further afield. Additionally, limitations placed on the author duo to the global Covid-19 pandemic also reduced the opportunity to travel for interviews. Hence, data collection was limited to online and phone interviews.

Access to specific valuable resources were also restricted due to the existence of extensive paywalls from Conference Proceedings and market reports which disabled the author from accessing such data. Examples of this include “Captured CO_2 Treating and Transportation: Challenges and Lessons Learned” and other QatarGas-related papers which are either not available publicly, or only accessible via the full 27th World Gas Conference (WGC 2018) proceedings (International Gas Union, 2018; QatarGas, 2018, p. 8).

3.5 Other Factors

The *ethical* framework of the methodology dictates practices used should protect the rights of individuals, communities, and environments used in the study against any form of infringement, manipulation, and malpractice. In the UK, the ESRC Framework for Research Ethics clearly defines all ethical guidelines needed to carry out research in the UK. This research will have to be carried out to work within the law, and to professional guidelines and moral action. Accordingly, consent must be sought for gathering of data from sources, confidentiality must be respected in terms of how data is stored and protected, especially in any case where there may be a condition of anonymity. Finally, the research should be based on the premise of avoiding harm and benefiting humanity, as the moral compass that drives sustainable development goals.

The study must be *generalisable*; the findings and workflow of this research must be replicable for use cases in other countries, as the findings not only should help to illuminate a path for Qatar towards CCSU, but also work as a guideline for other country analyses to be carried out following the same format. A generalisable study will have the benefit of being valued repeatedly and being utilised in similar circumstances.

4. Analysis – Suitability for Qatar

4.1 Introduction and Context

The following chapter analyses the potential of the identified CCSU technologies for Qatar as having potential for genuine and measurable environmental and economic impact. Accordingly, information from Qatari officials, the author's survey response and in-depth analysis of existing studies are used to arrive at quantitative and generalisable data.

The country itself provides an interesting case study in terms of the region that the nation finds itself in, the environment and geological features provided by the landscape, and the natural resources that the country's economy has taken advantage of, the latter of which has also led to the political position the nation find itself in, with interest and reliance from external nations.

As discussed through the rest of this chapter, the country has a number of opportunities to utilise the natural environment for its CCSU, and as highlighted the need for this is apparent due to the natural resources provided by the region. Extraction of the latter requires a high amount of energy, which then needs refining and transporting to other nations, all of which adds greatly to the carbon footprint of the country. On top of this, the boost to the economy of the nation from the high-demand resources they are able to provide leads officials to seek investment in improving infrastructure and quality of living – these large-scale construction projects also generate large amounts of CO_2, leading to a further increased footprint. By finding suitable technologies to utilise in the region for CCSU, this impact can be greatly reduced.

4.3 Sequestration via Natural Methods

4.3.1 Renewable Potential

The current aim for Qatar's Renewable energy and electricity generation is to produce 200-500 MW of solar energy per year (2020) and 8% of consumption per capita by 2022 (Welfle and Alawadhi, 2021). An argument must be made about the very nature of energy security in Qatar, which is almost entirely based on fossil fuels. While it has been argued in this study that Qatar can capture carbon by improving its fossil fuel capture and storage facilities, little focus has been placed on the country's potential position as a renewable energy producer. The Regulatory Indicators for Sustainable Energy show Qatar's overall score as 56/100, with low scores on Renewable Energy including: lack of carbon pricing and monitoring; network connection and use; utility in transport; lack of financial and regulatory incentive or support; and a medium legal framework and plan for expansion (RISE, 2020). While carbon can be taken out of the industrial process to mitigate gas and oil exploration to some extent, it is worthy to analyse whether a total replacement with renewable energy will be able to offset the whole fossil fuel industry in Qatar or not. Qatar is well-positioned for solar power, with a total practical potential of 4.917 kWh/kWp (theoretically, 5.899 kWh/m2), 5MWp installed capacity, and a practical potential of a large majority of its area, as shown in Figure 11 (level 2 denotes areas with practical potential) (Global Solar Atlas, 2019).

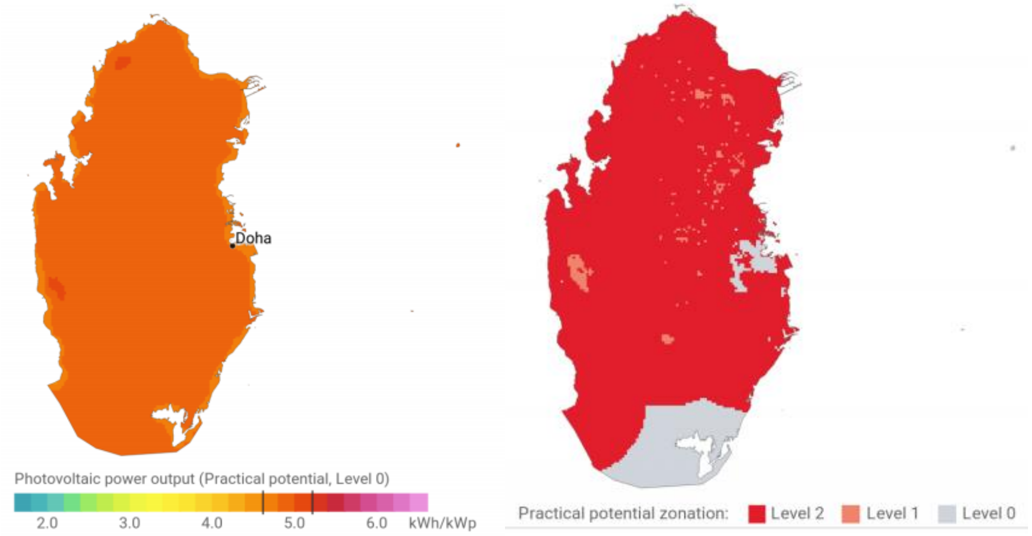


Figure 17 - Solar Capacity in Qatar (Global Solar Atlas, 2019).

Despite this major national potential, there is the predicament of cost if the energy sources are too far from inhabited or industrial areas. A study by Jahangiri, et al. (2020) utilises fuzzy MCDM technique of FTOPSIS to identify the production of hydrogen and electricity from solar and wind energy. The study arrives at the lowest potential price of 11.495 $/kWh for electricity, and 2.092 $/kg for hydrogen, while Ar-Ruways and Doha International Airport presented the best location for eco-friendliness and cost effectiveness respectively A combined Wind-PV-Grid system had the highest potential.

4.3.2 Greenification

Realising Qatar's total potential for CCSU must be carried out through an integrated strategy which not only includes industrial potentials, but also natural strategies which can help to meet other pressing climate change issues in Qatar. In addition to the already-discussed CCSU technologies related to the energy sector and other industries, innovative approaches to environmental engineering can provide additional means of capturing carbon through the environment using biological processes. The main development in this field includes the Sarah Forest Project (SFP); an initiative to ‘greenify the desert’ through a combined approach which includes solar power generation, cooled greenhouses, revegetation of the arid land, the production plants for algae, mariculture, salt, halophytes, livestock farming, bioenergy, and CO_2 waste management, in the overall framework of ‘restorative growth’ through a ‘saltwater value chain’ (Sahara Forest Project, 2019). Theoretically, with flawless execution, the concept of the SFP has the potential to reshape Qatar’s microclimate, combat desertification in the country and potentially greenify all coastal areas and, eventually, in-land. Meanwhile, this ‘permaculture’ attitude to CCSU can aid as a pragmatic solution towards local independence for food, renewable energy and water needs (Hitchin, 2014). The potential for biological applications of CCSU can be extended to using captured carbon as feedstock for microalgae cultures. However this technology is not yet fully understood, and researchers are currently undertaking feasibility studies for this at Qatar University (Schipper, 2019). Meanwhile, the Qatar pilot for Sahara Forest Project has been discontinued and moved to Jordan as the future site of the project, hence, despite the potential, its feasibility in Qatar has become more unrealistic in the medium term future.

Nevertheless, natural remedies are not limited to the now defunct SFP project, i.e., building upon natural mangrove forests by supporting greening projects such as Sahara Forest Project can address additional issues at the food-water-energy nexus. Khadar (2020) estimates that mangroves sequester up to 25.5 million tonnes of carbon per year and provide 10% of the essential dissolved carbon supplied into the world's oceans. On the other hand, due to the hypersaline environments in Qatar, mangroves, namely the A. marina plant, store relatively low levels of carbon, both above and below the ground, accounting for 45.70 ± 3.70 tC ha^{-1} (Chatting, et al., 2020). Information on the potential of halophytes in extreme environments is not entirely consistent or complete, presenting elusive potential for capture. A study by Glenn, et al. (1992) proposes the potential for halophytes as a new land base in 130×10^6 ha of land to potentially capture 0.7 Gt C. This domain, sometimes dubbed as "haloculture" is an emerging field, with only 91 results currently that mention it on Google Scholar (2021a). Potential in Qatar goes beyond direct CCSU and towards other indirect means of mitigating carbon through diverse use in biofuels, food, fodder, medicine, building materials, fibre, water remediation (Khorsandi, 2016).

The idea of planting resistant plants is often unexplored in climates such as Qatar. Nevertheless, mangroves in Qatar play a crucial role in allowing its rare natural ecosystems to thrive while also helping towards natural CCSU. Qatar has over 560 km of coastline and no permanent freshwater bodies, while most of its soil is calcareous and 'agriculturally unproductive'. Salinity in its soil has also increased in productive regions due to agricultural malpractice, and most of the country has no vegetation, except specific irrigated sites in the north (Britannica, 2020).

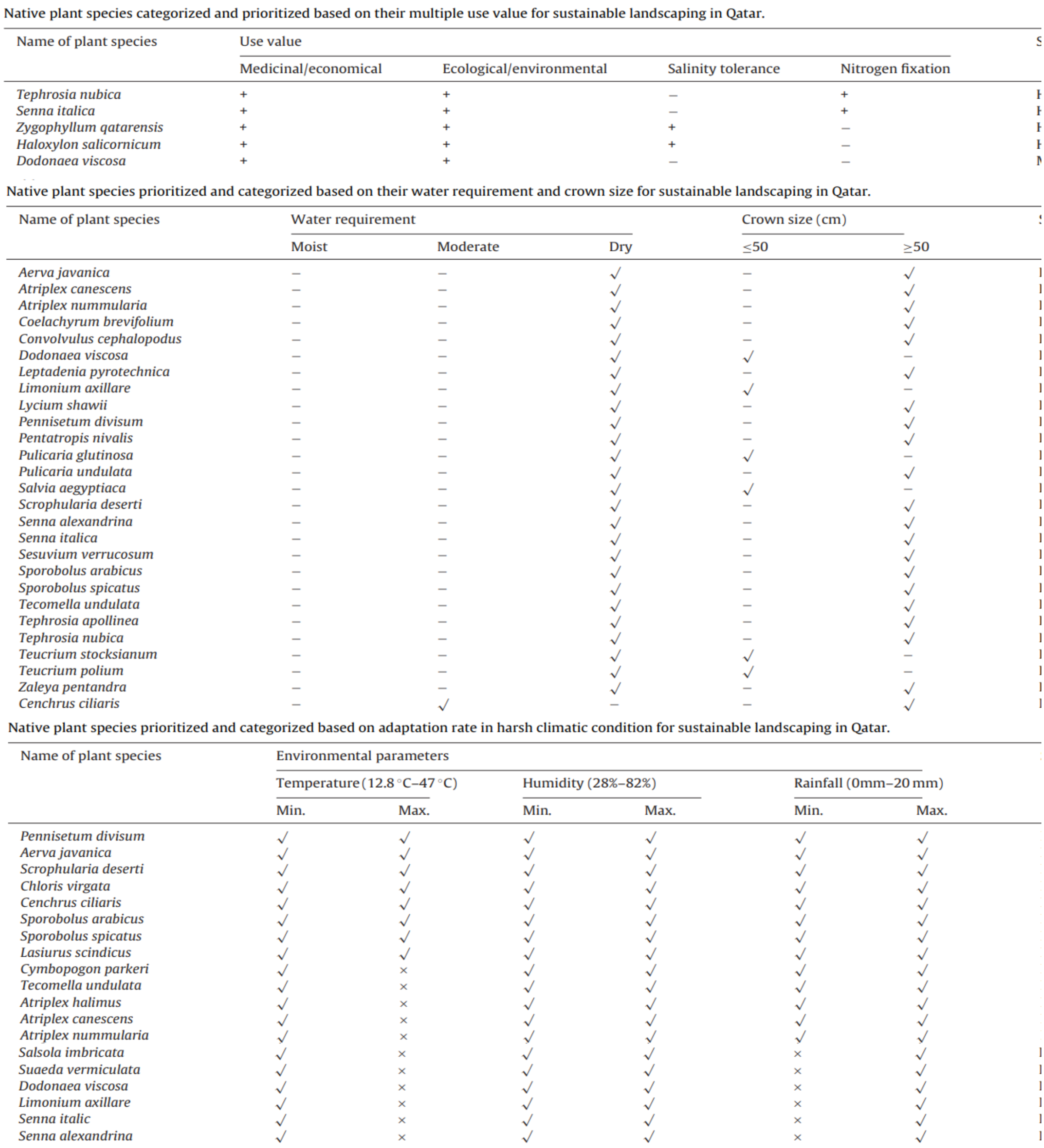
Table 4 - Energy Requirements & Carbon Capture Capacity of Various Processes, Agents and Technologies in Qatar (Habib & Al-Ghamdi, 2020; Cusack, et al., 2018).

Process / Agent	**Energy Requirement**	**CO_2 Equivalent Emissions**
Water Desalination (1 m^3)	4.09 kWh	12.79 kg CO_2 /m
Sewage Effluent Treatment (1 m^3)	0.12 kWh + 0.021 kWh	0.64 kg CO_2 /m
Mangroves of Western Persian Gulf		0.019 kg C_{org} m^{-2} yr^{-1}
Seagrass of Western Persian Gulf		0.009 kg C_{org} m^{-2} yr^{-1}
Saltmarshes of Western Persian Gulf		0.008 kg C_{org} m^{-2} yr^{-1}

Case studies also exist for Qatar around the use of food waste to produce biochar, as a means of dealing with both industrial and domestic waste management in the country. Produced via the pyrolysis process, dependent on conditions such as temperature and absence of oxygen, food waste can be turned into carbon-rich mixture of solid, liquid and gas products, respectively being called biochar, bio-oil and synthesis gas. By-products of this process can be used as a natural soil rehabilitating agent used in agriculture, as well as utility in creating adsorbent products in other CCSU processes. The main caveat to this process is that different food waste has varying chemical compounds and moisture content, producing different percentages of char, ash, and volatile material. This will require separate processing of different food waste for ideal control over outcome and may require further separation of waste at source. Nevertheless, incorporation of the waste lifecycle into CCSU is an important and suitable option for Qatar based on its water, waste and energy nexus (Elkhalifa et al., 2019).

To understand the CCSU potential of natural urban landscaping, information about native species of trees and plants for the gulf region is used to measure its atmospheric carbon removal potential. This research identifies three species of *Prosopis Juliflora*, *Tamarix Aphylla and Acacia Nilotica* as having positive potential to respectively capture 860/819, 291/250 and 247/206kg CO_2 per year per tree, when adjusting for irrigation with both desalinated water and treated sewage effluent. Some smaller trees did not manage to significantly impact carbon removal, with some examples shown to contribute to it (Habib & Al-Ghamdi, 2020, pp. 280-287). Note that other factors must be recognised - i.e., *Prosopis Juliflora* is considered a highly invasive species with damage to existing crops and attraction to mosquitoes as a contributor to the transmission of malaria (BioNet-EAFRINET, 2021).

To tackle this factor, Phondani, et al. (2016) carried out a similar study including over 12 criteria and 49 related indicators to assess the suitability of native plants in terms of weather condition tolerance, multiple use value, crown size and water requirement. They have also added their findings to Qatar's GSAS/QSAS Sustainability Assessment framework (similar to LEED & BREEAM in the US/UK). The report includes the "Quantity of carbon sequestration rate" as one of the indicators, amongst many others. Nevertheless, the study's analysis does not yet quantify this metric, and it is based on producing generalised scoring for water requirement, crown size and multiple use value. Accordingly, those with a high value in each of these categories can be seen in Figure 12:



Native plant species categorized and prioritized based on their multiple use value for sustainable landscaping in Qatar.

Name of plant species	Use value			
	Medicinal/economical	Ecological/environmental	Salinity tolerance	Nitrogen fixation
Tephrosia nubica	+	+	–	+
Senna italica	+	+	–	+
Zygophyllum qatarensis	+	+	+	–
Haloxylon salicornicum	+	+	+	–
Dodonaea viscosa	+	+	–	–

Native plant species prioritized and categorized based on their water requirement and crown size for sustainable landscaping in Qatar.

Name of plant species	Water requirement			Crown size (cm)	
	Moist	Moderate	Dry	≤50	≥50
Aerva javanica	–	–	√	–	√
Atriplex canescens	–	–	√	–	√
Atriplex nummularia	–	–	√	–	√
Coelachyrum brevifolium	–	–	√	–	√
Convolvulus cephalopodus	–	–	√	–	√
Dodonaea viscosa	–	–	√	√	–
Leptadenia pyrotechnica	–	–	√	–	√
Limonium axillare	–	–	√	√	–
Lycium shawii	–	–	√	–	√
Pennisetum divisum	–	–	√	–	√
Pentatropis nivalis	–	–	√	–	√
Pulicaria glutinosa	–	–	√	√	–
Pulicaria undulata	–	–	√	–	√
Salvia aegyptiaca	–	–	√	√	–
Scrophularia deserti	–	–	√	–	√
Senna alexandrina	–	–	√	–	√
Senna italica	–	–	√	–	√
Sesuvium verrucosum	–	–	√	–	√
Sporobolus arabicus	–	–	√	–	√
Sporobolus spicatus	–	–	√	–	√
Tecomella undulata	–	–	√	–	√
Tephrosia apollinea	–	–	√	–	√
Tephrosia nubica	–	–	√	–	√
Teucrium stocksianum	–	–	√	√	–
Teucrium polium	–	–	√	√	–
Zaleya pentandra	–	–	√	–	√
Cenchrus ciliaris	–	√	–	–	√

Native plant species prioritized and categorized based on adaptation rate in harsh climatic condition for sustainable landscaping in Qatar.

Name of plant species	Environmental parameters					
	Temperature (12.8 °C–47 °C)		Humidity (28%–82%)		Rainfall (0mm–20 mm)	
	Min.	Max.	Min.	Max.	Min.	Max.
Pennisetum divisum	√	√	√	√	√	√
Aerva javanica	√	√	√	√	√	√
Scrophularia deserti	√	√	√	√	√	√
Chloris virgata	√	√	√	√	√	√
Cenchrus ciliaris	√	√	√	√	√	√
Sporobolus arabicus	√	√	√	√	√	√
Sporobolus spicatus	√	√	√	√	√	√
Lasiurus scindicus	√	√	√	√	√	√
Cymbopogon parkeri	√	×	√	√	√	√
Tecomella undulata	√	×	√	√	√	√
Atriplex halimus	√	×	√	√	√	√
Atriplex canescens	√	×	√	√	√	√
Atriplex nummularia	√	×	√	√	√	√
Salsola imbricata	√	×	√	√	×	√
Suaeda vermiculata	√	×	√	√	×	√
Dodonaea viscosa	√	×	√	√	×	√
Limonium axillare	√	×	√	√	×	√
Senna italic	√	×	√	√	×	√
Senna alexandrina	√	×	√	√	×	√

Figure 18 - Analysis of Native Plants in Qatar and their Environmental Potential (Phondani, et al., 2016).

Such a study must be built upon to also include the rate of carbon capture for each plant - those with high scoring in all parameters may be valuable starting points for further research; i.e. no native plant can be identified with High Scoring on all factors, however, *Senna Italica* can present as a resilient option with some economic value as a natural dye or medicine (PlantUse, 2015). More importantly, this Criteria & Indicators approach is a valuable methodology for policy-creation, and a matrix-based decision-making system to analyse various plants, and their potential for simultaneous CCSU.

4.4 Survey Response Analysis

4.4.1 Respondent Sectors

Table 5 – Number of Respondents from Different Sectors.

	Academia	**Government**	**Industry**	**Other**
No. 1	1			
No. 2	1			
No. 3	1			
No. 4	1			
No. 5	1			
No. 6	1			

From the 105 potential respondents that were chosen for this research, there wasa skew observed towards respondents within academia, as connections were sourced from relevant studies; however, an excess of over 20 potential respondents from other industries who were contacted did not respond. While this potentially was also compounded by the restrictions of the COVID-19 pandemic, a trend also emerged that respondents in Qatar were generally not interested in partaking in the study, a factor that is potentially related to the non-public, non-transparent and exclusive nature of the government-backed-and-run industries in Qatar within this field. This assumption is in line with the response of Qatar's Energy Minister in the Mees (2019) interview previously highlighted. Further research on this topic shows that there is generally a low level of transparency in the region according to the 2017 Resource Governance

Index (RGI), while Qatar ranks higher than most regional countries. The issue of transparency is highly related to the State-Owned Business aspect of industries in such countries. While the RGI report does not include lack of openness to outside inquiry as a metric for their transparency metrics, it does state that some barriers towards information disclosure by Qatar Petroleum and other officially-aligned businesses in Qatar are due to a lack of desire to disclose to outside companies without: a clear business case; need for including disclose requirements; and lack of multi-stakeholder approaches (RGI, 2021). Nevertheless, Qatar is making improvements in this field and, regionally, it is currently at a satisfactory standing for its RGI score as shown in Figure 13:

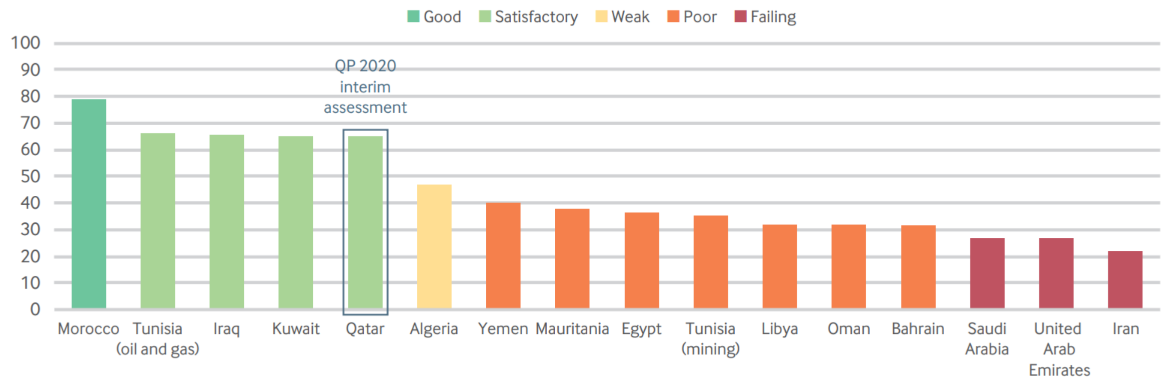


Figure 19 – Plot of the Resource Governance Index Score for MENA SOEs, including Qatar Petroleum (RGI, 2021).

4.4.2 Industry Potential

Table 6 – Survey Responses About Potential of Industries for Carbon Reduction ("x" representing those with potential – No.5 responded with ranked choices).

	Oil	**Gas**	**Cement**	**Waste**	**Steel**	**DAC**	**Natural**	**Other**
No. 1	x	x						
No. 2		x						
No. 3								Power

No. 4	x	x						
No. 5	3	2	1	4	1	6		5 Fuel Combustion
No. 6	x	x	x					

Overall, the main themes in all industries revolve around the correlation between the CO_2 concentration and the related cost or energy penalty. Furthermore, industrial potential for CCSU should only be considered in conjunction with low carbon energy and processing options; i.e., replacing fossil fuel energy sources with renewable solutions radically eliminates fossil fuel use, instead of incremental improvements through retrofit-based capture. Accordingly, CCSU should be considered as a temporary medium-term solution for combustion purposes, not the be-all and end-all. Furthermore, industry roadmaps should exist for each field on the spectrum of national and global extents. Considerations on the industrial constraints of carbon capture will be discussed in more depth in the Discussions chapter.

4.4.2.1 Oil, Gas & Power Generation

Surveys demonstrate that the oil and gas industries and the utility of these industries for fuel combustion towards power generation has the highest potential within Qatar. Considering this industry is already a high emitter of CO_2, GTL and LNG processing present a key target in Qatar’s roadmap (Korre, et al., 2012; Shell, 2011). The key insights in this field include:

- Prioritisation of capture processes at fossil fuel production plants, rather than power generation plants, as those can be more easily replaced with renewables in the future. However LNG and GTL processes will likely remain a global export for the foreseeable future regardless of the domestic energy sources. Furthermore, the power sector and desalination sectors must move away from energy intensive processes.

- Natural Gas and Fuel Combustion's high potential is due to the high CO_2 Production to Capture ratio

- Low concentration CO_2 from Oil Refining is not entirely efficient for CCSU.

- High concentration CO_2 for Natural Gas Sweeting and ammonia production are efficient low-cost CCSU opportunities.

- Competition of fossil fuel processes (combustion, waste incineration and desalination) with clean eco-efficient energy sources, and energy penalty trade-offs

- Existing separated CO_2 from Oil and Gas can be used for EOR or chemical production.

4.4.2.2 Direct Air Capture

Feedback consistently rated DAC as the least suitable. The reason for this has been cited as the technology's expensiveness and lack of high efficiency. This information correlates with the literature review carried out in this research and, despite the global and news-grabbing appeal of the technology, it is certainly not a medium with real current potential.

4.4.2.3 Steel, Cement & Industry

Considering Qatar's growth stage and the need for construction-aligned raw materials, the production of steel and cement are likely to continue and they present a high capture opportunity for CCSU. While energy for power can be exchanged with renewables to some degree, energy for construction industries is more difficult to replace. These survey responses are, to some extent, in line with existing research. Leeson, et al. (2017) carry out a systematic review of over 250 papers, analysing CCS in industries to highlight their equal importance to the power sector, while also emphasising specific challenges, such as inconsistent cost reporting, lack of a clear front runner and the importance for development not to be delayed. Only 10% of the literature they reviewed included cost data, ranging between \$20-120 per tonne of CO_2 avoided. Results indicated that: the paper and pulp industry have the least amount of cost data available; the cement industry has the highest capture potential of easily-processable flue at the lowest price; and iron and steel require capture from low-quality sources. Current technology does not have the capacity to mitigate more than 25% of any industry maximum by 2050, even if deployed on 80% of all plants. The research concludes there is a need for knowledge sharing in industrial CCS to reduce cost risk, improve financial backing from public sector and as a result, lower the "learning cost factor" which can significantly reduce costs. Overall, the scepticism about industrial potential was shared between both literature and survey responses.

4.4.2.4 Waste

Respondents mostly associated the Waste category with incineration and, while the category was open to interpretation, the author's intended utility was bio-waste CCSU processes. Consequently, responses highlighted issues of incineration relating to toxicity and high energy penalties. Inquiring further into Qatar's waste profile, it becomes evident that, from the 11.4 Mtpa of Total Waste Generated, 93% is "processed via landfill management" while 68% of total is organic waste. Accordingly, anything between 61%-68% of Qatar's organic waste is currently not utilised in any energy-producing means, presenting a potential gateway for research into carbon capture or energy reuse in the field at the Energy-Waste-Food nexus. This study also concludes that Qatar's Biomass Resource Potential, made up of animal waste, crop residues, sewage, and municipal solid waste is up to 9.9% of overall electricity consumption at 16.40 PJ_{elec} (Welfle & Alawadhi, 2021). The study does not offer any cost estimation in its technological estimate, although it is mentioned that the cost will likely reduce due to subsidisation towards climate change mitigation in coming years.

4.4.3 Measuring Economic & Environmental Metrics

Table 7 – Survey Responses About Best Practice for Measuring CCSU Objectives.

	Feedback
No. 1	- Still an open research question - Existing methods fall short in adequately capturing macro-economic impacts and local/regional/global environmental impacts.
No. 2	Economic benefits for job creation/retention, industry retention and attraction. Techno-economic analysis of CO_2 emission reduction versus CO_2 emission taxation. Environmental benefits for assessment of CO_2 (& other) emission reduction, i.e.: - Life cycle assessment or carbon accounting - Emissions measurement of actual CCS processes
No. 3	- Typical economic analysis (NPV, ROI, etc) puts CCS at a disadvantage - Environmental measure of CO_2 reduction per year - Evaluate sustainability objectives with economic measures, e.g El Halwagi et al. 2017
No. 4	- Individual analysis of impact on different affected industries
No. 5	- Eco-efficiency: Relationship between product/process's environmental impact and its economic value i.e., Cost of CO_2 avoidance
No. 6	- Cost per % CO_2 Captured from All CO_2 producing processes

Feedback on the various potential measurement mechanisms on the nexus of economy-environment presented several different mechanisms, largely based around various metrics relating to CO_2 and how reduction can be measured. The answers in this section are synthesised along with related answers in other question responses and included in the Economic Feasibility discussions in Chapter 5.

4.4.4 Gas-To-Liquid Suitability for CCSU

Table 8 – Survey Responses About the Combustion-Based Carbon Capture for GTL Plants.

	Pre-Combustion	**Post-Combustion**	**Oxygen-Fuel Combustion**	**Unsure / Other**
No. 1		1		Unsure
No. 2	Dependent on interpretation, skills and system design.			
No. 3	All depending on GTL process design e.g., ATR, POX or SMR.			

No. 4				Unsure
No. 5	n.a	1	n.a	
No. 6		Current	Future	

This question presented a high degree of uncertainty. Respondents were unable to distinguish between two types of GTL plant:

- where liquidised gas is also generating energy as a power plant (i.e. CHP); and
- where energy and emissions from the GTL process are directed through a system to recover CO_2 from the process.

There was also some consensus in responses about the potential for each method in different parts of systems; that due to the existence of multiple streams, arrangements will depend on feasibility of each stream to be regulated for CO_2 based on design, alongside the operators' skills and experience to capture at each source, i.e. using solvent-based systems.

4.4.5 Liquid Natural Gas Suitability for CCSU

Table 9 – Survey Responses About Carbon Capture Related to Combustion for LNG Plants.

	Pre-Combustion	**Post-Combustion**	**Oxygen-Fuel Combustion**	**Unsure**
No. 1				X
No. 2				1
No. 3	Exists as Part of Processes	Currently Easiest		
No. 4				Unsure
No. 5				Unsure
No. 6		Current Option	Long-term	

Similar to the question on GTL sustainability for CCSU, the majority of answers on this question were unfamiliar with the potential or misunderstood the word ‘plant’ as a power plant, rather than a processing plant. The potential of these plants for CCSU does not lie in the final product, as the LNG process is essentially just cooling down the gas to liquify it. Instead, it focuses on capturing CO_2 for the LNG trains and refrigerant cycle processors, as mentioned by an IEAGHG report (IEAGHG, 2019). Nevertheless, post-combustion was considered as the top option for retrofitting current plants.

4.4.6 Barriers for Adding CCS Initiatives to National Policy & Recommendations

Table 10 – Survey Responses About Policy Barriers & Opportunities for CCSU.

Respondent	Feedback
No. 1	Lack of systems studies to understand options. Current systems are ad-hoc and hence expensive. Existing local methods are not being utilised.
No. 2	Need for business model framework for entities in CCS chain and government.
No. 3	- Industry buy-ins
No. 4	- Resistance to change - Lack of top-down willingness - Lack of convincing pitches to demonstrate long-term benefit to leaders
No. 5	- Energy penalties & other competitors lead investors to turn to renewables instead - High uncertainty in development of marketable solutions - Good option for coal-driven markets - Good option for other industries (Aluminium, steel, cement) which depend on CCS as only solution towards sustainability.
No. 6	- Higher integration of public sector with private sector - Provision of support, subsidies, and logistics - Resistance to change

The identified barriers cover a wide range of reasonings spanning economics, logistics, marketing and governance. The main premise, however, revolves around the lack of a pragmatic push to systematically study CCSU, analyse its economic and environmental potential for all sectors in Qatar relative to other solutions, such as shifting towards renewables and business-as-usual. As with most other incumbent systems, the gravity required to pull interest into innovation, especially within a more centrally controlled market such as Qatar, requires very robust analysis. As an issue faced in this study, the Catch-22 between information unavailable for independent researchers and information needed by those actors to present potential solutions to impress top-level stakeholders is certainly a factor that should be considered in the analysis as well. Willingness for most decisions must ultimately come from key players, such as Qatar Petroleum (QP), as the leading entity in this field.

4.4.7 Potential for Natural Carbon Capture, Storage and Utility

Table 11 – Survey Responses About the Potential of Natural Sequestration.

Respondent	**Feedback**
No. 1	- Valuable if carried out with competitive costs and environmental impacts - Should be studied as a potential solution
No. 2	- No potential due to water resource shortage.
No. 3	- Potential through Mangrove / Algae - Not feasible for more water-intensive and soil-enhancement requiring contexts
No. 4	- Cannot depend on nature to auto-adjust to anthropogenic activity
No. 5	- Potential, but with costly economic and environmental trade-offs - Need for green bonds, green investment, carbon offsetting, etc.
No. 6	- Possible with strong policy push and political will - Major investment in natural resource management initiatives

The potential for natural CCSU, meaning methods that utilise plantation, agriculture, or any biological processes to capture and store carbon, presented highly varied responses. The obvious factor exists that the lack of water resources and soil capacity makes growth of most plants extremely difficult. On the other hand, potential has also been reported in terms of resilient plants which are perhaps native to the region and have evolved to withstand extreme conditions. Supporting literature shows some research being carried out in this field, namely through resources available at the Qatar University Culture Collection of Cyanobacteria and Microalgae (QUCCCM). Further research is required on the potential of various indigenous plants for growth in such regions for their carbon capture capacity, as well as commercial potential for biomass (Schipper, et al, 2019). In order to be seriously considered in national policy, such research must grow towards a more holistic planning of natural resources that includes: techno-economic cost analysis; cost estimation studies; and comparison next to potential of green bonds and carbon credits.

4.4.8 Suitability of Carbon Storage and Utilities in Qatar

Table 12 – Survey Responses About Qatar's Potential for Carbon Storage and Utility.

	Depleted Gas & Oil Reservoirs	**Saline Aquifer**	**Geological Storage**	**Conversion to Carbon Nanofiber**	**EOR**	**Other**
No. 1	1				1	X
No. 2	1				1	
No. 3					1	All
No. 4					Y	
No. 5				Last	n.a	
No. 6	x	x			x	

The question on Storage and Usage returned with varying levels of value. The responses clearly show that EOR from using easily captured carbon (from LNG/GTL/plants, etc.) presents the most economically feasible option for the short term for also maximising use of existing infrastructure in a profitable manner. The potential for EOR/EGR is, however, dependent on the economic feasibility of the Oil and Gas market as a global switch towards renewables is pursued. Without the need for EOR, the utility of depleted reservoirs and saline aquifers increases, especially as the former has existing infrastructure in place. Other advanced and innovative utility mechanisms, such as conversion to carbon fibre and other products, represent a very marginal portion of the market and are not currently feasible yet.

Meanwhile, further research in other countries has been identified that builds on existing reviews of the potential theoretic capacity for capture and storage. This is a wide web of processes, source materials, outputted materials, and storage options which can occur because of CO_2 capture and utilisation, with varying levels of cost effectiveness. The study by Jarvis & Samsatli (2019) provides an extensive and comprehensive summary of many technologies, including important KPIs included for processes such as Operating Expense (OPEX), Capital Expense (CAPEX), CO_2 utilisation, product price, average Technical Readiness Level (TRL) (the maturity level of a particular technology) and electricity usage. A similar study needs to be carried out for Qatar to identify the potential of these metrics in the country.

4.4.9 Ranked Suitability of Carbon Capture Mechanisms

Table 13 – Survey Responses Ranking Capture Mechanisms by Suitability in Qatar.

Technology	**No.1**	**No.2**	**No.3**	**No.4**	**No.5**	**No.6**	**Avrg**
Direct Air Capture	1	1	1	n/a	5	2	2
Pyrolysis from Agricultural Waste		4	1	n/a	2	3	2.5
Micro-Algal Bio Fixation		3	3	n/a	3	4	3.25
Anaerobic / Waste-Based Fuel Cells		3	N/A	n/a		3	3
Post-Combustion Absorption		5	4	n/a	5	3	4.25
Post-Combustion Adsorption		4	4	n/a	3	1	3
Post-Combustion Membrane Separation		3	4	n/a	3	1	2.75
Post-Combustion Cryogenic Separation	1	3	4	n/a	5	1	2.8
Solvent-based Post & Pre-Combustion		5	4	n/a	5	1	3.75
Pre-Combustion Absorption		5	4	n/a		1	3.33
Pre-Combustion Adsorption		4	4	n/a		1	3

Chemical Looping Oxygen Fuel Combustion		5	4	n/a	2	1	3

Averages were taken from the ranked responses on the various proposed technologies. While Respondent No.4 did not contribute to this question, each result was calculated by averaging the number of respondents to that specific question. Accordingly, results are summarised in Figure 15:

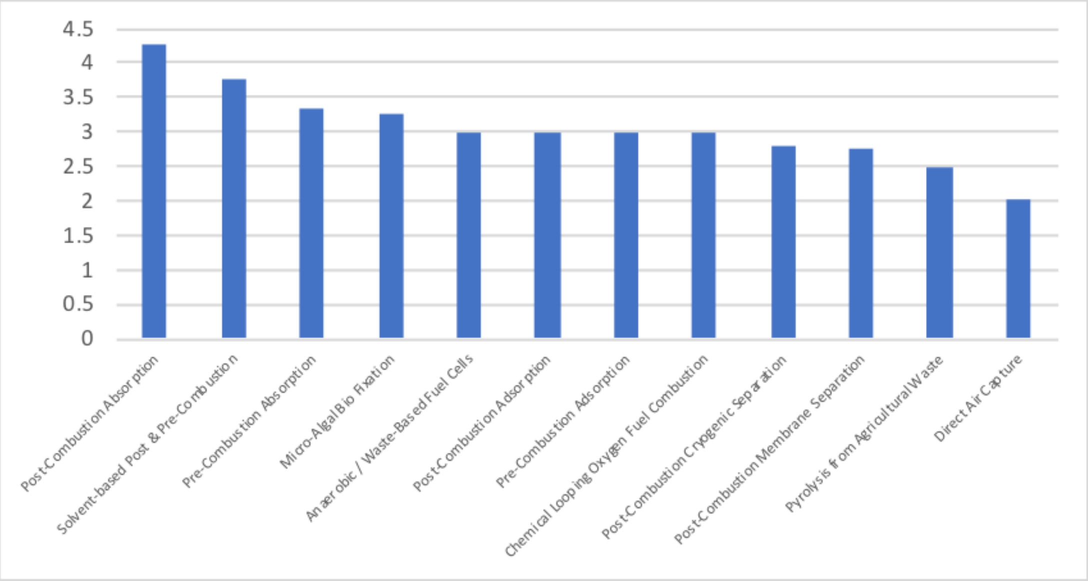
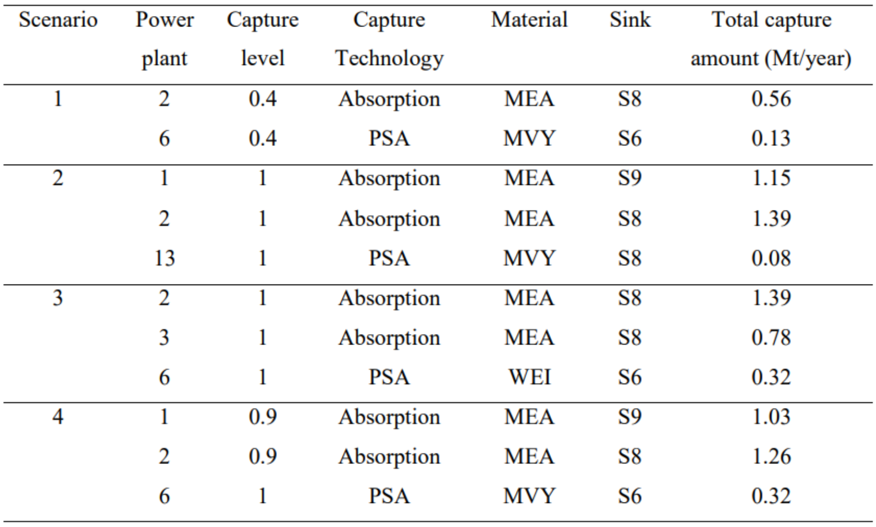


Figure 20 – Plot of Average Survey Ranking of Different CCSU Technologies (1 least - 5 most suitable).

These findings can be combined with the findings from Zhang, et al. (2017) whose economic feasibility based on all of Qatar’s existing plants utilised Absorption, Pressure Swing Adsorption, Vacuum Swing Adsorption and Membrane separation as suitable options for the country. In this study, the only plants deemed economically feasible for carbon capture were Ras Laffan-a (1), Ras Abu Fontas B1 (2), Ras Abu Fontas A (3), Al-wajbah (6) and Doha South Super Powerplants (13).

Table 14 - Summary of Carbon Capture Potential in 5 Power Plants Using Different Capture Mechanisms Under Various Scenarios (No domestic carbon trading [1], domestic carbon trading [2], fair cost distribution under same saving ratio [3] or fair cost distribution under Nash approach [4]) (Zhang, et al. 2017).



Scenario	Power plant	Capture level	Capture Technology	Material	Sink	Total capture amount (Mt/year)
1	2	0.4	Absorption	MEA	S8	0.56
	6	0.4	PSA	MVY	S6	0.13
2	1	1	Absorption	MEA	S9	1.15
	2	1	Absorption	MEA	S8	1.39
	13	1	PSA	MVY	S8	0.08
3	2	1	Absorption	MEA	S8	1.39
	3	1	Absorption	MEA	S8	0.78
	6	1	PSA	WEI	S6	0.32
4	1	0.9	Absorption	MEA	S9	1.03
	2	0.9	Absorption	MEA	S8	1.26
	6	1	PSA	MVY	S6	0.32

The responses also generalised that the ultimate suitability of all technologies will be dictated through the overall system design and combination with renewable options. Nevertheless, overall average suitability of proposed technologies scored 3.02/5, with pre- & post-combustion absorption, and solvent-based post-combustion ranking the highest. Pyrolysis, DAC, Cryogenic Separation and Membrane Separation were considered below average. The more in-depth feedback on each technology has been collated in Table 15:

Table 15 - Survey Feedback on Barriers and Potential of Different CCSU Technologies.

Technology	***Feedback***
Direct Air Capture	- Most challenging option - Does not fit industry emission profiles - Low technology readiness & reliability (to) - Not currently suitable for Qatar - Inefficient infrastructure
Pyrolysis from Agricultural Waste	- Needs efficient capture mechanism - Low TRL

	- Only feasible in large scale agricultural contexts - High CCSU potential, very expensive & inefficient
Micro-Algal Bio Fixation	- High energy input - Low techno-economics & CO_2 efficiency - Valuable for outdoor open pond low-energy desalination
Anaerobic / Waste-Based Fuel Cells	- Underdeveloped in Qatar - Presents high potential
Post-Combustion Absorption	- High TRL - Applicable for commercialization in Qatar - Logistical barriers to implementation
Post-Combustion Adsorption	- Low TRL and commercial viability
Post-Combustion Membrane Separation	- Low TRL and commercial viability - Dependent on membrane criteria
Post-Combustion Cryogenic Separation	- Low competitiveness potential - Already at industrial scale
Solvent-based Post & Pre-Combustion	- High TRL (post) - Not feasible for retrofit (pre)
Pre-Combustion Absorption & Adsorption	- Not feasible for retrofit (pre)
Chemical Looping Oxygen Fuel Combustion	- Low TRL - Needs significant investment - Low commercial viability - Suitable for high heat (solar concentration)
Other (Please Specify)	- Carbon to Plaster-Like Construction Materials (Gálvez-Martos, Elhoweris, Yousef, & Al-horr, 2020) - Reforestation and innovative landscape greening

4.4.10 CCSU Process Barriers

Table 16 – Survey Responses About Processes in the CCSU Supple Chain with Most Barriers.

	Capture	**Storage**	**Transportation**	**Utility**	**Policy**
No. 1					X
No. 2					X
No. 3	2			3	1
No. 4	x			x	x
No. 5	5	1	2	3	4
No. 6	x	x		x	x

The main takeaway from this question has been the requirement of policy to spearhead the technologies going forward. This feedback includes the need for policymakers to:

- Offset adoption costs for operators and make it commercially more attractive
- Improve integration and provide guidelines on utilisation
- Streamline the administrative process required for set-up in all relevant industries

On the other hand, one respondent firmly believed that policymakers will implement the necessary processes once CCS technologies are able to economically compete with alternatives, including renewables and existing systems. In this view, the technology is well-developed but needs further commercial viability. Combining these opposite views, another perspective is that barriers exist in all stages, yet it is those in capture and policy which dictate the industry trends.

4.4.11 Qatar's Potential for Replacing Fossil Fuels with Solar Energy

Table 17 – Survey Responses About Solar Energy Potential in Qatar.

Respondent	**Feedback**
No. 1	- Potential costly issues with electrical grid stability beyond 20% dependence - Fully renewable energy mix is too expensive - Gas is important for transition away from fossil fuels & needed in medium-term
No. 2	- High feasibility
No. 3	- Renewable capacity can be increased - Increase grid solar capacity to 20% - Requires correct energy policies - CCSU still required for natural gas process-related emissions
No. 4	- Renewables not yet commercially competitive with fossil fuels - Politics and personal benefit plays a part - Fossil fuels are too big of a source of income
No. 5	- Feasible but Qatar must be world leader in gas & oil innovation - Long-term 30-year policies should include renewable strategy - Qatar already leader in energy efficiency - State-of-the-art facilities such as Shell GTL
No. 6	- Solar potential due to geographic conditions - Transition requires long-term strategic national energy plan

While the potential for solar energy has been anticipated by all respondents, most of these only see it to be partially feasible for the short-term due to Qatar's position as a leading gas producer and potential industry leader in the world - an important national strategy in the transition away from fossil fuels. While innovations in solar energy have potential and must be pursued to diversify the energy mix, they will not replace the need for CCSU technologies in the economically-vital gas and oil sectors.

5. Discussion – Measuring Carbon Reduction & Policy Advice

5.1 Introduction

The 2014 report by Meltzer, Hultman & Langley reported on the fragmentation of Qatar's current CCS policy, as well as the need for moving beyond a project-oriented approach towards a National Programme, including:

- A *national storage mapping initiative*: identification of all saline aquifers; geological formations; and mature oil fields where CCSU can take place.
- A *legal and regulatory framework* for environmental liability planning and overall risk management. This also includes management of carbon pricing and how such an international effort could potentially affect the price of gas as an export product in Qatar. Examples of other national regulatory frameworks may be beneficial for a comparative development of a legal national document.
- A *global reporting of CCS projects* and their associated challenges. Regional collaboration can play a significant role for reporting, however current political challenges are a critical barrier towards this. Nevertheless, Qatar can engage other international players at this stage. Development of indigenous CCS technologies can aid Qatar to cement its globally-leading role in the EOR fields, with the aim of generating national income via global technological export and consultancy. Such initiatives can be organised through various international forums, including the Global CCS Institute and UNFCCC.

5.2 Appropriateness of Technologies for Qatar

Two of the main areas where the technologies are appropriate for the region of Qatar are in oxy-fuel combustion capture and geological storage. The former example applies to the building industry, specifically cement production and steel manufacture. With the large scale amount of building work that takes place in the region, implementing these capture technologies will help to significantly reduce the country's carbon footprint and go a long way towards meeting their targets for Carbon Capture they have set out. The influence of this can also stretch to the surrounding regions where, due the large scale income generated from the oil and gas industry, there is heavy investment in infrastructure and building to boost the economy further. Therefore by Qatar being able to demonstrate the utilisation of these technologies to offset the impact of those projects, other neighbouring nations can follow suit.

For the latter, Qatar has many options for geological storage though the potential knock-on effects of utilising these methods must be taken into consideration. It has been identified that the country has saline aquifers to consider employing for this purpose, where the CO_2 can be injected into high-concentration salt waters to mineralise, but this must not accidentally leach into the country's water supply or show any potential to escape into the atmosphere, rendering the method useless. It can also be stressed that, in the area as a whole, depleted hydrocarbon fields will also be available for CO_2 to be pumped into. Whilst these stores have been proven to be able to hold the emissions with a remote risk of them escaping to the atmosphere, due to their previous ability to hold oil and gas reserves, consideration has to be made as to how the gas is transported to these locations. The latter can be done through liquification, or through the use of EOR and EGR processes, effectively replacing the oil and gas in existing, undepleted hydrocarbon fields to replace the desired product.

5.2.1 Suitability of CCSU Technologies in Qatar

Depending on unique geopolitical and socioeconomic conditions, each country must find its own path towards sustainability and Qatar presents a unique position in this pursuit. This country and the Gulf Cooperation Council (GCC) region has significant issues with water and food scarcity, high emissions per capita, oil-based economies, and vulnerability in satisfying its growing socioeconomic demands (Meltzer, Hultman, & Langley, 2014).

5.2.1.1 Current Projects

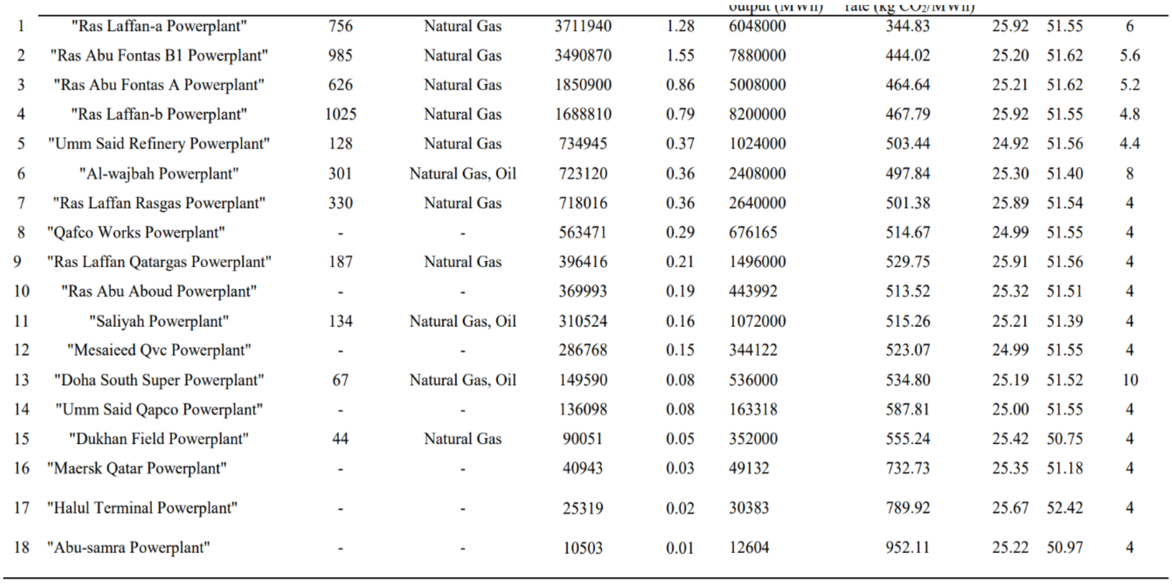
Qatar’s energy industry is largely tied into the state-owned enterprises that are involved in most aspects of the business, as well as creating legislation and regulations. Nevertheless, some private participation of local and international companies also occurs in this field. The international companies (IOCs) mostly operate under exploration and production-sharing agreements (EPSAs), while minority shares from publicly traded companies are traded on the Qatar Stock Exchange. A summary of key players in the country’s energy industries are shown in Table 18:

Table 18 – Summary of Main Oil & Gas Companies in Qatar.

Organisation	**Type**
Qatar Petroleum (QP)	State-owned
Qatargas Consortium	4 Venture Partnerships; QP (65%) as main partner & IOCs (Total, ExxonMobil, Mitsui, Marubeni, ConocoPhillips and Shell)
RasGas	3 Venture Partnerships; QP (70%) as main partner & ExxonMobil (30%)
Barzan	QP (93%) & ExxonMobil (7%)
Pearl GTL	QP & Shell
Oryx	QP (51%) & Sasol (49%)

Furthermore, information from 2015 lists 18 of the 29 existing powerplants in Qatar as shown in Table 19, including each plant’s relevant information, i.e., fuel type, output, and carbon emissions rate (Zhang, et a. 2017):

Table 19 - List of All Powerplants in Qatar as of 2015 (Zhang, et a. 2017).



						output (MWh)	rate (kg CO_2/MWh)			
1	"Ras Laffan-a Powerplant"	756	Natural Gas	3711940	1.28	6048000	344.83	25.92	51.55	6
2	"Ras Abu Fontas B1 Powerplant"	985	Natural Gas	3490870	1.55	7880000	444.02	25.20	51.62	5.6
3	"Ras Abu Fontas A Powerplant"	626	Natural Gas	1850900	0.86	5008000	464.64	25.21	51.62	5.2
4	"Ras Laffan-b Powerplant"	1025	Natural Gas	1688810	0.79	8200000	467.79	25.92	51.55	4.8
5	"Umm Said Refinery Powerplant"	128	Natural Gas	734945	0.37	1024000	503.44	24.92	51.56	4.4
6	"Al-wajbah Powerplant"	301	Natural Gas, Oil	723120	0.36	2408000	497.84	25.30	51.40	8
7	"Ras Laffan Rasgas Powerplant"	330	Natural Gas	718016	0.36	2640000	501.38	25.89	51.54	4
8	"Qafco Works Powerplant"	-	-	563471	0.29	676165	514.67	24.99	51.55	4
9	"Ras Laffan Qatargas Powerplant"	187	Natural Gas	396416	0.21	1496000	529.75	25.91	51.56	4
10	"Ras Abu Aboud Powerplant"	-	-	369993	0.19	443992	513.52	25.32	51.51	4
11	"Saliyah Powerplant"	134	Natural Gas, Oil	310524	0.16	1072000	515.26	25.21	51.39	4
12	"Mesaieed Qvc Powerplant"	-	-	286768	0.15	344122	523.07	24.99	51.55	4
13	"Doha South Super Powerplant"	67	Natural Gas, Oil	149590	0.08	536000	534.80	25.19	51.52	10
14	"Umm Said Qapco Powerplant"	-	-	136098	0.08	163318	587.81	25.00	51.55	4
15	"Dukhan Field Powerplant"	44	Natural Gas	90051	0.05	352000	555.24	25.42	50.75	4
16	"Maersk Qatar Powerplant"	-	-	40943	0.03	49132	732.73	25.35	51.18	4
17	"Halul Terminal Powerplant"	-	-	25319	0.02	30383	789.92	25.67	52.42	4
18	"Abu-samra Powerplant"	-	-	10503	0.01	12604	952.11	25.22	50.97	4

Current research on the geological potential for CCSU in Qatar is spearheaded by the Qatar Carbonates and Carbon Storage Research Centre (QCCSRC) in Imperial College London - a 10-year collaborative project between the university, Qatar Petroleum, Shell and specific sub-organisations of the Qatar Foundation, as a multi-national $70 million collaboration to develop an understanding about the geological conditions in Qatar, the behaviour of fluids in rocks and visualisation of these conditions using X-Ray and digital modelling, and other related topics (Imperial, 2019). Further action as of 2017 included: grants by Qatar Foundation to research environmental technologies including CCSU; existing developed infrastructure for CCSU in the Pearl Gas-to-Liquid (GTL) plant; investment in other recovery plants; as well as providing the legislative, regulatory and governmental roadmaps towards CO_2 capture in the country and developing a local league of scientists who can actively continue this research on the domestic level (Alsheyab, 2017).

The landmark project that catapulted CCSU potential in Qatar into the public eye was the country’s 2019 announcement that it will build the region’s largest carbon capture and sequestration facility, and that it plans to sequester 5 million tonnes of CO_2 per year by 2025 (current capacity at 2.1 million tonnes per year). The plan includes the construction of pipelines across the country over 10 years to enable transporting captured carbon to various plants for EOR processes in the country's vast oil fields (Al Jazeera, 2019). This announcement is in line with others from the Qatar Petroleum CEO and Qatar's Minister of State for Energy, Saad al-Kaabi, who has been working to consolidate Qatar's oil and energy plans, including progress on Carbon Capture facilities. In an interview with MEES (2019), al-Kaabi mentioned that they plan to spend $100-200 million on CO_2 capture, storage and utility, while the country's current plans are two separate projects:

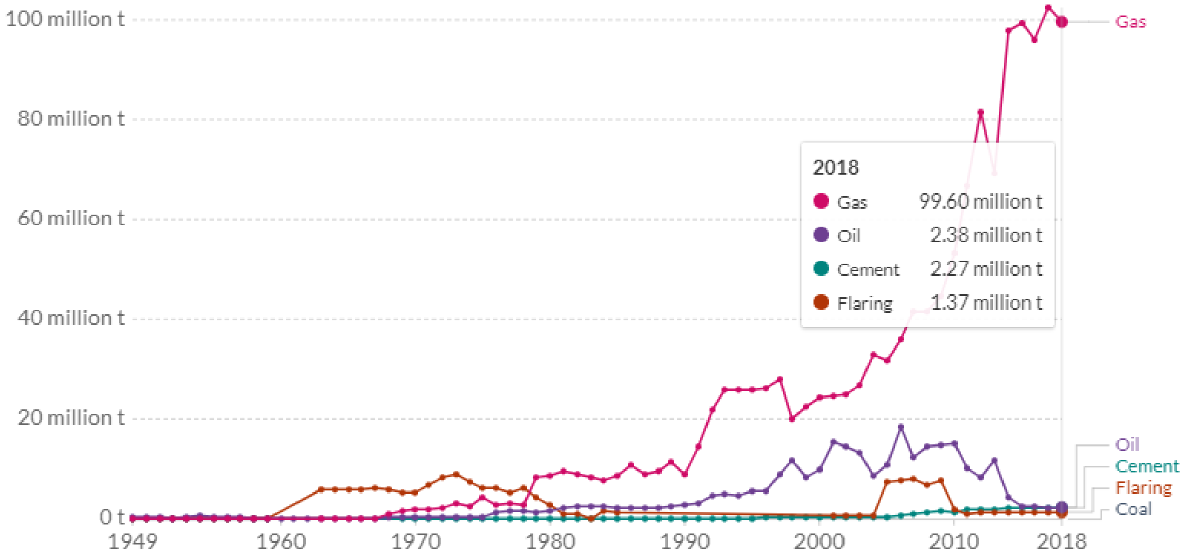
- A separate pure capture and utility facility from gas productions
- EOR at the Dukhan oilfield incorporating countrywide pipeline infrastructure, using injected CO_2 captured from gas production

5.2.1.2 Ras Laffan

The separate project, based at Ras Laffan, is currently commissioned by Qatar Petroleum (QP) with a starting operating date set for 2025. At the time of the indexing of existing CCSU projects around the world by IOGP, the Ras Laffan plant is only the fourth CCSU project in the Middle East. All other existing projects are also based on capture from LNG and gas plants, with aims for EOR (IGOP, 2020). The reoccurring theme of EOR is a key domain for CCSU in Qatar as the industry leaders aim to exhaust as much oil as possible from existing rigs before they embark on new oil exploration projects. According to al-Kaabi, this is due to exploration being expensive and success rates potentially reaching as low as 10-15%, hence before risking building new infrastructure at new locations, existing mature fields must be utilised as much as possible - EOR enables this (The Peninsula, 2019).

5.2.2 Capacity & Key Metrics in Qatar

It is estimated that Qatar’s annual energy consumption is approximately 46.1 billion kWh, while the country’s CO_2 carbon footprint is 87 million tons (IEA, 2018). Data from Our World in Data shows that the majority of Qatar’s main energy and carbon emissions sources are coming from gas (99.60 million tonnes), while oil, cement and flaring make up 2.38, 2.27 and 1.37 million tonnes of CO_2 respectively, totalling over 105.6 million tonnes per year.



Source: Global Carbon Project (GCP) and Carbon Dioxide Information Analysis Center (CDIAC)Global Carbon Project (GCP) and Carbon Dioxide Information Analysis Center (CDIAC)

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Figure 21 – Plot of Carbon Emissions by Key Fuels & Industries.

Additionally, this resource presents data on the GHG emissions by sector, showing that electricity, heat, manufacturing, construction, transport, fuel, fugitive emissions, industry, waste, agriculture, and buildings make up the key emissions in carbon dioxide equivalents.

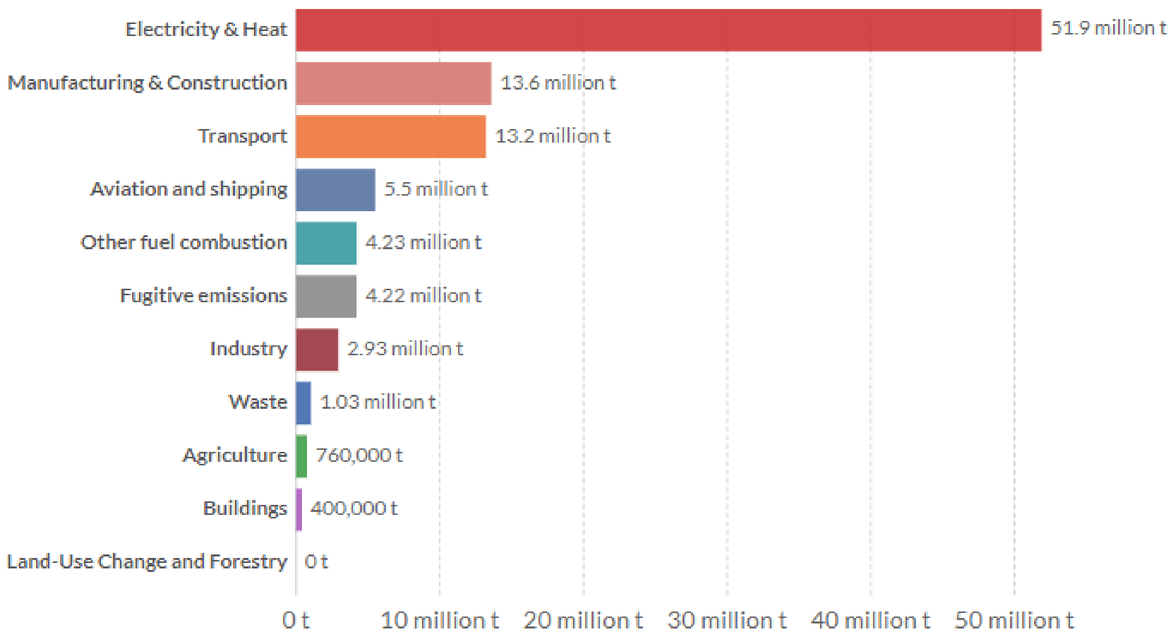


Figure 22 – Plot of GHG Emissions as carbon dioxide-equivalents by Sector in Qatar from 1990-2016 (Ritchie & Roser, 2020).

Qatar’s capacity to store some of its carbon into geological formations lies most importantly in its saline Aruma aquifer, a large subterranean area that makes up 16% of the country’s total land mass. The high potential for this storage possibility comes from the combined advantage that the aquifer covers a land area of 1985 km^2, therefore it can store 230 megatonnes of CO_2 in a 200 year span. Additonally, water that is stored in the aquifer is considerably less saline than water from the Gulf, meaning that utilising this untapped water source can reduce the footprint and dependency on the environmentally-damaging and energy-intensive process of desalinisation (Ahmed & Nasrabadi, 2012). Furthermore, saline water extracted from these sources or the Gulf can be used for the development of microalgae ponds which are highly suited to Qatar’s non-arable landmass, hot climate with abundant sunshine, accompanied by a low start-up cost (Wilson, Salama, & Farag, 2012). The potential for using the brine left over from the desalination process includes the production of Nesquehonite, a construction material with cementitious properties which can aid in replacing the vastly energy-intensive process of cement production for building and infrastructure projects (Glasser et al., 2016). Further research on Nesquehonite production has been carried out for Qatar with specific focus on the economies of scale, as well as process and material availability, showing that despite high operating costs, the product can be economically competitive - $410 USD per tonne in comparison to the overwhelmingly imported construction materials (Gálvez-Martos, et al., 2020). This system utilises carbon capture via alkaline absorption and magnesium from brine leftover from the common water desalination process.

On the other hand, some challenges remain in the full utilisation of carbon storage due to: the lack of adequate technology in capturing carbon from various sources; difficulty in mapping reservoirs and aquifers; engineering safe carbon storage strategies with no chance of carbon leakage; inadequacy in technology to monitor storage facilities; international standardisation of the process; and resolving the trade-off with further extraction of oil from depleted reserves (Stevens, Kuuskraa, Gale, & Beecy, 2001). The potential for this process can aid in the Enhanced Oil Recovery (EOR) process, reduce the cost of oil production and help in ensuring oil fields are utilised to the maximum level (Meltzer et al., 2014). Furthermore, any attempt to utilise these novel and not-often-tested technologies must balance their potential for dealing with carbon footprint with an overall understanding of other pollutants, toxic waste, contamination of natural resource, and further energy emission pathways in the storage and transportation process. This can be modelled through a pragmatic Life Cycle Assessment (LCA) to weigh the advantages and disadvantages of the process (Korre, et al., 2012).

Taking into account the gas fields of Qatar largely lie in the northern areas of the country and the large storage feasibility of the country laying within its southern aquifers, CCSU technology for Qatar must also develop a comprehensive transportation infrastructure which can safely dispose of CO_2 by transporting it in the same density as liquid form, to allow injection into geological formations. This presents added potential for energy use in the CCSU process and reduced overall feasibility for net carbon sinking. This concern also extends to the CCSU and transportation infrastructure required to capture CO_2 from natural gas fields and production units based within the Gulf, as the risk for damage to the environment can be significant should any leakage of CO_2 occur in the considerably more risk-prone aquatic environment. Accordingly, further research is required to understand the modes of transporting CO_2 on land and in the sea, and the levels of energy loss that should be expected from such processes.

Recommendations for research towards sustainable development in Qatar by Rand institute suggests investment in CCSU topics, mainly relating to storage and also capture directly at the natural gas combustion power generators (Nidhi Kalra et al., 2011). Further collaboration and sharing of knowledge resources between the countries of the GCC is required to build a database of environmental research for use in CCSU efforts and combine expertise in these countries with similar concerns. However, recent rifts in the relations between Qatar and other GCC countries and severing of diplomatic ties between the parties has dented hopes of such collaboration (Al Jazeera, 2018). Hence, it can be deduced that regional political issues may be a significant issue towards improving CCSU technology in these national contexts. At the same time, Qatar’s major financial capacity, relatively-developed infrastructure and state-of-the-art academic institutions and industries are a valuable source for the development of international partnerships beyond the region, such as those within the US-China clean energy partnership and other energy leaders including Norway and Australia, as a microcosmic example of how CCSU technologies can be utilised in other countries (Meltzer et al., 2014). It should also be noted however that current high GDP-per-capita and wealthy output does not directly equate to investment capability, as the country’s oil and gas dependent industry does not have enough capacity to withstand shocks to the market, and the financial reserves and debt capability of the country are not as developed (Babonneau et al., 2021).

5.2.3 Potential of Identified Technologies for Qatar

As mentioned in the literature review, CCSU technologies differ in the processes through which they separate the carbon from other elements, and in the ways the carbon is either utilised or stored. As can be seen above, regardless of industry, most of the industrial capture mechanisms operate through either post-conversion, pre-conversion, or oxy-fuel combustion capture. Pre-combustion capture is marked by separating the carbon from oxygen through absorption or adsorption to produce synthetic gas - the separation of hydrogen as a by-product can be used in other industries. The technology's drawback comes from the high investment costs associated with the need to include the reaction chambers in the power plant from the origin of design - it is not currently possible to retrofit these into existing plants (Blomen, Hendriks, & Neele, 2009). Absorption using absorbent acids is the way through which CO_2 is separated from the synthetic gas, with the potential to lead to very high carbon purity levels of 98-99%, though this requires high electricity costs (Porter et al., 2017). Similar research is being carried out to understand the net capture, energy penalty and cost feasibility of the utilising amine-based solvents for the separation process (Moioli et al., 2014). With regards to adsorption, experimental studies are being carried out to use microscopic polymeric membranes as a way to reduce the need for a simplified and cheaper separation process - however, the manifestation of such membrane technology has not yet moved far beyond the laboratory yet (Shan et al., 2018).

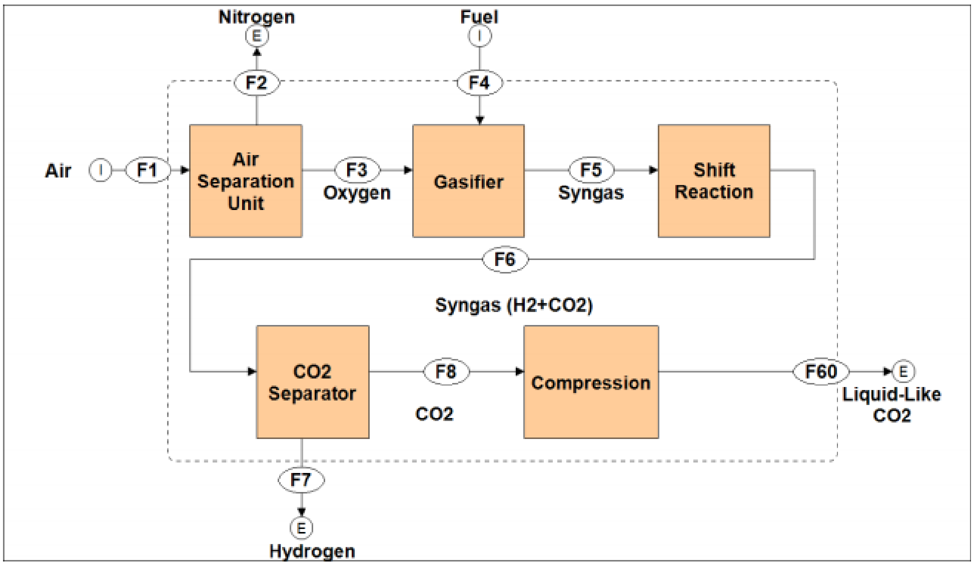


Figure 23 - Schematic Process Visualisation for Pre-Combustion Carbon Capture (Alsheyab, 2017).

Furthermore, post-combustion mechanisms utilise the CO_2 produced after the burning of fuel for power generation by capturing it through amine-based solvent absorption technologies, with high potential for commercialisation, but issues with volatility, corrosion, and energy excessiveness exist (Babamohammadi, et al., 2015; Subramanian, et al., 2017). Alkaline solvents with similar issues (Peng, Zhao, & Li, 2012), ionic liquids with reduced chance of volatility and corrosion and being based on the use of liquid salts (Perez-Blanco & Maginn, 2010) are among other experimental ideas which are not yet commercialised on a mass scale. Furthermore, there are other adsorption technologies through a variety of innovations, but not all relate to usability for the case of Qatar and most are still in the experimental stage, hence some have been omitted for review in this study. Examples include the production of zeolites as a by-product of volcanic ash and potential as an adsorption membrane (Makertihartha, et al., 2017) and the production of activated carbon from agricultural product waste; an industry which does not exist on an industrial scale in Qatar and does not present significant potential in the country (Hagemann, et al., 2018).

While the adsorption and absorption technologies above capture carbon through physio-chemical processes, there is also the potential to utilise post-combustion membrane separation, by installing sponge-like materials on the flume of power plants and stopping the CO_2 from entering the atmosphere at this last stage of the production process. The technology has not yet reached high commercial or efficiency values, but it presents some of the best opportunities for retrofitting onto existing plants (Subramanian, et al., 2017).

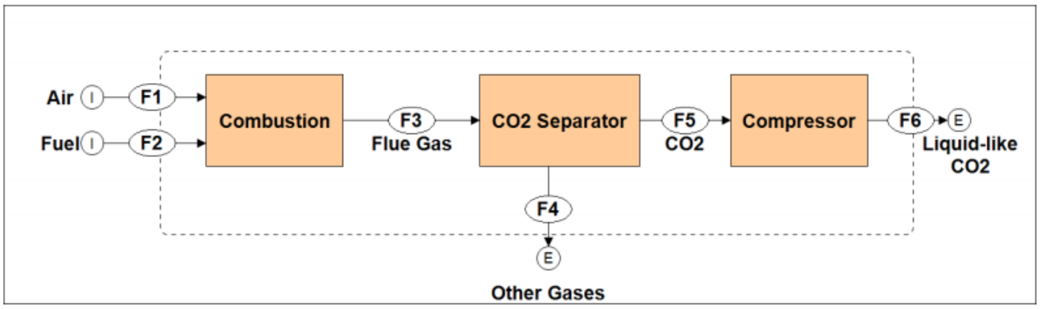


Figure 24- Schematic Process Visualisation for Post-Combustion Carbon Capture (Alsheyab, 2017).

Finally, in terms of combustion-related technologies, oxy-fuel combustion processes allow for the separation of oxygen from the air before the combustion process, allowing for the removal of other elements including nitrogen and water. This leads to significantly cleaner combustion processes and reduced need to use chemicals or secondary processes. Nevertheless, this process is not yet commercially-viable, and there are significant barriers with energy efficiency and cost in the separation of oxygen from natural air (Kolbitsch, et al., 2010).

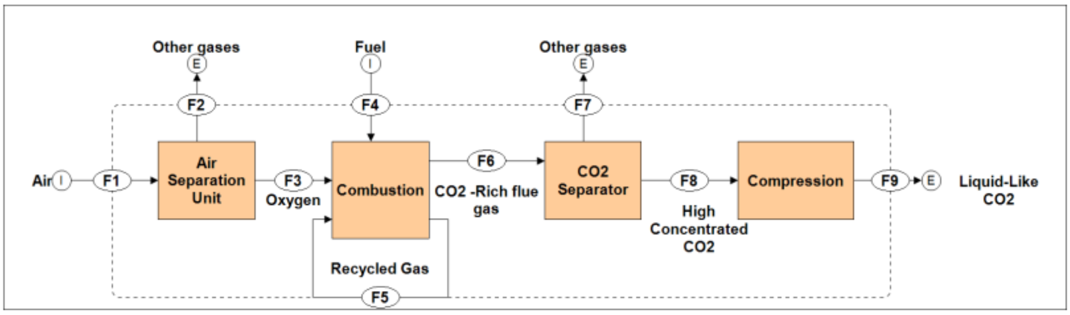


Figure 25 - Oxy-Fuel Combustion Carbon Capture (Alsheyab, 2017).

5.2.4 Integrated LCA System Design

Mapping Qatar's various industries and national infrastructure towards pragmatic CCSU solutions should be considered in Qatar’s CCSU policy. While initiatives to replace fossil fuel generating sources are gaining ground and becoming more prominent, a meaningful analysis of the impact of their replacement with other sources requires attention to many other upstream and downstream factors that go beyond GHG emissions at the energy plant. Toxic materials as by-products, non-GHG air pollutants, as well as mineral, land and water use extents are some key metrics in this regard. However, most importantly, the capacity to generate the same amount of energy as fossil fuels, without making concessions for any of the other criteria, is the critical balance that is required to truly assess the comparative potential for alternative energy sources. Carbon capture, transportation and storage represents a part of the energy lifecycle and, for comparative accuracy, all stages of the lifecycle including: fossil fuel production; transportation; power generation; CO_2 capture; CO_2 conditioning; pipeline transportation; and CO_2 injection and storage, as well as the economic and environmental aspects must also be considered (Korre, Nie, & Durucan, 2012). An example of the full lifecycle assessment (LCA) for a system is provided by Korre, et al. (2012) for a natural gas combined cycle system with post-combustion CCSU system. This system, in Figure 21, shows the level of detail that is required for a complete integrated comparative analysis of different systems.

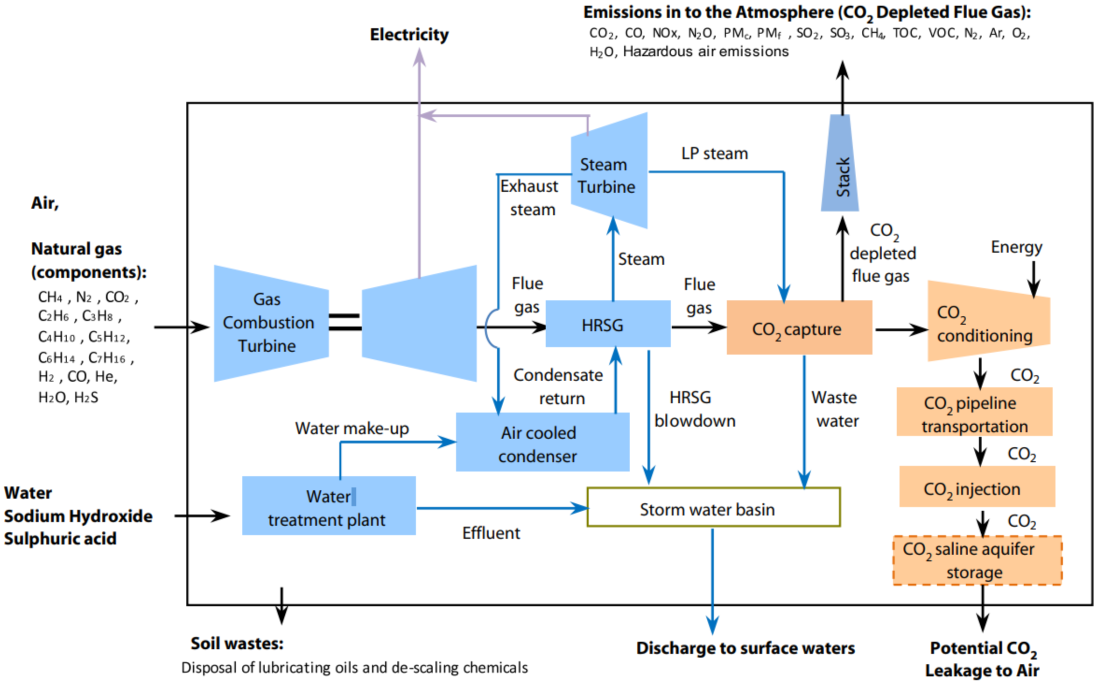


Figure 26 - Detailed LCA for a Post-Combustion CCSU System.

The requirement of recovering energy and resources from the process within an integrated system can also be extended to the need to recycle water, as this resource is highly valuable and requires capture where possible as well. AlNouss & Eljack (2019) estimate that a 500MW power plant requires more than 45,000 m^3 of water per hour to maintain cooling and other processes. In a country such as Qatar, where water is almost exclusively desalinated through energy intensive processes, it is imperative that water recovery must be pursued, i.e. via AlNous & Eljack (2019)'s proposed dehydration hybrid technology system which integrates power plant and desalination systems, providing the potential for up to 42% water recovery.

Similar to water recovery and integrated desalination systems, there is also potential to combine renewable energy into existing systems in Qatar. The study by Al-Obaidli, et al. (2019) utilises existing configurations in Qatar's energy infrastructure, including open cycle gas turbine (OCGT), combined cycle gas turbine (CCGT), multi-stage flash (MSF), and seawater reverse osmosis (SWRO) to propose three alternatives: concentrated solar power (CSP); solar PV; and Biomass Integrated Gasification Combined Cycle (BIGCC) - these can provide 52-67% CO_2 emissions reduction and 8-32% system levelized cost reduction.

5.3 Methods of Pragmatic Economic Carbon Modelling

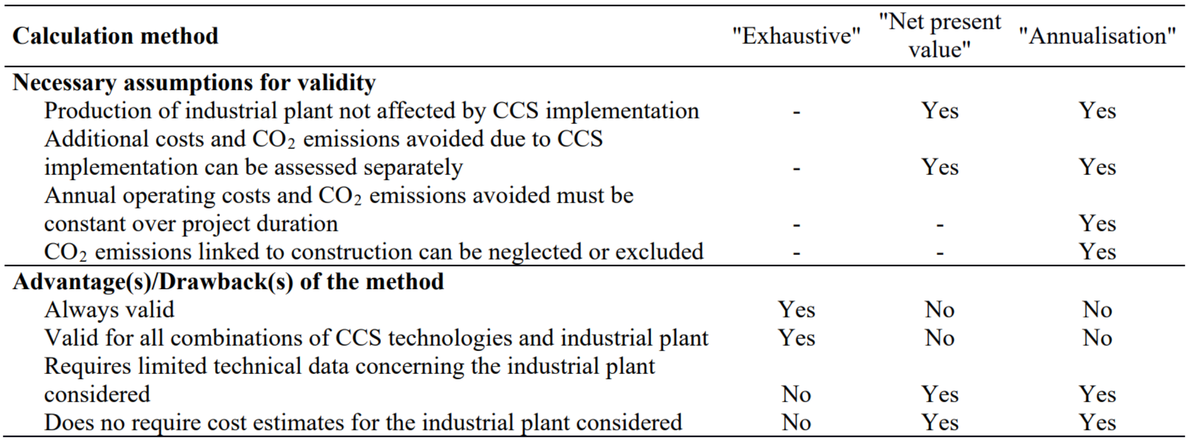
Current plans by Qatari officials include spending over $100-200 million on CCSU, as well as integrating plants for environmental protection which are yet unannounced (Mees, 2019). Considering that the budget available for this investment is finite and that officials must prioritise all potential options, it is important that pragmatic techno-economic cost analysis studies are carried out to ensure the investment choices reflect the realistic feasibility of solutions. In this chapter, the author utilises a thorough search on relevant studies to identify key methods of quantifying the potential of CCSU methods, presenting their pros and cons. It must also be noted that there is a great degree of uncertainty to be cautioned when using most comparative methodologies, as a high degree of estimation is required to make such decisions. For example, a study by van der Spek et al. (2017) found that there can be up to a 65% difference in the analysis of the total capital requirement, and 66% difference in equipment costs for the same post-combustion solvent-based carbon capture system. Roussanaly (2019) also presented a comparative study of evaluating three different CO_2 cost-avoidance modelling methods used for industry, while summarising the various assumptions, advantages, drawbacks of the impact of data uncertainties, low Technology Readiness Level (TRL) technologies, and variations in utilised costs. This study combines literature on cement, steel, refinery, hydrogen and natural gas processing plants, for three typologies of: exhaustive method; net present value method; and annualization method. The main premise of all three studies is the calculation of CO_2 avoidance cost. While the three methods are intricately linked, they are mainly distinguished through the assumptions required in each and how these affect the outcome. The main differences can be summarised as:

-“Exhaustive” is derived from power generation calculation methods; measuring the relation between the difference of Levelised Cost of Key Materials (products, input or combination) at the plant with and without CCS.

-“Net Present Value” & “Annualisation” are derived from production cost estimations, by calculating unit costs after discounted CCS cash flows, not including the cost of the plant. These methods are more useful for retrofit applications and are simpler to execute, though can be more difficult to understand for more complex systems.

Furthermore, the study lists the assumptions, advantages and drawbacks of each methodology in Table 20:

Table 20 - Summary of Assumptions, Advantages/Drawbacks of Industrial CO2 Avoidance Cost Calculation Methods (Adapted from Roussanaly (2019).



Calculation method	"Exhaustive"	"Net present value"	"Annualisation"
Necessary assumptions for validity			
Production of industrial plant not affected by CCS implementation	-	Yes	Yes
Additional costs and CO_2 emissions avoided due to CCS implementation can be assessed separately	-	Yes	Yes
Annual operating costs and CO_2 emissions avoided must be constant over project duration	-	-	Yes
CO_2 emissions linked to construction can be neglected or excluded	-	-	Yes
Advantage(s)/Drawback(s) of the method			
Always valid	Yes	No	No
Valid for all combinations of CCS technologies and industrial plant	Yes	No	No
Requires limited technical data concerning the industrial plant considered	No	Yes	Yes
Does no require cost estimates for the industrial plant considered	No	Yes	Yes

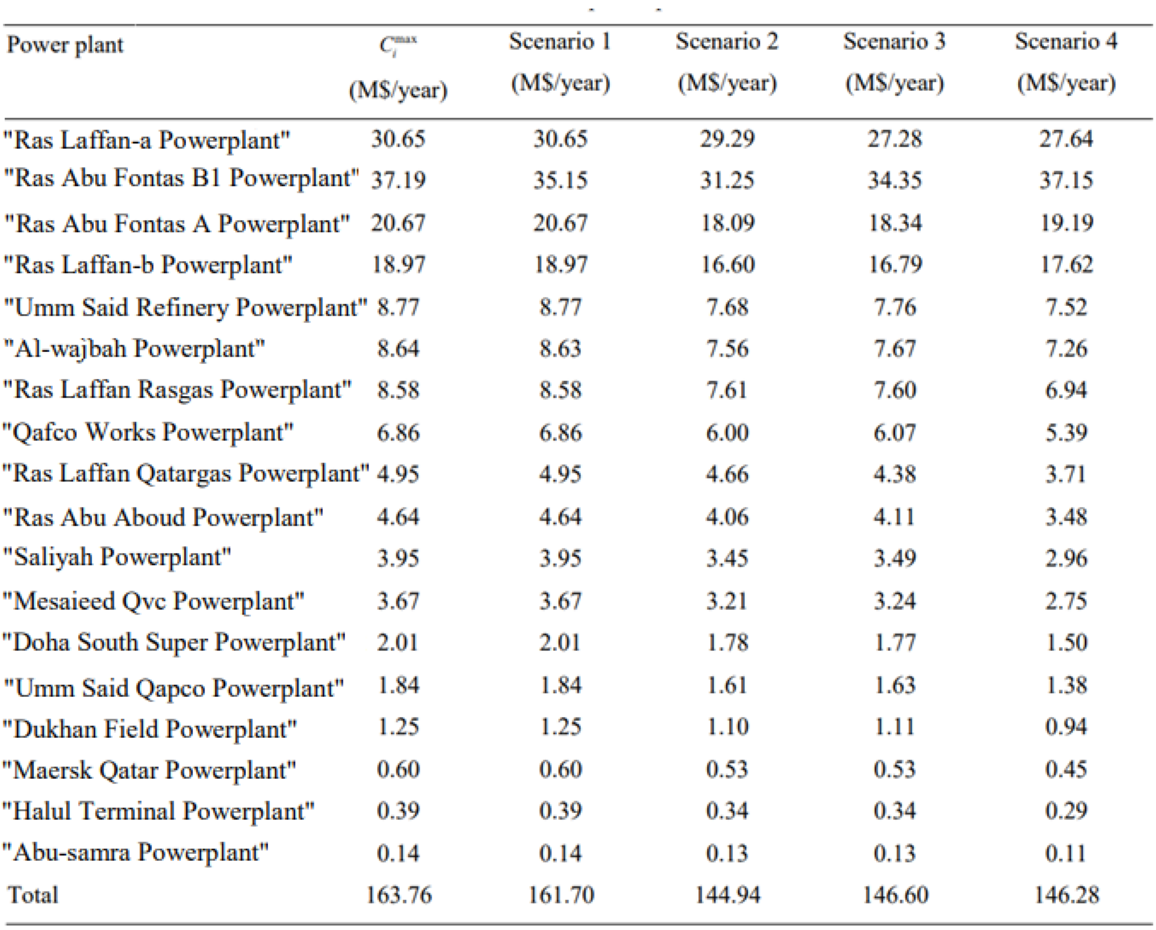
5.3.1 Carbon Credit Trading vs Capture & Storage

Economically, the practical potential of CCS technologies is dependent on the balance of feasibility with the purchase of carbon credits for excess emissions. Zhang, et al. (2017) use Mixed Integer Linear Programming (MILP) and Game Theory to arrive at the conclusion that installation of CCS systems is only feasible amongst the power plants with higher CO_2 emissions, while the purchase of carbon credits remains the best approach for other plants. The author also considered that pragmatic system design for fair cost distribution can be improved upon by building an evolved power distribution and pipeline system. This research considers the total cost of each power plant as the combination of: the dehydration cost; carbon capture cost; CO_2 transportation cost; CO_2 injection cost; and international and domestic carbon trading cost - overall system revenue (made up of carbon trading revenue and CO_2 utilisation revenue). This is shown as the equation below and it can be combined to generate the cost for all power plants:

$$C_i = DC_i + CC_i + LC_i + LJ_i + p^{buy} B_i - p^{sell} S_i + CT_i - p^{utilisation} RE_i$$

This study considers 18 of Qatar’s 29 existing power plants and savings for each based on a balance of fair cost distribution and carbon trading, shown in Table 21:

Table 21 - Summary of Carbon Capture Potential for 18 of Qatar's Powerplants Adapted from [Zhang, et al. (2017)].



Power plant	C_i^{max} (M$/year)	Scenario 1 (M$/year)	Scenario 2 (M$/year)	Scenario 3 (M$/year)	Scenario 4 (M$/year)
"Ras Laffan-a Powerplant"	30.65	30.65	29.29	27.28	27.64
"Ras Abu Fontas B1 Powerplant"	37.19	35.15	31.25	34.35	37.15
"Ras Abu Fontas A Powerplant"	20.67	20.67	18.09	18.34	19.19
"Ras Laffan-b Powerplant"	18.97	18.97	16.60	16.79	17.62
"Umm Said Refinery Powerplant"	8.77	8.77	7.68	7.76	7.52
"Al-wajbah Powerplant"	8.64	8.63	7.56	7.67	7.26
"Ras Laffan Rasgas Powerplant"	8.58	8.58	7.61	7.60	6.94
"Qafco Works Powerplant"	6.86	6.86	6.00	6.07	5.39
"Ras Laffan Qatargas Powerplant"	4.95	4.95	4.66	4.38	3.71
"Ras Abu Aboud Powerplant"	4.64	4.64	4.06	4.11	3.48
"Saliyah Powerplant"	3.95	3.95	3.45	3.49	2.96
"Mesaieed Qvc Powerplant"	3.67	3.67	3.21	3.24	2.75
"Doha South Super Powerplant"	2.01	2.01	1.78	1.77	1.50
"Umm Said Qapco Powerplant"	1.84	1.84	1.61	1.63	1.38
"Dukhan Field Powerplant"	1.25	1.25	1.10	1.11	0.94
"Maersk Qatar Powerplant"	0.60	0.60	0.53	0.53	0.45
"Halul Terminal Powerplant"	0.39	0.39	0.34	0.34	0.29
"Abu-samra Powerplant"	0.14	0.14	0.13	0.13	0.11
Total	163.76	161.70	144.94	146.60	146.28

5.3.2 Comparative Cost of Emissions Mitigation Using Process Integration

Lameh, et al. (2020) utilise a method of Marginal Abatement Cost (MAC) modelling to analyse the potential for savings and cost abatement through the integration of renewable energy sources and CCSU mechanisms in relevant industries. While the study compares three global locations, it also offers Qatar-specific insights. The unique viewpoint of this study is that it includes the potential of renewable energy to entirely replace carbon-intensive fossil fuels that require CCSU for mitigation, while also including storage and utility as a means to make profit (i.e., EOR). Operation, efficiency, energy requirements, CO_2 purity and other factors are included to create the following equation and subsequent MAC curve (Lameh, et al., 2020):

$$MAC_{CCUSij} = \frac{C_i - R_j}{\eta_j - \gamma_i}$$

Where: i is source; j is sink; C is carbon capture and compression specific cost ($/t$CO_2$ captured); γ is the secondary emissions from energy requirements (tCO_2 produced / tCO_2 captured); R is value-added products ($/t$CO_2$ allocated); and η is net carbon removal efficiency (tCO_2 removed / tCO_2 allocated). This calculation can be carried out for various industries and combined for a country profile curve, shown in Figure 23:

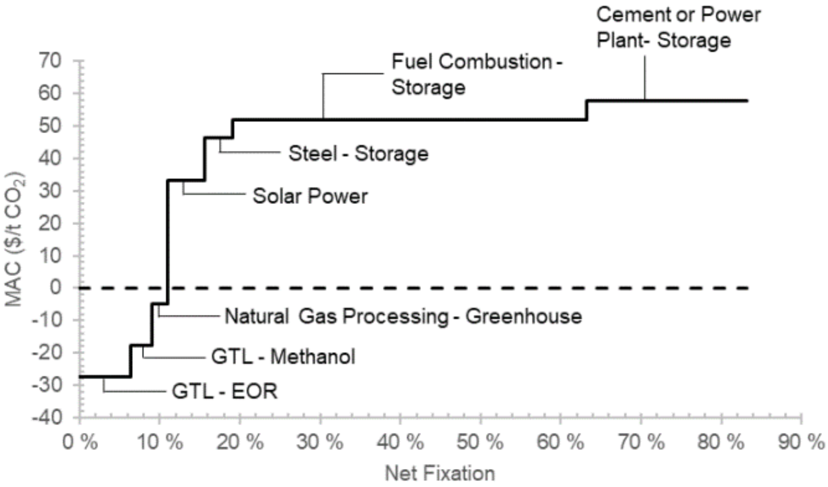
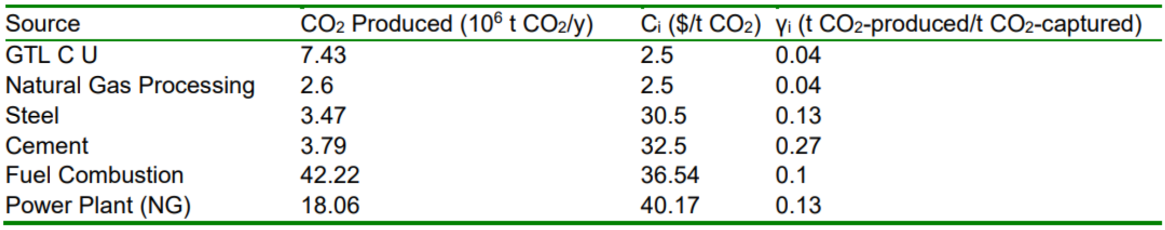


Figure 27 - Plot of MAC Curve for Various Processes in Qatar (Lameh, et al. 2020).

The findings suggested that GTL and Natural Gas Processing can produce negative MAC, meaning they can be profitable, while suggesting that switching to solar power can be cheaper than investment in various storage mechanisms, including fuel combustion, cement, power plant, or steal capture and storage. This finding presents a valuable critique of the potential for more innovative CCSU, when a pragmatic switch to solar can eliminate the need for carbon-intensive energy entirely. Lameh, Al-Mohannadi & Linke (2020) combine data from existing research according to energy prices, as well as $/t$CO_2$-captured, amount of CO_2 produced, and the ratio of CO_2 produced versus captured from the country's main emitting and economically-important sources.

Table 22 - Emissions Sources and Related Parameters in Qatar (Lameh, et al., 2020).

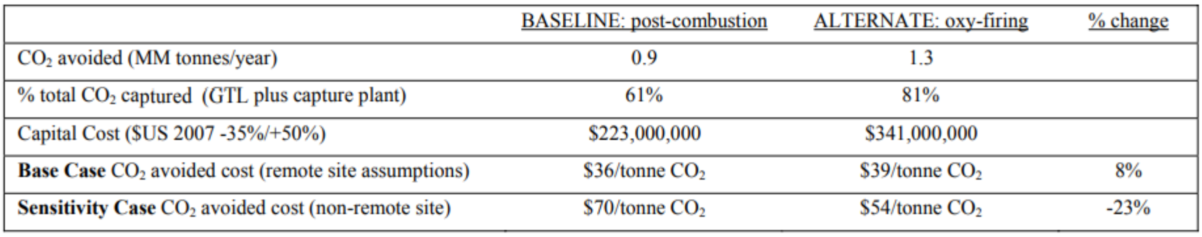


Source	CO_2 Produced (10^6 t CO_2/y)	C_i (\$/t CO_2)	γ_i (t CO_2-produced/t CO_2-captured)
GTL C U	7.43	2.5	0.04
Natural Gas Processing	2.6	2.5	0.04
Steel	3.47	30.5	0.13
Cement	3.79	32.5	0.27
Fuel Combustion	42.22	36.54	0.1
Power Plant (NG)	18.06	40.17	0.13

5.3.3 Comparing Costs of GTL CC Using Post-Combustion and Oxy-Firing

To reduce variables in the comparative paradigm, Heimel & Lowe's (2009) cost estimation method considered the carbon capture stage of the process in a GTL facility, focusing on the operational and capital costs of retrofitting with either post-combustion or oxy-firing. This methodology has the obvious shortcomings of not including carbon credits, or those associated with storage, transportation, and utility. Nevertheless, the sensitivity test allowed for considering site-specific factors, and showed higher cost (8%) for oxy-firing in remote sites, and post-combustion in non-remote sites (23%) (Heimel & Lowe, 2009).

Table 23 – Comparing the Carbon Capture Cost of Post-Combustion & Oxy-Firing Retrofit on GTL Plants (Heimel & Lowe, 2009).



	BASELINE: post-combustion	ALTERNATE: oxy-firing	% change
CO_2 avoided (MM tonnes/year)	0.9	1.3	
% total CO_2 captured (GTL plus capture plant)	61%	81%	
Capital Cost (\$US 2007 -35%/+50%)	\$223,000,000	\$341,000,000	
Base Case CO_2 avoided cost (remote site assumptions)	\$36/tonne CO_2	\$39/tonne CO_2	8%
Sensitivity Case CO_2 avoided cost (non-remote site)	\$70/tonne CO_2	\$54/tonne CO_2	-23%

5.3.4 Meta-Study Comparing Techno-Economic Studies from 2007-2017

The study by Adams II, et al. (2017) is unique in its scope and utility, as it combines a wealth of existing data up to 2017 by carrying out an in-depth analysis which streamlines this in a way that allows comparison of 114 different executions of technologies from various locations and years for coal and gas. Another interesting characteristic of this study is the use of a metric of "tCO_2e per MWh of net power output" as Global Warming Potential (GPH), instead of CO_2. The study's findings can be aptly summarised for the purpose of this paper through the graph in Figure 24. The Cost of CO_2 Emissions Avoided (CCA) is plotted against various capture method groupings, including Natural Gas Combined Cycle (NGCC) and Supercritical Pulverized Coal (SCPC) using uniform and as-reported fuel prices. The Cradle-to-Grave Emissions, Levelized Cost of Electricity and overall Efficiency of each technology is also presented.

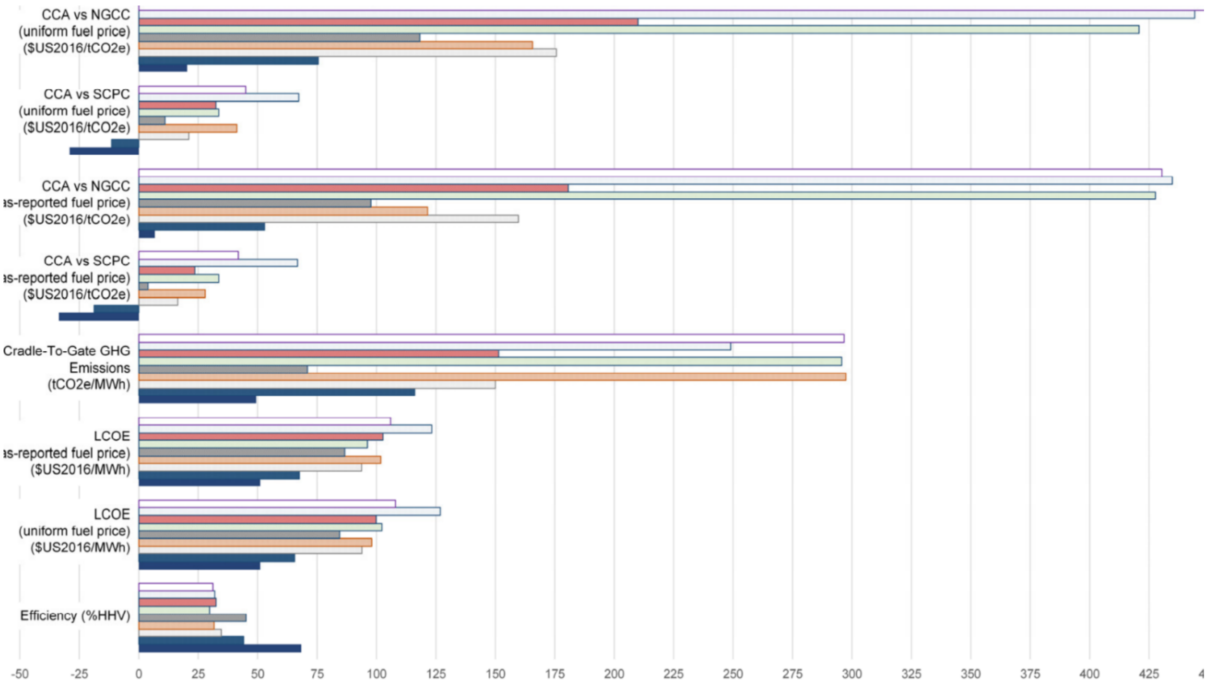


Figure 28 - Summarising Comparatie Analysis of Multiple Carbon Capture Technologies (Adams II, 2017). [SCPC: (Supercritical pulverized coal); IGCC: (Integrated gasification combined cycle); COXY: (Coal-based oxyfuel combustion); CMEM: (Coal-based membrane separations); IGFC: (Integrated gasification combined cycle); CaLC : (Calcium-looping carbon capture); CCL: (Coal-based chemical looping combustion); NGCC: (Natural gas combined cycle); NGFC: (Natural gas (solid oxide) fuel cell)].

5.3.5 Multi-Sectoral Energy System Optimisation Modelling

Currently carried out as a PhD project by Bohra (2020), the Qatar Energy System Model and Analysis Tool (QESMAT) is a long-term system to create a centralised model combining residential, commercial, industrial, transportation and agriculture sectors. This model balances the need for technology investment and export strategy at the nexus of power generation, water desalination, key industries, electric vehicles, and solar energy. The study, however, does not consider CCS to currently be economically feasible for investment – the justification is that, until forced reduction of oil and gas production is enforced and the price of carbon increases to $50/tonne, the change is unlikely to occur. The study lists 45 key technologies in Qatar in various groupings, to project the following scenario towards carbon neutrality:

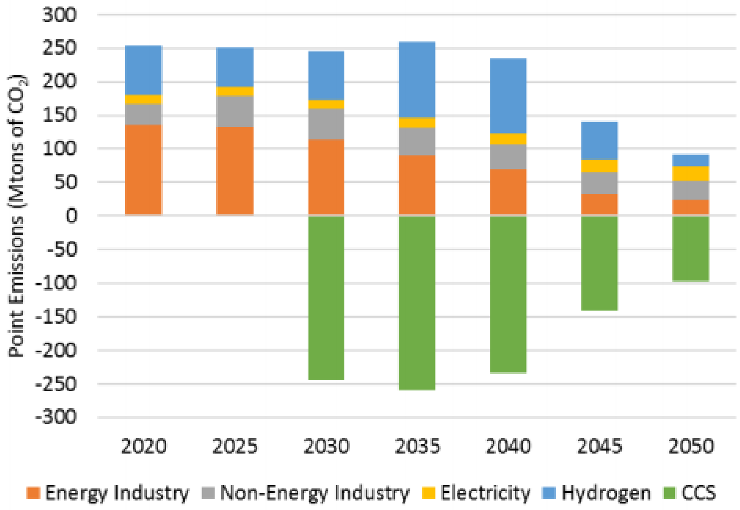


Figure 29 - Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019 (IEA 2021) - Plot of Emissions by Sectors from 2020-2050, including CCS Potential Towards Net Carbon Neutrality (Bohra, 2020).

While this project does not provide in-depth insight about specific CCSU technologies in Qatar, it does provide context for CCSU and its need in the larger scale of energy usage. Seeing CCSU beyond its microcosm and within the context of national strategies is valuable as a systems-within-systems framework. In terms of holistic policy planning, this mechanism is needed to combine carbon-cost analysis for all key industries within the same system, while allowing granular development in each field to evolve and produce more refined estimations.

5.3.2 Summary of Cost Analysis Methods

In this summary section, some of the key methodologies for cost estimation discussed throughout Chapter 5 are presented. Some additional studies are also included which were not explored in depth previously, yet may provide additional information on the potential of cost-avoidance modelling methods. The decision to not delve deeper into these additional studies comes from the necessary limitation caused by lack of access to the entire papers, therefore only being able to source information from abstracts or limited data available surrounding the work.

Table 24 - Comparison of Various Techno-Economic Assessment Methodologies for Carbon Capture Related Technologies and Frameworks.

Authors	Methodology	Concept	Pros & Cons
Lameh, et al., 2020	MAC Curves/ Process Integration principle	Comparative Cost of Emissions Mitigation Using Process Integration	- Considers existing sectors - Specific to Qatar - Includes Numerous Industries - Considers Replacement with Renewables - Sets Minimum Cost Targets
Heimel & Lowe, 2009	Systematic Evaluation Approach	Comparing Cost of CO_2 Avoided Via Retrofitting	- Limited to Capture Stage - Highlights Site Specificity - Generic & Not Qatar-Specific - Dated Study - Limited to Many Assumptions
Zhang, et al., 2017	Mixed Integer Linear Programming (MILP) and Game Theory	Balancing potential of Carbon Capture Technology (CCT) with carbon credit trading.	
Adams II, et al. (2017)	Review & Meta-Study of Studies Since 2007 – Streamlining Methods into	Comparing Cradle-Plant-Exist Cost of GHGs	- Adjusted for scale, currencies, location, year, capture rates, pressure, plant gate. - Accounts for NO_x & other pollutants via GPH - Broad level of assumptions and

	Comparable Data		methodologies - Only considers Capture Stage - Generalised with caution but not Qatar-specific - Combines literature up to 2017
Jahangiri, et al. (2020)	Fuzzy MCDM technique using HOMER software and FTOPSIS	Determining best location for solar & wind plants for electricity & hydrogen	- Nexus of environmental-cost analysis - Site-specific analysis - Valuable methodology for finding alternatives to fossil fuel (carbon avoidance from source)
Bohra (2020	Novel Multi-Sectoral Centralised Model	Model energy consumption	- Multi-Sectoral - Designed for centralised policy-making
Roussanaly (2019)	CO_2 Avoidance Cost Estimation	Comparative Study of Cost Estimation Methods	- Pragmatic method for various industries - Focus on assumptions & advantages
Al-Mohannady, et al. (2020)	Mixed Integer Linear Programming via decomposition	Two step optimisation of carbon reduction and renewable uptake	- Carbon integration in industrial cities - Multi-step optimised methodology - Optimised for low cost CO_2 transportation, treatment, and compression.
Jarvis & Samsatli (2019)	Comprehensive Review & Comparative Analysis	Integrated CO_2 value chain creation, including cost & energy metrics	- KPIs based on APEX, OPEX, electricity consumption, TRL, product price, net CO_2 consumption - Thorough multi-product/process chain - UK-based and not related to Qatar - Typology of study necessary for Qatar
Roh, et al. (2018)	Computer-Aided Sustainability Analysis of CCU	Simultaneous calculation of techno-economic & CO_2 reduction metrics	- Utilising a bespoke software ArKa-TAC$_3$ - CO_2 Analysis is LCA - Adopts a super structure model framework - Not Qatar-specific
van der Spek, et al. (2017)	LCOE, OPEX/CAPEX Estimation,	Modelling cost uncertainty & variability in CC technology analyses	- LCOE is most sensitive economic method - Pedigree / diagnostic visualisation can present added value - Even same systems have vastly different cost potentials

5.4 Roadmap to implementing CCUS in Qatar

This project has conducted a thorough investigation into the possible routes for CCUS in Qatar, summarised in figure 30. However, Qatar is currently at a crossroads in terms of CCUS deployment with 3 possible pathways ahead (Table 25).

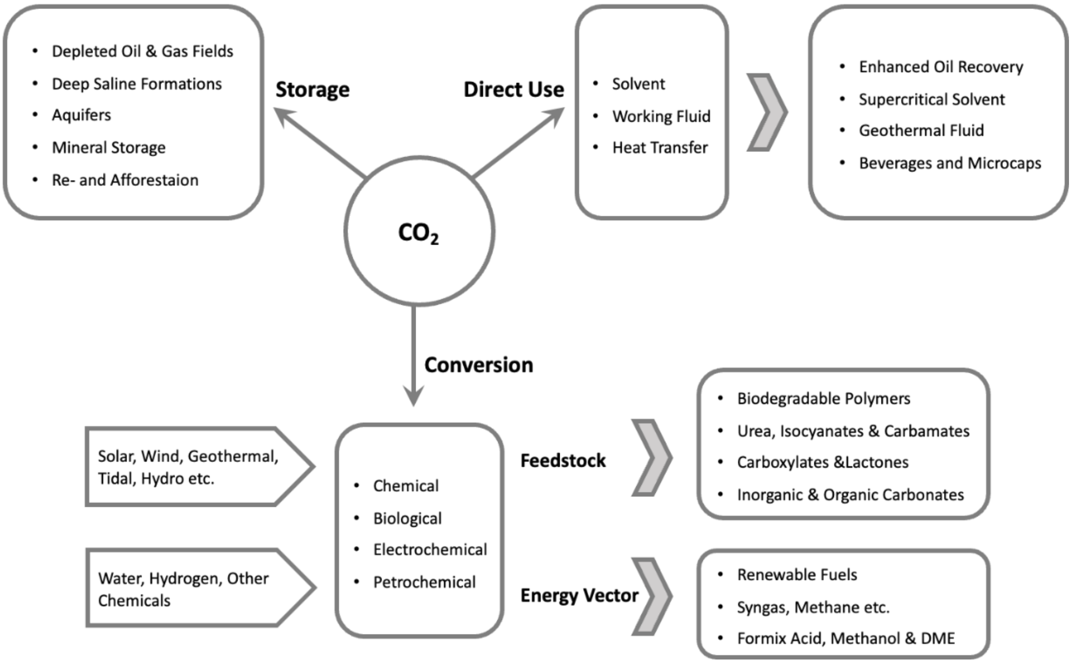


Figure 30 - Possible pathways for CCU & CCS in Qatar. Adapted from Adapted from: Jarvis & Samsatli (2019)

Table 25 – Outline of potential future scenarios for Qatar with regards to CCUS deployment (Adapted from: Afry and GaffneyCline, 2022)

Scenario	Description
Follower	- Qatar prepares for decarbonisation but does not lead it, waiting for dominant technologies to emerge. - The expertise of the region allows it to catch up but at the cost of market share.
Business as Usual	- Qatar maintains the status quo and favours long term oil and gas production over decarbonisation efforts. - Pilot projects will be carried out by both private and state companies. - There is no political will to accelerate the deployment of CCUS. - GCC states follow their own decarbonisation pathway with competition and little collaboration/cooperation.

Global Leader	- Qatar takes the lead on decarbonisation domestically and dominates the market for low carbon products. - Qatar exports its knowledge and expertise to other countries and becomes a global hub for CCUS.

To date, Qatar's attempts to develop CCS technology have been fragmented and domestic initiatives have largely been project-oriented (Meltzer et al., 2014). For Qatar to become recognised as a leader in CCS technology by the GCC region and globally, a concerted effort should be made to develop expertise on CCS. This section outlines a potential roadmap for successful widespread deployment of CCUS adoption in the Qatar (figure 31).

Figure 31 - Framework for widespread deployment of CCUS in Qatar

5.4.1 Phase 1: Building Expertise

In phase 1, Important data for supporting policy decisions is obtained.

Here, Qatar should seek to carry out crucial research and planning activities that will ensure CCUS is delivered cost-effectively in phases 2 and 3. In particular, Qatar should work to advance particular CCS technologies, which exploit Qatar's extensive experience with EOR and gas extraction, with the goal of exporting these technologies to other countries (Sawaly et al., 2022).

To support domestic CCUS; research, technological development, and engineering design work will be conducted, and the finance required for scale up is supplied. This work will include a detailed appraisal of potential CO_2 storage sites across the country, where information on individual stores and their associated volumes is collated. Qatar University’s Gas Processing Centre (GPC) has taken important steps to begin mapping this information, however significant gaps still remain (Alsheyab, 2017).

A review of national policies ought to be conducted concurrently to make sure that obstacles to the widespread use of CCUS are addressed. To guarantee that standards and policies can support cooperation later, the initial measures for cross-border coordination and collaboration should be taken. Indeed, acquiring expertise and learning lessons from the experiences of countries such as the UK, Sweden, or other GCC states should be a top priority. To achieve this Qatar should seek to establish bilateral and regional partnerships to share knowledge, and join international forums such as the Carbon Sequestration Leadership Forum and Global CCS Institute. Such steps would help ensure that global policies on CCUS are advanced in ways that support Qatar’s CCUS initiatives, and membership of the Global CCS Institute could help provide support for and facilitate the deployment of commercial-scale CCS projects (Rasool, 2021, Townsend and Gillespie, 2020; Babonneau et al., 2022)

5.4.2 Phase 2: Increasing government support and incentives for CCUS

5.4.2.1 Policy Framework

Based upon the information and evidence gathered during phase 1, the Qatari government should seek to develop a legal and regulatory framework for the advancement of CCS, and further develop the existing regulatory framework for the capture and storage of CO_2 for EOR, where there exists significant gaps regarding long-term storage and questions of responsibility should leakage occur (Martin-Roberts et al., 2021, Zhang, 2021) . Such issues could be addressed during phase 1 through comprehensive environmental assessments of CCS storage sites; determining appropriate technologies for CO_2 containment; conducting risk assessments for industrial applications; and introducing industry best practices and guidelines for storage and monitoring (Martin-Roberts et al., 2021; Zhu et al., 2021).

5.4.2.2 Financing

Qatar has already produced a few CCUS projects, but deploying CCUS at a large scale will require a commercial driver. Around the world, numerous business models for CCUS have been created that can offer lessons for Qatar, which can be categorised as either subsidy, revenue support, grants, loans, direct investment, or combinations of these (Kapetaki and Scowcroft, 2017; Esposito et al., 2011; Kapetaki et al., 2016). Getting the ownership structure, revenue streams and incentive structure right in Phase 2 is essential for helping CCS to develop successfully, as unsuitable business models can increase costs and result in less or no CCS developments (Yao et al., 2018). Since Qatar lacks a strong domestic driver for CCUS, a strong business model and incentive scheme will also need to be deployed.

5.4.2.2.1 Establishing a carbon price

To ensure that CCUS is both economically and commercially viable, it is recommended that Qatar actively supports both regional and global efforts to price carbon, and works closely with other nations, which have prior experience in pricing carbon (Auwa, 2022). This step is required to allow the continued consumption of fossil fuels in a carbon restricted world (Eljack and Kazi., 2021; Babonneau et al., 2022).

As an illustration, the EU and China worked together under a €25 million finance arrangement to build up pilot carbon trading systems in a number of Chinese towns. A nationwide scheme was designed for deployment in 2020 with a starting price for CO_2 $10 per ton and rising to $30 per ton in 2030 (Weng and Xu., 2018; Fang et al., 2018). Similar carbon pricing will likely present some challenges for Qatar in the first instance due to the resultant increased oil prices. However, as Qatar is one of the biggest exporters of natural gas, pricing carbon should make clear the climate change benefits of gas and hasten a transition away from coal, providing economic benefits for the country. It has been demonstrated that the higher the carbon price, the greater the role of ETS in incentivising the development of clean energy technologies (Liu and Zhang, 2021). Conversely, exorbitant carbon prices and/or excessive government control can have the opposite effect (Fang et al., 2018).

5.4.2.2.2 Business Models

Successful CCUS business models decouple value chain risk with separate models for capture, transport, storage and utilization (Muslemani et al., 2020). It is recommended that in Phase 2 the Independent Power Producers (IPP) single buyer model (see model 2: figure 32) be used as trusted model for capture where applicable (e.g. electricity production, hydrogen production and potentially direct air capture). IPPs invest in generation technologies and recover their cost from the sales, such models have been successfully implemented in the GCC for electricity and therefor provide a good framework to use for CCUS with a single buyer that fits with the natural monopolies many of the NOC’s enjoy (Bigutane, 2022; Eberhard, 2016). IPPs can be great help to country's energy sector, particularly when the public sector do not have the required financial capacity for investment (Gardiner and Montpelier, 2000).

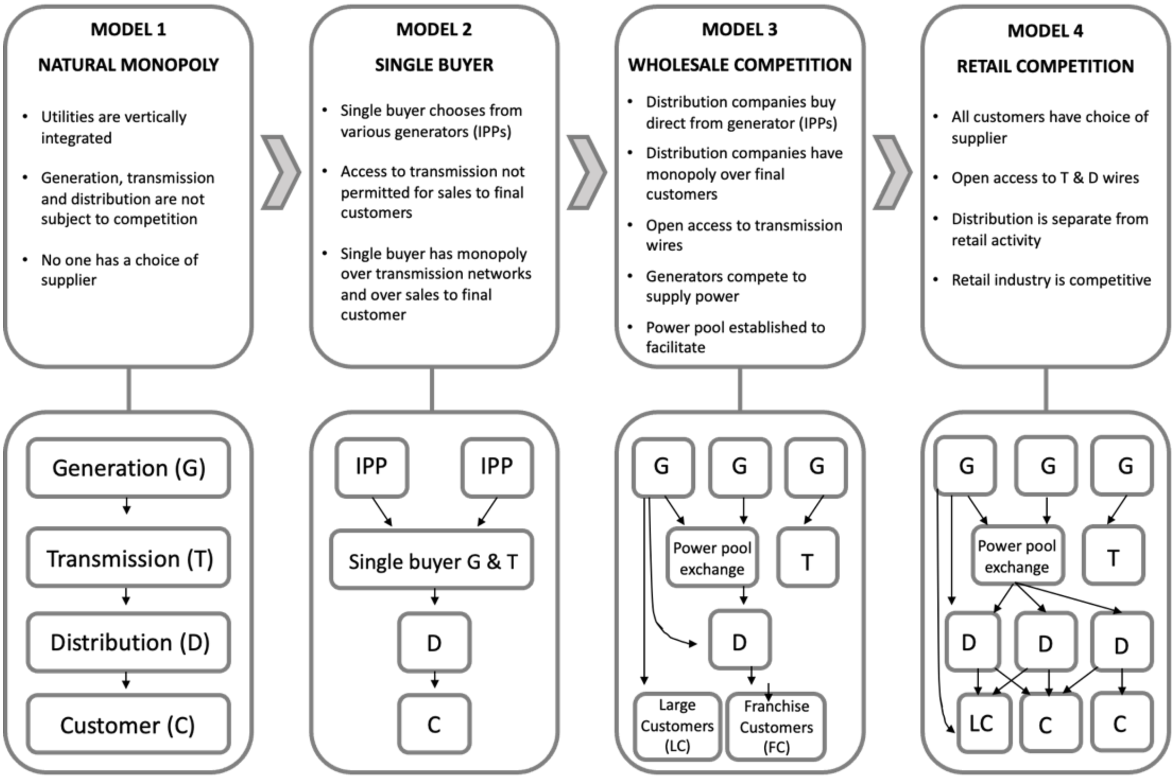


Figure 32 - Summary of the four different models used to describe the integration of Independent Power Producers (IPPs) into the grid. IPPs or non-utility generator (NUG) are private entities, which own and or operate facilities to generate electricity and then sell it to a utility, central government buyer and end users. Adapted from: Eberhard, 2016

For most other industries where the single buyer model is not appropriate, a business model consisting of direct payments linked to volume captured and risk sharing to decouple cross chain risk (delays or failures in transport or storage) should be the foundation of any model that is adopted.

Finally, to ensure that Qatar successfully progresses to Phase 3 (Mass deployment), the government should take the lead in early engagement and negotiations across the GCC in order to develop a trading framework that handles imports and cross border transport. Carbon imports from outside the GCC should be anticipated and charged an import fee for access to the T&S network.

5.4.3 Phase 3: Mass deployment

The goal of Phase three is to develop a sustained CCUS industry supply chain that can achieve adequate installation rates. Throughout this period, an ongoing evaluation of the funding mechanism will guarantee that it continues to provide value for money. As phase 3 comes to a close, domestic CCUS is established as a mature industry. By this point, it is anticipated that the regulatory, fiscal, and policy frameworks are stable, and that only small adjustments would be necessary to reflect shifting goals or strategies. A support system for "carbon scrubbing" will need to be established as DACCS is eventually implemented, which should eventually expand to include the remaining sectors that cannot be decarbonized.

This proposed roadmap is intended only as a guide that should be adaptable to shifting circumstances and global progress to net zero. Continued monitoring and sense checking will be essential to ensure that these plans have the flexibility and opportunity to be modified as conditions change. This is especially true for project execution, where global knowledge exchange and lessons learned from past projects will likely contract engineering and execution timescales. Being a leader and taking action sooner may, in theory, result in lower annual expenditures that are also "assured" by present oil and gas earnings.

6. Conclusion

6.1 Summary of Findings

This research aimed to answer a pragmatic set of questions surrounding the potential of CCSU technologies in Qatar, namely those surrounding the current trends in the country's CO_2 profile, especially in key national industries. In order to achieve this, a comprehensive review of the latest developments in CCSU technologies was carried out, outlining a wide range of technology groupings at various TRL levels. Furthermore, an in-depth national analysis was carried out to pinpoint existing CCSU projects and inquire in more depth about the potential of CCSU technologies in Qatar. To do so, recent secondary sources on the topic were blended with a set of survey responses acquired from relevant industry stakeholders in Qatar. For the main part, this study focused on the industrial sectors, namely energy and manufacturing of key products, with some emphasis being placed on the natural habitat and the Energy-Waste-Food nexus. Industry and non-energy use were found to consume the most energy, with transport, residential, commercial, and others having a lower, more stable footprint. The main strategy was to discover key systematic reviews in various fields related to CCSU and combine them with the author's own exhaustive review where research gaps exist. Accordingly, in-depth data was discovered about all of Qatar's main powerplants (until 2017), the key institutions and bodies engaged in CCSU research in the country (QCCSRC, Pearl GTL Plant, Ras Laffan, Dukhan EOR, etc.). Findings also indicate that processes which are harder to be replaced with renewables in the future may present a greater long-term value for CCSU retrofitting or innovation, i.e. LNG and GTL which will remain Qatar's main exports for the medium term and that also provide easier-to-capture and pure carbon.

Sensitivity to local environmental and socioeconomic conditions and the TLR are two main factors that determine the relationship between cost and carbon reduction potential of different CCSU mechanisms. For example, technologies such as DAC are far too expensive for their current CO_2 reduction potential, while mature technologies such as post-combustion adsorption has the most readiness and retrofitting potential for existing plants without the need for expensive closures. Technologies such as oxy-fuel combustion present a high potential for new powerplants but are not cost-effective for retrofit. For powerplants with high carbon emissions (arguably linked with the amount of output), the cost of carbon capture can be offset by the savings generated from reduced spending on carbon credits. Meanwhile research on the disposal of membrane and solvent-based capture is also not developed enough - the research is focused too heavily on carbon dioxide and not enough on other pollutants.

Regarding storage and utility, the most prominent field for study remains as Qatar's Aruma aquifer with its vast storage capacity; nevertheless, there is still a need for significant safety studies before making the project practical. Research from this storage option directly led towards combination with Carbon Utility solutions, including utilising the aquifer's water for microalgae production and leftover brine for Nesquehonite production. These systems have the potential to be combined with biomass production, carbon capture and natural habitat remediation through energy efficient native plants that have evolved to withstand such conditions. Projects such as SFP and research at facilities such as QUCCCM are crucial for better integration of the habitat into CCSU dialogue, as current techno-economic assessments are missing from this field. Water scarcity is a major problem and the separate development of desalination and energy industries is a grave mistake in the grand strategic direction, especially considering the amount of water needed in powerplants and energy required in desalination plants. Renewable energies - such as wind energy near airports, solar PV energy and biomass - also have a place in this nexus of industries (reportedly up to 20% of the national grid in the medium term) as a means of cutting CO_2 emissions from the source of electricity production entirely. In fact, the potential of biomass has been significantly under-reported in carbon literature, considering the combined difficulties of food and water scarcity as well as lack of widespread organic waste recycling in Qatar.

Natural gas plants are also interlinked with the production of ammonia and other low-cost utility products. EOR can reduce the need for the financially risky task of exploring new oil and gas fields, while utilising existing infrastructures to the maximum. Nevertheless, Qatar's gas production is taking over as the leading fossil fuel industry for the future, as reflected in the countries' carbon metrics; this also means that carbon capture in the oil sector will not be as efficient as gas. Overall, there is a need to combine the comprehensive study of technologies in all stages of the CCSU process, to generate comprehensive CO_2 value chains with correctly-assumed cost estimations.

6.1.2 Policy Recommendation

In terms of policy, a greater focus on environmental taxation and the reporting of company and industrial duties in terms of compulsory and publicly-disclosed reports is required. This offers a great way to ensure: the availability of reliable information for data; improvement of financial backing through risk reduction; reduction of the "learning cost factor"; and increase market transparency. These are a few of the factors that create barriers in knowledge-sharing industrywide progress, impede on the ability to create thorough cost estimations, and enable practical compromises to be made in the carbon-cost decision-making axis. In countries such as Qatar where the main industries are State Owned Enterprises (SOEs), information-sharing poses both challenges and opportunities in the data that is chosen to be shared, in terms of sensitivity, ease of flow of information between industry, governance and academia, and creation of commercial attractiveness for private businesses. Other factors along centralised support include streamlining and improvement of administrative processes. These must be encapsulated within national programming, which includes a robust legal and regulatory framework. Overall, there is need for the development of a computer-aided tool for the lifecycle cost & GHG emissions estimation of all of Qatar's key multi-sectoral industries along their full value chain at the Energy-Waste-Food-Manufacturing-Water nexus. Within a complete policy framework as such, research topics and industrial data can be harmonised to fit within a national plan towards deployment. The economic feasibility study and analysis of various cost analysis methods have identified numerous methods and key research in holistic cost and CO_2 reduction planning, making this research a state-of-the-art report on the route forward in Qatar. Modelling for uncertainty, technology analysis, CO_2 metrics, Levelised Cost of Energy calculation, LCA, development of OPEX/CAPEX KPIs, measurement of TRL, cost of infrastructure development and potential stops in production, carbon optimisation for transport and in-depth reporting of assumptions and advantages are some factors that are necessary within this framework.

6.2 Limitations

One of the study's main weaknesses inevitably turned out to be the survey and acquisition of first-hand information about industries. Despite contacting over 100 potential interview subjects, only 6 responses were received. This was predominantly due to two factors: the occurrence of the COVID-19 pandemic during the project, which disrupted the ability to meet in person and the availability of subjects through their available means of contact; and a sense of reluctance was observed about sharing industrial knowledge with a researcher that is not directly affiliated with any immediately recognisable business interests in Qatar. There is a degree of secrecy to the industry in Qatar, which permeates to availability for research interviews. Nevertheless, a similar pattern of unresponsiveness was noticed in field-specific interviewees in other countries as well. This obstacle necessitated the continuation of the study through additional desktop research means, namely the in-depth analysis of various cost estimation mechanisms in Chapter 5.

6.3 Recommendations

This review has uncovered specific research gaps that are necessary to fill for the field to progress. First, following the findings of Pieri, et al. (2018), who considered the holistic CCSU value chains of key studies in the field, it has become evident that most research has not adequately focused on social factors and environmental factors beyond CO_2. CO_2 is not the only pollutant that is produced in all the industrial processes discussed in this study. Thus, there is the necessity to study further into other potential environmental concerns from the production of carbon capture infrastructure, i.e. the embedded carbon in construction materials required for retrofitting or transporting CO_2, or the ongoing material required for capture including manufactured membranes, industrial chemical solvents and the safe disposal of these materials after use. Furthermore, social impact assessment studies are required for holistic management of CCSU expectations; these include the number of people required to work, train, and ensure extra roles are carried out at the additional CO_2 value chain.

Second, plant and nature-based methods of CCSU may not yet have the capacity to offset direct industrial output of CO_2. Yet, they need to be considered in the overall carbon policies as a means of reducing reliance on foreign input of goods and materials, which must surely be considered in a Lifecycle Carbon Avoidance Assessment of nationally-consumed and produced goods in Qatar.

Third, respondents were almost entirely unaware of FC technology, except a brief nod to its potential in the country from one interviewee. The field of FCs remains as a novel and modern domain of carbon capture that has shown to have potential for high efficiency, yet almost no knowledge of which was reported in surveys. Performing a Google Scholar search including "solid oxide fuel cell" and "carbon capture" returns no results before the year 2000, while half of the research on the combined topic has been carried out since 2017 (Google Scholar, 2021b). On top of this, only 110 results are found including the additional keyword of Qatar (Google

Scholar, 2021c), with experience and a partial scan showing a limitation of meaningful and in-depth inclusion of these keywords within one study.

Further Work

The work conducted in this paper so far suggests that there is more information to be gathered from the example of Qatar itself, most specifically in the form of survey responses from Qatari officials themselves, which were shown to be severely lacking. Whilst this was able to highlight some of the socio-economic issues of the area in looking to introduce these new technologies, it dilutes the strength of the arguments made for implementing the recommendations as there is a lack of viewpoint from Qataris themselves on which to build these recommendations against.

Whilst this paper is aimed to focus on the example of Qatar, the limited scope also lends to reducing the strength of the arguments and recommendations put forward as there is no standard to hold these against. With this in mind, it would be beneficial in further work to provide a comparison of Qatar against a country further along the road of implementing CCUS technology, applying any of the lessons learned in these regions to this specific area also, such as the USA. There is also the opportunity to compare against a nation that also relies on the oil and gas industry to support its economy, or against one with contrasting climatic or socio-economic conditions – the Scandinavian countries would be strong examples of useful comparisons in these instances.

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Appendices

Appendix 1: Respondent 1

***Q.0. Please specify your sector (*Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration?

Oil	Gas	Cement	Waste	Steel	Direct Air Capture	Natural Landscaping	Other
X	X						

Q.1.b. Elaborate if possible: Utilization options, energy efficiency options, low carbon processing options and low carbon energy supply should be considered alongside sequestration.

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology? This is still an open research question. In my opinion, the existing methods all fall short in adequately capturing macro-economic impacts and local/regional/global environmental impacts.

Q.3 Which Combustion-Based Typology of CO_2 capture do you consider to be most suitable for retrofitting onto the GTL power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure /
	X		

Q.3.b. Elaborate if possible: Not sure what “GTL power plants” refers to exactly. Some GTL plants already use pure oxygen for the process.

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure / Other
			X

Q.4.b. Elaborate if possible: LNG should have electric drives and be driven by an electricity mix containing more and more renewables as is now happening in Norway. No need for combusting all the fuel in gas turbines resulting in major emissions.

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? A lack of systems studies to understand the options. Even though the methods (developed in Qatar) are there to analyse the problem across CCS, CCU and renewable energy. Without such a study that reveals the promising options for a given country/region, the ad hoc selection of solutions without in depth analysis is bound to be very expensive.

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? Every little helps as long as reductions are achieved at competitive costs and environmental impacts. Reducing CO_2 footprints requires a portfolio solution ant this should be studied as one of many candidates.

Q.7 Which carbon storage and utilities methods present the best option for Qatar?

Depleted Gas & Oil Reservoirs	Saline Aquifer	Geological Storage	Conversion to Carbon Nanofiber	Enhanced Oil/Gas Recovery

Q.7.b. Elaborate if possible: This is for geologists to answer. I suspect depleted reservoirs and EOR. However, when the world buys less oil there will probably be less need for EOR.

Q.8 Carbon Capture Mechanisms: Innovations across the planet aim to remove carbon from industrial processes. Our research has identified many emerging, research-level and operational examples of such mechanisms. From 1 being non-suitable, and 5 being most suitable, how suitable do you find each of these for the context of a hot arid country such as Qatar?

Technology	Suitability (1 to 5)	Additional Feedback
Direct Air Capture	1	The most challenging capture option that makes little sense given the emissions profile of industrial processes.
Pyrolysis from Agricultural Waste		
Micro-Algal Bio Fixation		
Anaerobic / Waste-Based Fuel Cells		
Post-Combustion Absorption		
Post-Combustion Adsorption (Sorbents, Porous Organic Frameworks, etc.)		
Post-Combustion Membrane Separation (Inorganic, Hybrid, Polymeric)		
Post-Combustion Cryogenic Separation	1	Unlikely to become competitive
Solvent-based Post & Pre-Combustion (Amine & Alkaline)		
Pre-Combustion Absorption		
Pre-Combustion Adsorption		
Chemical Looping Oxygen Fuel Combustion		
Other (Please Specify)		The right technology choice is dictated by the overall system across sources, sinks (CCS, CCU) and chosen renewable / clean energy options. All remaining above technologies can be competitive in some

		situations I expect.

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
				X

Q.9.b. Elaborate if possible: There needs to be a systems study of the options first to develop a sound strategy that can be translated into policy. Any premature implementations will likely take away future opportunities based on our studies so far. It is not good to implement solutions in the absence of an overall policy and strategy,.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels?

It is easily done for the first 20% or so of electricity before grid stability becomes a costly issue. Solar energy does not alone enable sufficient reductions of emissions (not all emissions are from energy use and a fully renewable energy mix is very expensive, which will likely make industry uncompetitive). For the oil and gas industry, CCU and CCS need to be explored. Qatar cannot stop producing gas either as the world needs that transition fuel.

Appendix 2: Respondent 2

Q.0. Please specify your sector (**Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration?

Oil	Gas	Cement	Waste	Steel	Direct Air Capture	Natural Landscaping	Other (
	X						

Q.1.b. Elaborate if possible: Given that the CO_2 emissions are high, capture costs are low and already an integral part of the process, gas processing (GTL and NG processing) can be considered an initial target in for CCS in Qatar. Power Plant can to some extent be replaced by renewables, hence reducing the scope for CCS.

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology? (Assuming you mean CCS and not just sequestration)

Measuring economic benefits => jobs creation / retention, industry retention and attraction. Techno-economic analysis of CO_2 emission reduction versus CO_2 emission taxation.

Measuring environmental benefits => assessment of CO_2 emission reduction and other emissions after application of technology. i.e. Life cycle assessment or carbon accounting & emissions measurement of actual CCS processes.

Q.3 Which Combustion-Based Typology of CO_2 capture do you consider to be most suitable for retrofitting onto the GTL power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
			X

Q.3.b. Elaborate if possible: To start with, GTL plants are not power plants, they produce liquid fuels (unless you mean the part of the plant that is generating utilities such as a CHP plant).

It is difficult to answer this question because the literature so far on the techno-economics of applying CO_2 capture to GTL plants is not abundant. Some type of pre-combustion capture (or rather, CO_2 capture that is applied to generated syngases) may already be an inherent part of the process so this may be an immediate option. However, the emission point sources on a GTL plant are multiple, so the success metrics of the application of a single capture technology (or multiple) may depend on the ambition, i.e. the CO_2 capture rate (how much of the plant's emissions do you wish to capture?). There may also be case specific considerations. From a skills point of view, operators of GTL plants may have some experience of solvent based capture systems, hence post-combustion capture may be applicable here. Oxyfuel combustion capture may have limits to the applicability to GTL plants, that is, it may only be applicable to certain parts of the process such as heaters and burners.

The only way to answer the question is to perform some extensive techno-economic assessments of various process configurations with CO_2 capture applied.

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
			X

Q.4.b. Elaborate if possible: Again, LNG processes are not power plants per se, unless you mean a natural gas fired power plant. In natural gas processing there is no combustion, hence none of the above options are really applicable. Typically amines are used to remove CO_2 during processing.

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? *There is a need to create the right business model framework between different entities in the CCS chain and government.*

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? I would say not due to water resource shortage.

Q.7 Which carbon storage and utilities methods present the best option for Qatar?

Depleted Gas & Oil Reservoirs	Saline Aquifer	Geological Storage	Conversion to Carbon Nanofiber	Enhanced Oil/Gas Recovery
X				

Q.7.b. Elaborate if possible: Enhanced Oil Recovery can be a good and economic option in the short term, but for a longer term switch away from fossil fuel use, depleted gas & oil reservoirs present opportunities for deep CO_2 reductions with the options of infrastructure reuse.

Q.8 Carbon Capture Mechanisms:

Technology	Suitability (1 to 5)	Additional Feedback
Direct Air Capture	1	The technology readiness level is low and cannot be relied upon.
Pyrolysis from Agricultural Waste	4	
Micro-Algal Bio Fixation	3	
Anaerobic / Waste-Based Fuel Cells	3	
Post-Combustion Absorption	5	
Post-Combustion Adsorption (Sorbents, Porous Organic Frameworks, etc.)	4	

Post-Combustion Membrane Separation (Inorganic, Hybrid, Polymeric)	3	
Post-Combustion Cryogenic Separation	3	
Solvent-based Post & Pre-Combustion (Amine & Alkaline)	5	
Pre-Combustion Absorption	5	
Pre-Combustion Adsorption	4	
Chemical Looping Oxygen Fuel Combustion	5	
Other (Please Specify)	5	Allam Power Cycle

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
				X

Q.9.b. Elaborate if possible: Technology is mature and can be deployed. However, suitable national and international policies must be adopted in order support development due to the increased costs that operators will incur.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels?

I think the feasibility is quite high.

Appendix 3: Respondent 3

***Q.0. Please specify your sector (*Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration? Table unanswered

Q.1.b. Elaborate if possible: I think one of the quickest wins Qatar can achieve is in transforming the power sector (including desalination activities). The oil and gas sector especially LNG production has plenty of already separated CO_2 (by-product from the gas sweeting process) that can be used in utilization either in enhanced oil/gas recovery or chemical production (with minor upgrades).

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology? Typical economic analysis of carbon capture e.g. NPV, ROI, etc. will be putting the technology at a disadvantage. Environmental impact in terms of CO2 reduction per year is quick measure. Carbon reduction efficiency makes the technology the preferred choice in long term mitigation. We noticed this from our previous work in (Al-Mohannad and Linke 2016, Hassiba et al. 2017). Some methods exist to evaluate sustainability objectives with economic measures e.g El Halwagi et al. 2017

Q.3 Which Combustion-Based Typology of CO_2 capture do you consider to be most suitable for retrofitting onto the GTL power plants? Table unanswered

Q.3.b. Elaborate if possible: *There's room for all depending on the design of the GTL process e.g. ATR, POX or SMR.*

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
Already exists as part of some processes	Easier for most facilities currently		

Q.4.b. Elaborate if possible: LNG post combustion would be best.

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? Industry buy ins

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? I believe it plays a role – but to a certain degree. Mangrove /algae would be the most suitable. Other activities will require soil enhancement and water allocation.

Q.7 Which carbon storage and utilities methods present the best option for Qatar? Table unanswered

Q.7.b. Elaborate if possible: All of the above! I think we should start with the low hanging fruits of re-using already separated carbon dioxide from industry (LNG, GTL) and make profit through EOR/EGR in addition to other CCSU tech then move to CCS. If the short term quick capture, QP holds both the carbon dioxide and the storage site and can start implanting enhanced recovery and CCS.

Q.8 Carbon Capture Mechanisms:

Technology	Suitability (1 to 5)	Additional Feedback
Direct Air Capture	1	It Definity has space but as of now in Qatar we have already separated CO_2 that can be used to reduce much of the local emissions before going into direct air capture solutions
Pyrolysis from Agricultural Waste	1	Creates CO_2 – so needs capture
Micro-Algal Bio Fixation	3	
Anaerobic / Waste-Based Fuel Cells	N/A	
Post-Combustion Absorption	4	
Post-Combustion Adsorption	4	
Post-Combustion Membrane Separation	4	
Post-Combustion Cryogenic Separation	4	
Solvent-based Post & Pre-Combustion (Amine & Alkaline)	4	
Pre-Combustion Absorption	4	
Pre-Combustion Adsorption	4	
Chemical Looping Oxygen Fuel Combustion	4	
Other (Please Specify)		

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
2			3	1

Q.9.b. Elaborate if possible: Policy without it no action can be taken for sequestration. Utilization might be more attractive but also you need policy from the main stakeholder to allow integration.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels? The R.E. capacity for sure can be increased. The current grid is 100% gas based and can take up to roughly 20% of solar. If merged with the correct policy this can be increased. R.E. however will not reduce the process-related emissions (i.e., from chemical reactions) or CO_2 associated with natural gas.

Appendix 4: Respondent 4

***Q.0. Please specify your sector (*Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration?

Oil	Gas	Cement	Waste	Steel	Direct Air Capture	Natural Landscaping	Other
Y	Y						

Q.1.b. Elaborate if possible: I think fuel combustion has the most potential for Carbon Sequestration as it is produced the most compared to other sources as well as having a relatively good production to capturing ratio of the CO_2.

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology? To access the different types of industries that will be affected and write an analysis on how each one will be impacted.

Q.3 Which Combustion-Based Typology of CO_2 capture do you consider to be most suitable for retrofitting onto the GTL power plants? Unsure

Q.3.b. Elaborate if possible: n/a

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants? Unsure

Q.4.b. Elaborate if possible: n/a

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? I think convincing the ones in charge will be an obstacle because people tend to avoid major changes in the way of their life. Espicially to make something a national policy that will affect many people can be a hard decision to take, so presenting the idea in the correct manner and showing how beneficial it is for the long term plan will be crucial for its success.

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? I think we should not always count on nature to take care of things as we are changing the environment we live in and in a negative way sometimes. Due to this, some actions need to be done by us humans to mitigate the problems that lie ahead for the future.

Q.7 Which carbon storage and utilities methods present the best option for Qatar?

Depleted Gas & Oil Reservoirs	Saline Aquifer	Geological Storage	Conversion to Carbon Nanofiber	Enhanced Oil/Gas Recovery
				Y

Q.7.b. Elaborate if possible: I think enhanced oil/gas recovery would be one of the best methods for carbon usage. This is due to the huge amounts of oil and gas that are available in Qatar and using Carbon to recover it as tertiary drive can be one of the sustainable methods of extraction.

Q.8 Carbon Capture Mechanisms: n/a/

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
X	x			x

Q.9.b. Elaborate if possible: I think policy would be one of the major barriers as paperwork and confirmations have to be taken from multiple people. Also Utilizing it in the most efficient and beneficial way can be quite difficult as there are several options to choose from.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels? I think at the moment it is definitely hard to switch to renewable energy completely as fossil fuels is much more easier and cheaper to use. This comes into many factors that are in play such as politics and personal benefit. I think Qatar can eventually switch to renewable energy but that might take a good amount of time as it is dependant on fossil fuels and is used as a major source of income.

Appendix 5: Respondent 5

Q.0. Please specify your sector (**Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration?

Oil	Gas	Cement	Waste	Steel	Direct Air Capture	Natural Landscaping	Other (Please Specify)
3	2	(1)	4	(1)	6		Fuel combustion (5)

Q.1.b. Elaborate if possible: DAC is extremely expensive and inefficient, even if we think about it as the only really carbon neutral.

Fuel (e.g. gas) combustion and waste (I guess this means incineration) have an actual problem not only technically from its implementation, which drive a high energy penalty, but of competition with actual clean energies. Renewable energy tends to be more ecoefficient. Maybe, in Qatar, due to its high dependency of natural gas for electricity and water production, CCS could drive a temporary solution in the short term due to the more flexible approach of production costs in Qatar (due to the coupling with desalination). Waste incineration, in addition, carry other toxicity problems needing of particular attention in the Qatari climate. Oil refining generally produces low concentration CO_2 (except in ammonia/hydrogen production) Natural gas sweetening, ammonia production etc, are actually low-hanging fruits for carbon sequestration, since its concentration is already high enough for low cost capture. Cement and steel are of remarkable economic importance in Qatar due to the importance of the construction activity. It could be considered one of the main targets of CCS developers now due to several reasons: The high concentration of CO_2 drives lower energy penalties. CO_2 emissions in these industries are unavoidable (they are not only dependent on fuel combustion but on reaction chemistry of their manufacture process; an alternative is really far away) The sectors have draft low carbon roadmaps, making CCS essential in their development. This means that the industry, globally, will incorporate CCS in new plants, while retrofitting existing in the period 2020-2050. Both industries are of key importance for the development of Qatar.

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology?

Eco-efficiency. This concept is defined by a standardised approach and relates an environmental impact of a product/process to its economic value. For example, the cost of CO_2 avoidance is an eco-efficiency measurement; but there are more indicators used to calculate the ecoefficiency. More info: https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12967

Q.3 Which Combustion-Based Typology of CO2 capture do you consider to be most suitable for retrofitting onto the GTL power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
n.a.	1	n.a.	

Q.3.b. Elaborate if possible: GTL produces CO_2 of high concentration and the term combustion (post pre oxy) doesn't really match exactly the technology (e.g. reforming/gasification). The best option is post-processing, as the process can be designed to produce a pure CO_2 stream. The other options seem unfeasible for syngas-based processes.

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants? Unanswered

Q.4.b. Elaborate if possible: Not familiar with the technology itself to be able to propose one. If referred to existing plants, post-combustion seems the more feasible in retrofitting.

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? Economics, market, and very strong competitors. CCS is an environmentally friendly solution, but energy penalties (plus other competitors) make the options for energy investors to turn into renewables rather than CCS. There is also a very high uncertainty in the development of marketable solutions. For markets with high penetration of coal (see e.g. the case of Poland), CCS is a certain solution. Same for other industries (Aluminum, steel, cement), where basically the only viable option for a low carbon future is CCS (in addition to increase their renewable input).

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? Yes, as maths don't lie. But it comes at very high cost with a certainly high amount of environmental trade-offs. Green bonds, green investment, carbon offsetting, etc., are probably a more logical option.

Q.7 Which carbon storage and utilities methods present the best option for Qatar?

Depleted Gas & Oil Reservoirs	Saline Aquifer	Geological Storage	Conversion to Carbon Nanofiber	Enhanced Oil/Gas Recovery
			Last.	n.a.

Q.7.b. Elaborate if possible: EOR is not a carbon sequestration route. Conversion to carbon nanofiber or other usable products is marginal in the market (maximum 2-3% of total CO_2 emissions). Regarding depleted reservoirs, aquifers and geological storage, I don't know the particular state of the art and the current Qatari status on this regard.

Q.8 Carbon Capture Mechanisms:

Technology	Suitability (1 to 5)	Additional Feedback
Direct Air Capture	5	But extremely expensive and inefficient
Pyrolysis from Agricultural Waste	2	Very low TRL. Other options would come first.
Micro-Algal Bio Fixation	3	Requires high input of energy, and the techno-economics (and sometimes the CO_2 balance) are not optimal.
Anaerobic / Waste-Based Fuel Cells		Do not know the technology
Post-Combustion Absorption	5	Already at a high TRL, fully applicable in Qatar
Post-Combustion Adsorption (Sorbents, Porous Organic	3	Low TRL, but very promising.

Frameworks, etc.)		
Post-Combustion Membrane Separation (Inorganic, Hybrid, Polymeric)	3	Low TRL, but very promising (depends on the membrane performance and requirements e.g. pressure).
Post-Combustion Cryogenic Separation	5	Already at industrial scale.
Solvent-based Post & Pre-Combustion (Amine & Alkaline)	5	High TRL, fully applicable.
Pre-Combustion Absorption		Do not know the technology
Pre-Combustion Adsorption		Do not know the technology
Chemical Looping Oxygen Fuel Combustion	2	Very low TRL, suitable for high grade heat (e.g. solar concentration). These are ok for Qatari conditions, but requires high investment in development.
Other (Please Specify): https://www.sciencedirect.com/science/article/abs/pii/S2212982019310200	4	A solution designed for the Qatari market based on construction products. However, very limited in terms of captured CO_2. Soon, a paper to be published on its eco-efficiency.

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
5	1	2	3	4

Q.9.b. Elaborate if possible: Storage tends to be the main barrier, especially regarding technical feasibility and public acceptance. It is extremely linked to transportation, which acts as a cost barrier in the process.

The other three do not suppose a problem. If CCS shows a good performance in relation to its competitors, policy will foster its implementation. Same with products utilization (there is no problem if a product is economically viable and shows a carbon negative footprint to market it). Capture is a well-developed technology, and solutions are already commercially viable and implemented in certain plants.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels? Yes, it is feasible, but the main business of Qatar is fossil fuels. It really would be strange if one of the main producers of natural gas in the world won't be able to show the world solutions based in natural gas or oil. However, the world, in 30 years, would be based on renewables and Qatar policies should anticipate to such paradigm. How feasible (or when) that change will be is not in my knowledge, though.

However, Qatar has been exemplary in a few sustainability aspects. For example, building technologies and energy efficiency is of high standard there (probably due to the extreme climate), and has been able to assume a high quality for buildings. Same with some state-of-the-art chemical plants (you mentioned GTL – The Shell GTL in Qatar is studied by chemical engineering students around the world).

Appendix 6: Respondent 6

Q.0. Please specify your sector (**Academia / Government / Industry / Others):** Academia

Q.1. Based on the following figure, which industries do you consider having the most potential for Carbon Sequestration?

Oil	Gas	Cement	Waste	Steel	Direct Air Capture	Natural Landscaping	Other
x	x	X					

Q.1.b. Elaborate if possible: While cement provides the best capture ratio from the cement amount produced as shown in the Figure above, Natural Gas Power Plant and Fuel Combustion has a significantly higher CO_2 production and presents higher potential for capture in all its produced CO_2.

Q.2 What is the best mechanism for measuring the economic and environmental benefits of carbon sequestration technology? Cost for % CO_2 Captured from All CO_2 Produced

Q.3 Which Combustion-Based Typology of CO_2 capture do you consider to be most suitable for retrofitting onto the GTL power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
		x	

Q.3.b. Elaborate if possible: At current capacity, post-combustion will have the best value for money but with better planning and foresight, oxy-fuel can be a better solution for the long-term.

Q.4 Which method of CO_2 capture do you consider to be most suitable for retrofitting onto the LNG power plants?

Pre-Combustion	Post-Combustion	Oxygen-Fuel Combustion	Unsure
	x		

Q.4.b. Elaborate if possible: Oxy-fuel has higher long-term potential but post-combustion is the most economically viable choice at the moment.

Q.5 What are the key obstacles for turning CCS initiatives into National policy and strategy recommendations? Integration of high-level government policy with private sector, in a harmonised way that encourages private sector through public sector support and subsidies. Resilience to changing existing systems that work well now is also another major driver.

Q.6 Is the potential for natural sequestration through mangrove formation, desert reforestation, and other natural actions a realistic path for sequestration in Qatar? Yes, however, it requires strong policy push and major investment in natural resource management and major landscaping initiatives. Theoretically this is possible, it is just a question of will and determination.

Q.7 Which carbon storage and utilities methods present the best option for Qatar?

Depleted Gas & Oil Reservoirs	Saline Aquifer	Geological Storage	Conversion to Carbon Nanofiber	Enhanced Oil/Gas Recovery
X	x			x

Q.7.b. Elaborate if possible: In the future, there may be more advanced carbon utility potential, but at the moment, utilising existing identified aquifers and reservoirs is the best option.

Q.8 Carbon Capture Mechanisms:

Technology	Suitability (1 to 5)	Additional Feedback
Direct Air Capture	2	Perhaps near high emitting infrastructure
Pyrolysis from Agricultural Waste	3	Only more feasible in large scale if agricultural input is increased
Micro-Algal Bio Fixation	4	Saltwater microalgae suitable for outdoor growth in open ponds can be utiliseutilised in the desert, especially there is potential for using microalgae for water desalination
Anaerobic / Waste-Based Fuel Cells	3	Tackling organic / food waste in a more sustainable manner is a valuable method of sequestration, and although it may still be underdeveloped in Qatar, it has potential.
Post-Combustion Absorption	3	Potential for commercialization however have logistic issues
Post-Combustion Adsorption (Sorbents, Porous Organic Frameworks, etc.)	1	Not commercially viable yet
Post-Combustion Membrane Separation (Inorganic, Hybrid, Polymeric)	1	Not commercially viable yet
Post-Combustion Cryogenic Separation	1	Not commercially viable yet
Solvent-based Post & Pre-Combustion (Amine & Alkaline)	1	Not yet feasible for retrofit projects
Pre-Combustion Absorption	1	Not yet feasible for retrofit projects
Pre-Combustion Adsorption	1	Not yet feasible for retrofit projects
Chemical Looping Oxygen Fuel Combustion	1	Not commercially feasible yet.
Other (Please Specify)	4	Reforestation and innovative greening

Q.9 Which steps in carbon sequestration do you consider to be the main barriers to implementation?

Capture	Storage	Transportation	Utility	Policy
X	x		x	x

Q.9.b. Elaborate if possible: Almost all steps have barriers to implementation, while transportation seems to be the most advanced. Innovation is required mostly in capture and policy, dictating trends that are possible in storage and utility.

Q.10 Qatar's practical potential for Solar Energy is significantly high. How feasible is it for Qatar to switch to renewable energy, instead of continuing sourcing with fossil fuels?

Obviously, there is high potential due to the country's position and need to divest from fossil fuels, but this will need to occur over time and in a national energy plan that places energy diversification in its transition strategy.