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BUSINESS MODELS FOR CCS HUBS – CHALLENGES AND OPPORTUNITIES WITH A FOCUS ON MENA

PREPARED FOR THE CIRCULAR CARBON ECONOMY REGIONAL COLLABORATION INITIATIVE

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1.0 INTRODUCTION

Traditional CCS business models centered on "full-chain" models include all elements of CCS infrastructure including CO_2 capture, transport and storage. With the development of CCS hubs to facilitate large-scale CCS deployment, new business models are emerging with separate entities managing capture, transport, and storage. Emerging business models aim to mitigate risks by separating responsibilities and enhancing operational efficiency

This report presents an analysis exploring various business models for CCS that could be applicable to the MENA region. The analysis is completed by the Global CCS Institute (GCCSI) for The Circular Carbon Economy Regional Collaboration Initiative. The analysis focused on countries in MENA with existing CCS activities and interest, including KSA, United Arab Emirates (UAE), Qatar, Oman, Bahrain, Egypt, Algeria and Morocco.

The current CCS landscape in the MENA region is analyzed with a focus on current policy and regulations supporting CCS, prospective storage potential, CCS project status, and institutes and organizations that provide research and support for CCS development.

In addition, a broader analysis of the opportunities for CCS hub development exploring current emission sources and storage opportunities for initial CCS hub and network development is detailed below. The analysis reviews expanding CCS growth opportunities in the MENA region using the GCCSI's global economic optimization model (GENZO). Subsequent challenges to CCS hub and network development are also discussed.

The report concludes with several recommendations that could support CCS growth and business model development in the MENA region. Governments in the region can play a critical role in supporting these new business models, addressing infrastructure planning, liability concerns, and revenue stream establishment for effective CCS deployment.

2.0 CCS LANDSCAPE IN MENA

2.1 Overview of policy, legal and regulatory environment

2.1.1 National commitments under international climate change agreements

Countries in the MENA region have submitted their Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), outlining their ambitions to address climate change and reduce greenhouse gas emissions (GHG). Table 1 below highlights these ambitions for countries in the MENA region.

Table 1: NDC and net-zero ambitions. Source: [1] [2] [3] [4] [5] [6] [7] [8]

COUNTRY	NDC AMBITIONS	NET ZERO AMBITIONS
Saudi Arabia	• Reducing, removing, avoiding GHG emissions by 278 $MtCO_2e$ by 2030. • Saudi Arabia aims to have 50% of its electricity capacity from renewable sources by 2030.	Net zero by 2060.
UAE	• Emissions reduction target to limit emissions to 182 $MtCO_2e$ by 2030.	Net zero by 2050.
Qatar	• Qatar has set a 2030 target of reducing emissions by 25% below a business as usual (BAU) scenario; however, it does not provide this BAU scenario in the NDC.	Qatar does not currently specify the year it aims to reach carbon neutrality.
Oman	• Oman's latest NDC outlines a commitment to reduce emissions by 21% by 2030 compared to a BAU.	Net zero by 2050.
Bahrain	• Target of 6% improvement in energy efficiency by 2025 compared to a BAU scenario. Achieving the 6% energy savings target should cut GHG emissions by 3.4 $MtCO_2e$. • To increase renewable energy capacity by 10% by 2035.	Net zero by 2060.
Egypt	• By 2030, sectoral emissions reduction targets compared to a BAU include: electricity (37% below BAU), transport (7% below BAU) and oil and gas (65% below BAU). • Egypt has not communicated its BAU scenario, making it difficult to quantify the overall emissions level. • Other targets include 42% of electricity generation to come from renewables by 2030.	Egypt does not currently specify the year it aims to reach carbon neutrality.
Algeria	• Reduction of greenhouse gases emissions by 7% to 22%, by 2030, compared to a BAU scenario. • Aims to reach a target of 27% of electricity produced through renewable energy sources by 2030.	Algeria does not currently specify the year it aims to reach carbon neutrality.
Morocco	• 45.5% emissions reduction by 2030, against BAU; 18.3% unconditional and 27.2% conditional upon international assistance.	Morocco does not currently specify the year it aims to reach carbon neutrality.

2.1.2 Domestic climate policy settings that underpin international commitments (incl. net zero ambitions)

2.1.2.1 Kingdom of Saudi Arabia

2.1.2.1.1 Mitigation

Energy - Through the National Renewable Energy Program, the Kingdom is initiating comprehensive reforms, regulations, and policies aimed at catalyzing private sector investments, fostering research and development, and generating employment opportunities in the renewable energy sector. The program outlines a strategic roadmap to diversify local energy sources, spur economic development, and establish a robust local supply chain and industry for renewable energy.

Saudi Arabia is poised to emerge as a global leader in low-carbon hydrogen production, with plans to construct one of the world's largest low-carbon hydrogen facilities. Recognizing the pivotal role of CCUS in achieving Paris Agreement goals, the Kingdom envisions transforming Jubail and Yanbu into global hubs for CCUS. Leveraging the concentration of the manufacturing industry, proximity to sinks, and transport infrastructures, these hubs will play a key role in advancing CCUS technology. In addition to low-carbon hydrogen, the Kingdom is harnessing its abundant natural resources and CO_2 storage capacity to position itself as a leader in clean hydrogen production.

As part of its domestic energy sector reforms, Saudi Arabia aims to boost the use of natural gas in its energy mix. By 2030, the goal is for up to 50% of electricity generation to be fueled by natural gas and the remaining 50% sourced from renewables, thereby significantly reducing the carbon intensity of domestic energy production. In 2021, Saudi Arabia announced the allocation of its eastern 'Jafurah' gas field, the largest shale gas field in the country, for the purpose of displacing liquid fuel in power plants. Saudi Aramco expects this project to generate low-carbon energy equivalent of displacing around 500,000 barrels of crude oil [9].

Buildings, transport, and industry - The Energy Efficiency Program in Saudi Arabia is dedicated to enhancing energy consumption efficiency across three core sectors: industry, building, and land transportation. It encompasses a variety of initiatives aimed at optimizing energy usage, such as enhancing the efficiency of household appliances and air conditioning systems, refining feedstock utilization in crucial industries, boosting fuel economy in transportation fleets, and elevating the thermal efficiency of power generation, transmission, and distribution processes.

Circular Carbon Economy - To address greenhouse gas emissions systematically, Saudi Arabia has adopted a Circular Carbon Economy approach. At its core is the 4R's model:

- **Reduce** - reduce emissions through sustainable consumption, enhanced efficiencies, including fuel efficiencies, cleaner energy systems, electrification and renewables, and improving energy and process efficiencies.
- **Reuse** - reusing emissions without changing its chemistry.
- **Recycle** - recycling emissions or products containing GHGs into similar or different products with different chemical characteristics.
- **Remove** - removing emissions from the system, partially (if it will be reused or recycled) or fully (storage), which can be achieved through CCUS.

The Circular Carbon Economy National Program has been designed to implement the principles of this approach. Primary activities include:

- **CCE technology development** - Establishing roadmaps, identification of funding mechanisms, and key standards to be updated.
- **Domestic implementation** - Overseeing domestic implementation of scale-up technologies, supporting domestic industries to decarbonize and develop emission scenarios.
- **International engagement** - Coordinating with other international stakeholders on CCE technologies, promote CCE framework internationally and provide leadership [10].

Water - The Kingdom relies on desalination for approximately 70% of its domestic water supply. To mitigate greenhouse gas emissions, efforts are underway to optimize desalination technologies. This involves innovation to decrease energy consumption, utilizing renewable energy sources and increasing the use of treated wastewater to reduce reliance on desalinated water.

2.1.2.1.2 Adaptation

Coastal zones - Coastal management strategies are being implemented to combat erosion, enhance blue carbon sinks, and safeguard marine ecosystems from climate change threats. The Kingdom actively supports mangrove planting along its coasts and is committed to reinforcing coral reef restoration efforts in the northwestern Arabian Gulf. As part of the Saudi Green Initiative, a comprehensive national effort aimed at addressing climate change, enhancing quality of life, and safeguarding the environment, a pledge has been made to conserve 30% of its terrestrial and marine territories by 2030 [11].

Afforestation - In addressing desertification, Saudi Arabia is taking measures to stabilize sand movements around cities and roads. Arid and semi-arid rural areas are being developed through natural resource conservation, biodiversity initiatives, and ecosystem-based adaptation efforts. The Saudi Green Initiative, aligned with national climate goals, aims to plant 10 billion trees. This initiative will restore ecological functions, improve air quality, and combat sandstorms.

Urban planning / development - Across urban planning, the Kingdom of Saudi Arabia is implementing mass transport systems in urban areas like Riyadh, Jeddah, and Dammam to enhance sustainability, environment, and public health. The Riyadh metro, which has completed its construction phase, and the bus network are expected to significantly reduce car journeys and fuel consumption. Additionally, the expansion of the Saudi Railway network will decrease traffic congestion and greenhouse gas emissions. Vision 2030 initiatives include giga-projects such as NEOM, focusing on urban sustainability with 100% renewable energy usage.

The following adaptation contributions are expected to support Saudi Arabi's efforts to address climate change:

- Integrated Coastal Zone Management Planning: Developing plans to protect coastal infrastructure.
- Early Warning Systems: Establishing systems to reduce vulnerability to extreme weather events.
- Integrated Water Management Planning: Addressing water challenges through strategic programs and initiatives.
- Infrastructure and Cities Designs: Implementing policies to enhance sustainability and resilience in urban areas, including improving building efficiency to withstand heatwaves.
- Other efforts include the Cloud Seeding program, Green Riyadh program, Regional Climate Change center [1].

2.1.2.2 United Arab Emirates

2.1.2.2.1 Mitigation

Energy - By 2030, the UAE intends that significant energy delivered will come from zero-carbon sources such as renewables and nuclear, corresponding to a power grid emission reduction of 51% compared to the 2019 base year. The target will be achieved through a steep ramp-up of clean energy, primarily solar photovoltaic (PV), supported by nuclear power which is already in development. The UAE has launched the world's largest single site solar energy project. The UAE's current plans for 19.8 GW of clean energy sources (solar PV, concentrating solar-thermal power, and nuclear) by 2030 are being updated to reflect more ambitious targets.

UAE aims to solidify its global standing as a major producer of low-carbon hydrogen, targeting a 25% share in the global hydrogen market [12]. The UAE's Hydrogen Strategy incorporates various incentives to boost the growth of hydrogen production, including considerations for carbon pricing mechanisms and potential cap-and-trade systems on the demand side. On the supply front, it considers cost support to lower the overall cost of hydrogen production projects and guarantees for revenue support, aiming to facilitate low-interest sustainable financing options. The strategy emphasizes a holistic approach towards different types of low-cost hydrogen, encompassing blue hydrogen integrated with CCS. The goal is to achieve a production target of 7 million tons per annum (Mtpa) for blue hydrogen by the year 2050. By allowing CCS projects to benefit from these policy incentives, the strategy aims to expedite the adoption of this technology [13]

Water - The UAE is also decarbonizing its energy-intensive desalination sector by using low-carbon reverse osmosis (RO) technologies to produce potable water. Abu Dhabi will be home to one of the world's largest reverse osmosis plants, sufficient to meet the water demand of around 350,000 households.

Industry - By 2030, the UAE's emissions from the industrial sector will decrease by 5% compared with the 2019 base year level, while the country is increasing industrial output by around 100% by 2030, thus aiming to decouple GHG emissions from production growth. The UAE Demand Side Management (DSM) program aims to improve the industrial sector's energy efficiency by 33% by 2050, compared to BAU, by enacting a number of emirate and company level initiatives for the top 50 most energy-consuming companies in the nation, which collectively represent the vast majority of industrial emissions. Initiatives include ISO 50001 certification or submission of DSM improvement plans every three years, as well as annual reporting of energy demand and emissions to the relevant government authority. At COP28, the UAE announced the launch of the industrial decarbonization roadmap with the aim of reducing carbon industrial emissions by 2.9 gigatonnes cumulatively until 2050. The roadmap will focus on manufacturing and hard-to-abate sectors, stimulating the development and adoption of advanced technologies to drive emissions reduction [14].

Transport - Although its population is expected to grow 14%, accompanied by a 24% increase to nominal GDP, by 2030, the UAE will stabilize and even slightly decrease transport sector emissions by 1% by 2030, compared to 2019. The UAE is proactively driving the decarbonization of the transport sector through a series of initiatives, beginning with the construction of a 1,200 km freight rail network in 2014. A comprehensive policy package will focus on vehicle electrification. The package will include Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV) subsidies, such as CAPEX grants, lower registration fees and tolls for BEVs and FCEV, and additional road privileges, such as priority lanes and dedicated parking.

Waste - The UAE has approved additional policies to accelerate the decarbonization of the waste sector. A comprehensive policy package will increase recycling rates and will include mandatory recycling bins in residential and commercial buildings, drink container recycling incentives, and awareness campaigns focusing on waste avoidance and segregation. A second policy package will incentivize diversion of waste from landfills by raising gate fees and by creating a market for recycled materials by mandating that construction projects reuse construction and demolition waste and by introducing green production criteria for cement and concrete.

The UAE is also working towards achieving an integrated waste management plan by proposing and developing waste policies and legislation — such as the UAE's National Integrated Waste Management Agenda – that envision the adoption of integrated waste management for a sustainable quality of life through a circular economy approach to protect the environment. This also includes work on waste treatment projects to reduce the number of landfills in the country, with a goal of reaching 75% treatment of municipal solid waste.

Buildings - The country seeks to reduce emissions in the buildings sector by 56% to 27 million tons CO_2e by 2030 compared to the 2019 base year. In 2021, the UAE introduced the UAE DSM program which, among others, entails a periodic update of existing building codes to increase the efficiency of new buildings, retrofitting of inefficient buildings, and increased penetration of efficient cooling, roof-top PV, and solar water heating. As part of the UAE DSM program, the UAE introduced a national building code which, inter alia, sets minimum energy efficiency standards for all emirates. Overall, the program targets a 40% reduction in energy use and a 20% reduction in water demand for the built environment by 2050 compared to BAU.

Agriculture - A National Food Security Strategy has been defined which aims to improve food self-sufficiency by increasing local production of selected items by up to 15%. Despite the increase in local agricultural production, the UAE will decrease agriculture sector emissions by 22% by 2030, compared with 2019. The UAE aims to decrease demand for water resources and targets a reduction in the water supply needed for agriculture to 7.1 million cubic meters per day by 2036 (down from 8.2 million in 2016). In 2021, the Food Tech Valley initiative was launched as a new hub for clean-tech food and agricultural production. The Food Tech Valley initiative will explore innovative technologies and farming techniques — such as vertical farming, aquaculture, and hydroponics.

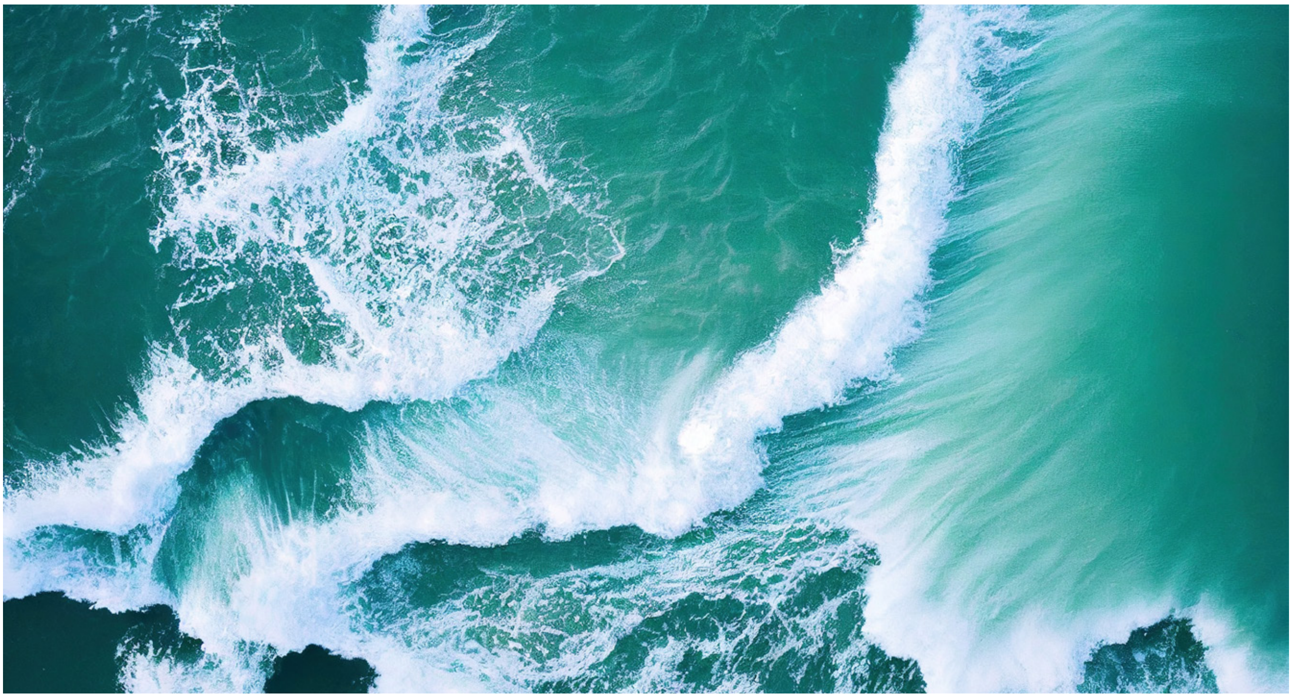
Negative emissions - The UAE is also committed to removing CO_2 from the atmosphere mainly by using nature-based solutions. The country will explore innovative Direct Air Capture (DAC) solutions that extract CO_2 directly from the atmosphere and is exploring additional options to further increase the planting of mangroves to reach 160 million by 2030.

2.1.2.2.2 Adaptation

Energy - The UAE is conducting regular maintenance of power facilities, exploring modernization with efficient technologies, expanding clean energy generation, and implementing risk management systems including risk insurance schemes. It is also promoting energy efficiency by installing smart meters, smart grid initiatives, and exploring low-emission cooling technologies and refrigerants.

Infrastructure - Recognizing infrastructure vulnerabilities, the UAE is promoting green buildings and refurbishing existing ones. It is developing sea-level resilient infrastructure and has established emergency response plans supported by coastal monitoring and early warning systems.

Health - To address climate impacts on public health, regulations have been issued to protect outdoor workers from extreme heat. A national committee has been formed to steer a public health response to climate change. Policies on environmental health determinants like air and water quality are being strengthened.



Awareness initiatives are underway for heat-related illnesses.

Environment - Establishing protected areas and promoting sustainable practices in economic activities like fishing and farming is a priority. Restoring ecosystems like coral reefs, wetlands and mangroves through rehabilitation efforts is underway. Sustainable groundwater management initiatives and marine water quality monitoring programs have been implemented.

Agriculture - The UAE recognizes the urgent need for sustainable food systems amidst challenges posed by climate change, including threats to crop yields and water scarcity exacerbated by agriculture's significant freshwater consumption. Initiatives like the National Food Security Strategy 2051 aim to bolster domestic food production and reduce waste, with specific targets set for carbon intensity, regenerative agriculture, alternative proteins, and water usage. Collaborations between public and private sectors drive innovation, such as the FoodTech Challenge and partnerships promoting sustainable agriculture.

Marine - The UAE has taken notable steps to conserve and restore blue carbon ecosystems like mangroves for their carbon sequestration abilities and coastal protection benefits. It launched the Mangrove Alliance for Climate at COP27 to accelerate global mangrove conservation efforts.

Insurance - Looking ahead, the UAE aims to include the insurance sector in climate risk assessments while raising industry awareness on incorporating climate risks into business practices through its Central Bank's initiatives [2].

2.1.2.3 Qatar

2.1.2.3.1 Mitigation

Economic diversification / tourism - Qatar is actively pursuing economic diversification, steering away from oil and gas dependence and embracing sustainable development. A key component of this strategy is the long-term vision for sustainable tourism, marked by initiatives such as the establishment of eco-friendly resorts and hosting major international events like the FIFA World Cup in 2022 and the Asian Games in 2030.

Energy - To enhance energy efficiency in the oil and gas sector, Qatar is committed to optimizing gas turbines, boilers, and improving fuel gas/steam measurement by 2025. The reliability of waste heat recovery systems will also be heightened. By optimizing power plant capacity and sharing resources across upstream facilities, the aim is to operate at more efficient levels.

QatarEnergy has partnered with General Electric (GE) to create a carbon capture roadmap to support the development of carbon sequestration projects, the utilization of hydrogen and the potential usage of ammonia in GE gas turbines to reduce emissions [15], [16]. QatarEnergy will also build the world's largest blue ammonia plant, which is expected to be operational in 2026 and capture 1.5 Mtpa of CO_2. The cost of the Ammonia-7 project is approximately $1.06bn [16].

To address environmental concerns, Qatar is actively working to reduce flaring and methane emissions in the oil and gas sector. Initiatives such as the Ras Laffan gas liquefaction plant, capture 2.1 Mtpa, with plans to increase this to 5 Mtpa by 2025 [17]. Furthermore, the introduction of a smart leak detection and repair program across all oil and gas facilities and the commitment of Qatar Petroleum to guiding principles aimed at reducing methane emissions across the natural gas value chain showcase the nation's dedication to environmental stewardship.

Water - Qatar is shifting towards less energy-intensive desalination technologies like reverse osmosis, aligning with its commitment to sustainable practices.

Transport - The transportation sector in Qatar has been earmarked for rapid modernization. The Doha Metro and Lusail Tram are major milestones in the development of public transportation and subsequent reduction of emissions from this sector. The level 3 accreditation status for Hamad International Airport is another major initiative towards sustainability. The country has also taken significant strides to adopt electrification of on-road vehicles by committing to electrify its public transport system and investing in installation of charging infrastructure across the country.

Buildings - Qatar has been transforming its building standards towards higher sustainability levels through the adoption of the Global Sustainability Assessment System (GSAS) standards. The number of projects registered for GSAS certifications has been rapidly increasing, thereby facilitating the transition towards green buildings.

Education - Qatar's Ministry of Education introduced Eco School programs in 1994, promoting environmental education. They have expanded by training teachers on climate change topics and integrating sustainability into curricula. Major universities feature solar panels and energy reduction policies. Qatar Foundation is developing green campus facilities and launching anti-plastic campaigns.

2.1.2.3.2 Adaptation

Some of the primary adaptation activities to be undertaken by Qatar include:

- Water conservation and improving water use efficiency through regulations, awareness campaigns and using treated sewage effluent.
- Restoring marine habitats like mangroves and increasing green spaces.
- Developing sustainable urban infrastructure and studying coastal impacts of climate change.
- Enhancing food security through increasing domestic agricultural production, building reserves and diversifying trade.
- Raising awareness on climate change through education programs and public campaigns [3].

2.1.2.4 Oman

2.1.2.4.1 Mitigation

Energy - To support emissions reduction in the power sector, Oman has committed to several renewable initiatives to increase the share to 35-39% of the energy mix by 2040. These projects primarily focus on solar and wind. The government plans to produce a net metering scheme allowing excess electricity sales to the grid in addition to other incentives such as green bonds by the central bank. There are plans to retire all diesel power plants by 2028. To decarbonize the oil and gas sector, there is focus on identifying CO_2 storage sites for CCUS, the replacement of existing infrastructure, and reduction of methane emissions through a GHG reporting scheme and domestic carbon market. Under its 2050 net zero target and hydrogen strategy, Oman has set itself the goal of 8.5 Mtpa of low-carbon hydrogen by 2050 [18].

Buildings - There is focus on enhanced energy efficiency through the implementation of building codes, linking international green building certificates to government incentives, and the expansion of energy audits to identify energy saving opportunities. In addition, a transition to LED lighting is highlighted as improving energy efficiency.

Industry - Oman will focus emission reduction efforts on the industrial sector, through gradual electrification of processes and replacement of traditional gas with low-carbon hydrogen in selected sectors, investment and deployment of CCUS technologies in hard-to-abate sectors with early demonstrator projects and a transition to alternative production methods by 2050, achieving a 50:50 split with renewable energy sources.

Transport - Oman will invest in the sustainable development of the transport sector, including investments into the electrification of vehicle fleets, with policy revision to facilitate BEVs and FCEVs and passing import laws that make EVs and FCEVs cost competitive with internal combustion engine vehicles and investment in EV charging stations. The government is also exploringsustainable aviation fuel and promoting biofuel blending as a means to reduce emissions from traditional vehicles.

Economic diversification - Emphasizing economic diversification, innovation, and technology integration, policies like "Tanwea'a" and the "Nazdaher" program aim to reduce reliance on oil and gas. Investments in renewable energy, eco-tourism, and sustainable sectors align with Sustainable Development Goals, fostering job opportunities, skills enhancement, and community empowerment.

2.1.2.4.2 Adaptation

Water - In a concerted effort to address water scarcity and environmental sustainability, Oman's government is prioritizing the decarbonization of the water sector. This involves the development and implementation of strategies to reduce carbon emissions from desalination plants. Additionally, the government is actively promoting water reuse through the integration of renewable energy sources, aiming to create a more environmentally friendly and efficient water supply system. To bolster water resources, substantial investments are being made in wastewater treatment plants, and the sewage network is being expanded across the country, ensuring comprehensive coverage for effective water management. Furthermore, the government is committed to promoting groundwater recharge initiatives, establishing stringent water quality standards for aquifers that receive treated sewage water.

Fisheries and marine - Oman recognizes the vulnerability of its fisheries sector to climate change and is taking proactive steps to mitigate potential impacts. Long-term climate vulnerability studies within the fisheries sector are being conducted to comprehensively analyze the effects on the physiology, life cycles, and environment of aquaculture species. The government is facilitating greater stakeholder engagement in both domestic and international large-scale fisheries, acknowledging and addressing the significant climate impacts faced by these industries. Additionally, the establishment of marine protected areas is a key strategy to safeguard valuable marine resources, while the development of conservation strategies specifically focuses on the vital mangrove ecosystems, contributing to the overall health and resilience of marine environments.

Agriculture - Oman is committed to promoting sustainable agriculture practices to enhance resilience in the face of changing climate patterns. Diversification of agricultural activities is being actively encouraged to ensure a more robust and adaptive agricultural sector. Efforts to control overgrazing and prioritize local breeding over livestock imports contribute to sustainable land use practices.

A comprehensive strategy has been developed to combat desertification and promote soil conservation, and the adoption of efficient irrigation methods is being promoted to conserve water resources. Additionally, a notable reforestation initiative aims to plant 10 million trees, providing both environmental and agricultural benefits.

Urban areas and infrastructure - The government is addressing the vulnerabilities of urban areas and infrastructure through a multifaceted approach. Vulnerability analyses are being conducted to determine the extent of land flooding, guiding the development of smart cities that utilize advanced services and modern technology for enhanced resilience. Urban transportation plans are actively being developed to reduce emissions, ease traffic congestion, and improve air quality. Simultaneously, the government is accelerating the development of the waste management sector, embedding principles of a circular economy to promote sustainable practices and reduce environmental impact.

Public Health - Recognizing the intricate relationship between climate change and public health, Oman's government is adapting healthcare facilities to meet the challenges posed by changing climate patterns. Increased research capacity is a priority, with a focus on assessing the health consequences of climate change. Public awareness campaigns are being implemented to inform the population about the adverse health effects associated with climate change. Moreover, the development of local data-driven health models enhances monitoring capabilities, ensuring a proactive and prepared healthcare system in the face of evolving climate conditions [4].

2.1.2.5 Bahrain

2.1.2.5.1 Mitigation

Energy - The National Energy Efficiency Action Plan (NEEAP) in Bahrain outlines a comprehensive set of 22 initiatives spanning various sectors. These initiatives aim to achieve a national target of a 6% reduction in energy consumption by 2025, expressed as a percentage of the average final energy consumption. This target has been officially adopted by the Cabinet.

Simultaneously, the National Renewable Energy Action Plan (NREAP), launched in the same year, identifies viable solar, wind, and biogas renewable energy options for Bahrain. The plan establishes national renewable energy targets, also endorsed by the Cabinet, aiming for 5% of peak capacity by 2025 and a more ambitious target of 10% by 2035.

In late 2023, Bahrain revealed its National Energy Strategy, outlining a roadmap to fulfill the climate commitments made at COP26. This includes aiming for a 30% reduction in emissions by 2035, with the ultimate goal of achieving net zero emissions by 2060. The Strategy relies on three levers: optimizing energy demand to reduce energy intensity and consumption, diversifying the country's power mix to include cleaner energy sources, and deploying carbon abatement technologies to decarbonize hard-to-abate sectors [19].

Economic diversification - As part of the broader mitigation strategy, economic diversification plays a crucial role. The government has strategically planned the development of six key economic sectors: financial services, information and communication technology, industry, logistics and tourism, and oil. Numerous initiatives have already been implemented, such as a new tourism strategy, streamlined visa procedures, a logistics sector development strategy, and a holistic approach to revising the pearling industry. These endeavors are expected to foster growth in Bahrain's non-oil sector, contributing to sustainable development.

2.1.2.5.2 Adaptation

Coastal zones/water - Bahrain is actively crafting a national adaptation investment plan, with a particular emphasis on coastal zones and water resources. Concurrently, a water resources policy is in development, supported by dedicated funding to model the effects of climate change on freshwater resources.

LULUCF/Afforestation - Pioneering an integrated approach, Bahrain is not only focused on traditional adaptation but is also leveraging mitigation co-benefits. A key initiative is the national afforestation project guided by thermal satellite imagery, which identifies suitable trees for emissions reduction. The upcoming action plan will provide detailed insights into green area types and percentages, initiatives encouraging community participation in tree planting, and revisions to building permits to incorporate landscaping.

Marine - In the domain of mangrove habitats, Bahrain is exploring comprehensive adaptation strategies, including a mangrove planting initiative, the establishment of a blue carbon inventory to monitor emissions in carbon pools, and the creation of an observatory to enhance understanding of the ecological services provided by mangrove habitats [5].

2.1.2.6 Egypt

2.1.2.6.1 Mitigation

Energy - Egypt plans to implement an integrate program to modernize the oil and gas sector, including adopting energy efficiency and low-carbon technologies in upstream and downstream activities. Some of the main initiatives include the Decent Life Initiative ('Hayah Karima') that aims to provide access to clean fuel in households. Natural gas pipelines have been connected to 86 villages, with plans to extend to an additional 180 villages, serving 476,000 residents. In addition, low-investment energy efficiency measures in petroleum companies are targeted to reduce 5% of the sector's energy consumption. Energy efficiency audits will be conducted in two refineries, one petrochemical plant, and two upstream oil and gas facilities.

Transport - Since road transport is by far the largest GHG contributor in the transport sector in Egypt, it is planned to drive low-carbon modal shift from private passenger and freight vehicles into mass transit primarily through the expansion in Cairo metro network, the development of Alexandria metro, the operation of new capital monorail and the operation of the light rail transit electric train. Other initiatives focus on greening bus services/aviation sector and increased sustainable road development.

Industry - Egypt is actively working to decarbonize its industrial sector by adopting various strategies. In the cement industry, measures include using alternative fuels, reducing clinker content by up to 80%, and improving energy efficiency, with a specific target of decreasing energy consumption from 3,710 to 3,540 MJ/ton. The sector has already initiated the use of alternative fuels, comprising 6.4% in 2015. The broader plan extends to resource-intensive industries and SMEs, targeting a 10% reduction in specific thermal energy consumption in key sectors like iron and steel, fertilizers, and ceramic tiles. The promotion of solar heating and rooftop PV systems aims to reduce energy consumption in the textile, food, and chemical sectors.

Buildings - Egypt is driving sustainability in building and urban development through key measures. This includes promoting renewable energy and energy efficiency, such as rooftop PV panels, 5,300 solar water heaters, and increased use of LED lighting by 2030. The focus extends to enhancing energy efficiency labels for appliances, eliminating non-energy-efficient equipment, and raising consumer awareness. Green building initiatives involve enforcing energy efficiency codes, renovating existing structures, and incentivizing sustainable practices, aiming to develop 16,960 residential units meeting green standards by 2030.

Tourism - Efforts are underway to foster low-carbon tourism developments and enhance sustainability in hotels and resorts, focusing on renewable energy adoption and energy efficiency measures. This involves promoting the use of solar power for electricity generation, water heating, and desalination, alongside implementing energy-efficient technologies such as LED lighting, improved building insulation, and efficient heating, ventilation and air conditioning systems.

Waste - Efforts are being made to enhance integrated waste management by upgrading infrastructure and increasing waste valorization to reduce landfill. This includes improving collection efficiency, constructing transfer stations and treatment plants, and closing uncontrolled dumpsites. Waste-to-energy initiatives aim to utilize waste as alternative fuel and generate electric power through modern technologies, targeting a 20% contribution by 2026.

2.1.2.6.2 Adaptation

The adaptation strategies in Egypt encompass four key areas: water resources and irrigation, agriculture, coastal zones, and urban development & tourism.

Water - Focus on rehabilitating 20,000 km of irrigation canals and implementing renewable water desalination for agricultural climate resilience, benefiting 33 million people. Strategies include water conservation, development of non-conventional water resources, and cooperation with Nile Basin countries.

Agriculture - Adaptation involves modernizing on-farm practices, increasing crop yield, and adjusting land use policies for climate resilience. Strategies include modern irrigation techniques, biodiversity preservation, and livestock protection.

Coastal zones - Measures target adapting the Northern Delta to sea level rise, protecting shorelines, and integrating coastal protection in Mediterranean cities. Strategies include a climate-resilient Integrated Coastal Zone Management Plan, nature-based solutions, and capacity building for effective management.

Urban development and tourism - Emphasis on directing city planning towards green architecture and ensuring sustainable practices in tourism. Strategies include assessing road networks, expanding protectorates to cover 17% of national marine and wildlife areas, and developing monitoring systems for climate change impacts [6].

2.1.2.7 Algeria

2.1.2.7.1 Mitigation

Algeria has outlined a comprehensive set of planned actions conditional on external support for finance, technology development, and capacity building to achieve sustainable development goals through energy transition and economic diversification.

Energy - Key goals include reaching 27% renewable energy in electricity generation by 2030, widespread adoption of high-performance lighting, thermal insulation of buildings, increased use of liquefied petroleum and natural gas, and reducing gas flaring to less than 1% by 2030.

Waste - Focussing on waste valorization, composting organic and green waste, and energy recovery/recycling of methane from landfill sites and wastewater treatment plants.

LULUCF/Afforestation - Initiatives involve afforestation, reforestation, and preventing forest fires.

Education - Awareness, information, and education actions are planned, including communication on climate change challenges and the implementation of a national program for climate change education, training, and research.

2.1.2.7.2 Adaptation

Algeria is actively developing a national adaptation plan in conjunction with the finalization of its climate contribution. The primary objective is to foster a climate-resilient economy, emphasizing the protection of the population, preservation of natural resources, and safeguarding key infrastructure against the risks of extreme weather events.

Key goals of the national plan include:

- Reinforcing ecosystem resilience against flooding and drought to mitigate the risks of natural disasters related to climate change.
- Combating desertification by addressing erosion and rehabilitating degraded lands.
- Integrating the impacts of climate change into sectorial strategies, particularly in agriculture, water management, public health, and transportation.
- Recognizing and addressing the implications of climate change on political stability and national security [7].

2.1.2.8 Morocco

2.1.2.8.1 Mitigation

Energy - Morocco's energy strategy focuses on investing in renewable energy to achieve a target of 52% of installed electrical power from renewable sources by 2030. This commitment is paired with efforts to reduce energy consumption in buildings, industry, and transport by 20% by 2030. Additionally, there's a plan to enhance energy production through the installation of an additional 450 MW capacity in combined cycle technology.

In 2024, the Moroccan government introduced the "Morocco Offer" aimed at fostering the growth of the low-carbon hydrogen industry. This initiative focuses on implementing a comprehensive and practical strategy to build essential infrastructure, partnering with selected investors under state contracts, and establishing effective sector governance [20].

Waste - Morocco's waste management strategy aims to minimize waste destined for controlled landfills and improve recycling and recovery rates by 2030. Specific targets include achieving 20% recycling of household waste, 20% recovery of organic matter from municipal solid waste (MSW), and 10% energy recovery from waste. To achieve these goals and create sustainable green jobs, the strategy emphasizes integrating informal waste collectors, establishing more Landfill and Recovery Centers (CEVs), encouraging the establishment of recycling facilities, and fostering public-private partnerships.

Water - The National Liquid Sanitation and Wastewater Treatment Program aims to steadily increase urban sanitation standards and wastewater treatment efficiency. By 2030, the goal is to achieve a universal urban sanitation network connection rate, ensuring 100% coverage. Additionally, the program aims to treat all wastewater to tertiary levels by 2030, with a specific focus on reusing treated wastewater for inland cities.

Agriculture - The agricultural sector seeks substantial modernization to boost GDP and exports. Initiatives include prioritizing sociological and territorial aspects of agriculture, promoting solidarity farming, and addressing vulnerable areas like oases and mountains. The plan also targets income improvement for millions of rural inhabitants and more efficient management of natural resources, particularly water. The Generation Green Strategy outlines objectives for sustainable agriculture, emphasizing tree planting programs, organic farming, and renewable energy adoption, particularly in irrigation.

LULUCF/Afforestation – Morocco prioritizes halting deforestation and rehabilitating degraded forests over the next three decades. Key interventions include revamping participatory approaches, tailoring development based on forest purposes, modernizing core operations, and restructuring institutions for effective forest management.

Transport - The Urban Public Transport Improvement Program focuses on enhancing urban mobility with sustainable, high-capacity public transportation systems powered by renewable energy sources. Additionally, plans include renewing the taxi fleet and establishing a financial mechanism to support urban transport infrastructure.

2.1.2.8.2 Adaptation

Meteorology - Morocco aims to enhance its meteorological capabilities by expanding its observation network to 1,000 stations and increasing radar coverage from 7 to 12 radars. Additionally, efforts will focus on improving weather and climate prediction models, conducting impact studies on climate change, and upgrading computational capabilities to meet forecasting needs.

Agriculture - The agriculture sector plans to extend irrigation to new areas covering 60,000 hectares and equip an additional 350,000 hectares with irrigation infrastructure. This initiative represents a significant investment aimed at bolstering agricultural productivity and sustainability.

Water - Morocco's water sector strategy involves various initiatives such as constructing six seawater desalination stations, improving drinking water distribution networks, and enhancing water quality through pollution reduction and increased reuse. The plan also targets reducing groundwater overexploitation, increasing rainwater collection, and accelerating projects to protect sensitive ecosystems.

Fisheries and marine - Efforts in the fisheries and aquaculture sector include establishing a coastal observation network, implementing sustainable management measures, establishing marine protected areas, and developing hatcheries for endangered species. These initiatives aim to ensure the long-term sustainability of Morocco's marine resources.

Forestry - The forest sector focuses on watershed development, erosion control measures, and infrastructure improvements in priority basins. Additionally, initiatives aim to enhance mountain area resilience, promote sustainable coastal management, and support the implementation of protected areas legislation.

Sensitive environments - In the sensitive environment sector, emphasis is placed on strengthening resilience in mountain areas, promoting integrated coastal management, and implementing measures to protect fragile ecosystems. These efforts contribute to reducing socio-spatial inequalities and addressing climate change impacts in vulnerable regions.

Land use/town planning - Initiatives in this sector include maintaining urban green spaces, promoting tree planting for carbon sequestration, and using treated wastewater for irrigation. Additionally, measures aim to optimize water resource use, reduce leaks in distribution networks, and promote water reuse in industrial processes and agriculture.

Health - The health sector focuses on improving information dissemination during periods of atmospheric pollution, enhancing health professionals' capacity for awareness campaigns, and developing emergency intervention plans for extreme weather events. Additionally, efforts aim to monitor air quality, reduce disease risks in marine livestock, and address health implications of climate change [8] .

2.1.2.9 Main priorities

In terms of mitigation strategies, decarbonizing the energy sector stands out as a common priority among all MENA countries. Additionally, there is significant emphasis placed on addressing challenges in hard-to-abate industries, transportation, and enhancing energy efficiency within buildings. Notably, many nations underscore the importance of economic diversification as a key aspect of sustainable development, facilitating a shift away from reliance on the oil and gas sector, which historically dominates their economies.

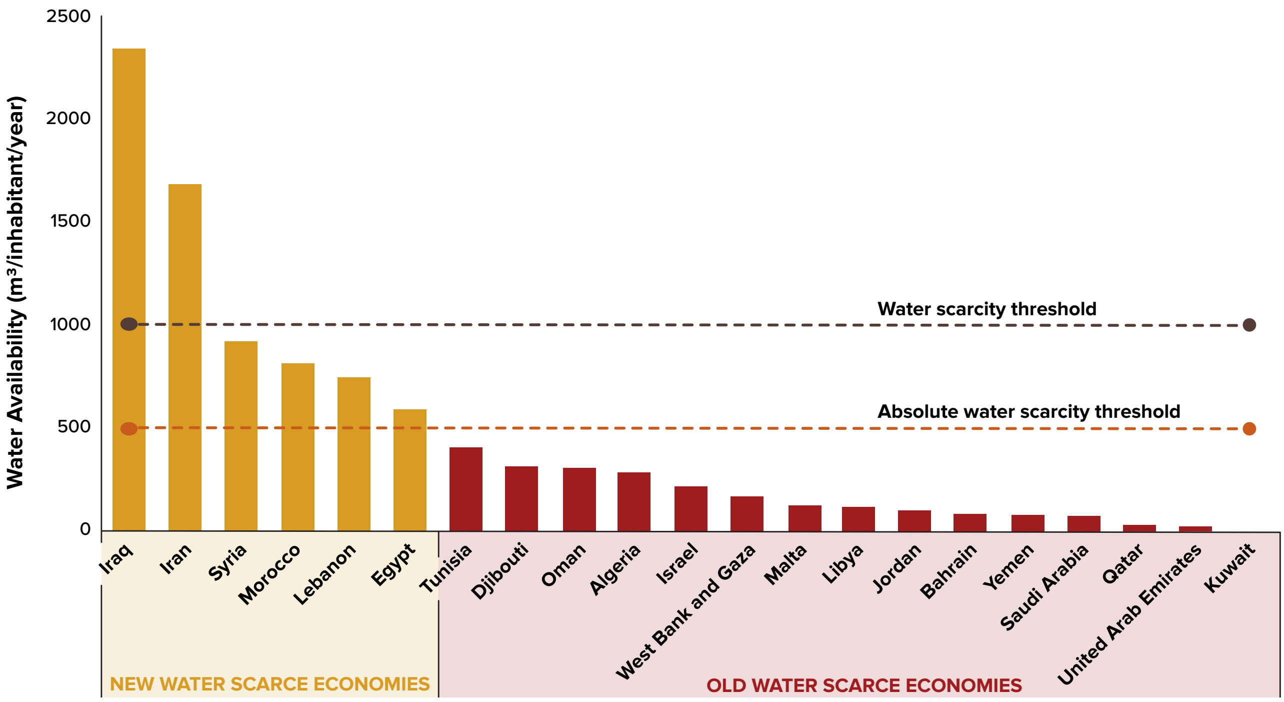
In terms of adaptation, all MENA countries recognize the critical significance of water resources management in the face of climate change. By 2030, the per capita water availability in the MENA region is projected to drop below the UN's absolute water scarcity threshold of 500m^3 per person per year. According to a 2023 World Bank study, the chart indicates that, with the exception of Morocco and Egypt, all MENA countries covered in this report are already below this critical threshold[21].

Given prevalent water scarcity across the region, there is a collective emphasis on improving water resource management practices. This includes promoting the utilization of treated water for agricultural purposes and advancing desalination technology to mitigate the energy consumption associated with water-related activities.

Increasingly frequent heat events in the MENA region are raising concerns as they boost energy demand for cooling while reducing the efficiency of power plants. Over the past four decades (1980-2022), the number of cooling degree-days in the MENA region has grown by 0.6% annually [22]. Higher projected summer temperatures are expected to increase peak electricity demand due to more extensive air conditioning use. If no action is taken, the demand for cooling could significantly drive the region's energy needs, which are anticipated to rise by 50% by 2040. Air conditioning demand alone is expected to surge by 57% by 2050 [23]. Without a decarbonized energy grid, these emissions could create a undesired outcomes, in which they contribute to climate-induced temperature rises, which in turn lead to an even greater need for cooling.

High temperatures not only raise electricity demand but also reduce the efficiency of power generation and distribution, adding further stress to the electricity supply. The performance of natural gas-fired power plants, which generate 74% of the region's electricity, can suffer due to warmer air entering the gas turbine compressor, negatively affecting their efficiency [23].

Figure 1: Renewable water resources per person/year, MENA region [21]



2.1.3 Domestic carbon crediting or trading schemes

2.1.3.1 Saudi Arabia

During MENA Climate Week 2023, Saudi Arabia announced the forthcoming launch of a domestic carbon crediting mechanism, the Greenhouse Gas Crediting and Offsetting Mechanism (GCOM). This domestic mechanism allows the generation of credits and certificates from emission reduction and/or removal projects. It is aligned with the principles of Article 6 of the Paris Agreement and registers projects across all sectors that adhere to GCOM's requirements. Such a mechanism can create a revenue stream for CCS projects, making it more financially feasible and can incentivize investments in these projects [24].

In 2023, Saudi Arabia's Public Investment Fund and Saudi Tadawul Group established the Regional Voluntary Carbon Market Company (RVCMC). In June, the RVCMC said it had successfully auctioned off 2.2 million tons of carbon credits in Nairobi. Oil giant Saudi Aramco, Saudi Electricity Company and Enowa were the main buyers at the auction [25].

2.1.3.2 United Arab Emirates

The Environment Agency-Abu Dhabi has called for proposals to establish a monitoring, reporting, and verification (MRV) system for GHG emissions, laying the groundwork for a potential cap-and-trade scheme.

The preparatory phase will focus on developing the MRV system for GHG emissions in Abu Dhabi. The subsequent compliance phase will involve implementing the MRV system, collecting and analyzing data on facility emissions to estimate the emissions market's size and liquidity. This data will also be used to calculate historical emissions for allocating allowances in the initial phase of the emissions trading system (ETS).

During the compliance phase, a final recommendation will be prepared and submitted to decision-makers regarding the establishment of a cap-and-trade scheme in Abu Dhabi or the UAE. If the data indicates sufficient liquidity and reliable information for allocation without overallocation risks, the recommendation will support proceeding with ETS Phase 1 [26].

In 2023, AirCarbon Exchange announced its exchange and clearing house in Abu Dhabi Global Market. ACX is the first fully regulated carbon and renewable energy certificates exchange, connecting global voluntary market participants to trade ACX contracts for spot carbon credits and renewable energy certificates [27].

2.1.3.3 Oman

The Oman Sustainability Centre (OSC), responsible for overseeing the implementation of the nation's net zero strategy, is actively pursuing the creation of two vital projects: a carbon market to facilitate the trading of carbon credits and a platform dedicated to measuring and reporting GHG emissions. Collaboration is underway with the Ministry of Energy and Minerals to establish carbon certification standards, particularly to assist Omani exporters targeting markets such as the United States, European Union, and Japan [28].

Incentive Alternatives to Carbon Pricing

In the absence of carbon pricing, there are various other incentives that can be utilized to support emissions reduction. For example, under Australia's Safeguard Mechanism, a performance-based incentive sets an annual emissions limit for high-emitting production facilities, with a reduction rate of 4.9% per annum until 2030. Safeguard facilities can offset excess emissions through purchasing carbon credits on the market, or Safeguard Mechanism Credits (SMCs) from other Safeguard facilities. Facilities that outperform the annual baseline automatically generate SMCs. If a facility fails to comply with the obligation to meet its baseline or offset excess emissions, it can face financial penalties [29]. For additional incentives for CCS deployment, please refer to section 3.2.1

2.1.4 Policy commitments to CCS deployment

Countries in the MENA region have made diverse policy commitments regarding CCS in their NDCs and through public announcements. These are outlined in the table below.

Table 2: CCS inclusion in NDCs and policy commitments

COUNTRY	INCLUSION IN NDCS	CCS POLICY
Saudi Arabia	• Underscores the significance of CCS and direct air capture as pivotal technologies in achieving net-zero goals. • References its commitment to adopting CCUS technologies, intending to transform Jubail and Yanbu into global hubs for CCS.	• Has set an ambition to capture, utilize and store 44 Mtpa of CO_2 by 2035. • Actively constructing a CCS hub in Jubail's industrial complex, focused on capturing CO_2 emissions from fossil gas plants, NG plants, petrochemical, steel and H2 with a capacity of 9 Mtpa starting in 2027 [30].
UAE	• Underscores the pivotal role of CCS in the decarbonization of heavy-emitting sectors. • References the formulation of a comprehensive CCS policy package, encompassing various contractors and regulated terms and conditions, along with liability transfer policies.	• Has set out a target of capturing 10 Mtpa of CO_2 by 2030 [31]. • The ambition is to achieve a production target of 7 Mtpa for blue hydrogen by 2050 [13]. • ADNOC has made a final investment decision to invest in one of the largest integrated CCS projects in the MENA region, which will capture 1.5 Mtpa [31].
Qatar	• Mentions CCS as a pivotal technology for reaching net zero and the inclusion of CCS with LNG facilities.	• Aim to store over 11 Mtpa of CO_2 by 2035. • QatarEnergy LNG plans to increase capture target to 5 Mtpa by 2025, driven through the North Field expansion [17].
Oman	• Incorporation of engineered negative emission methods, including the utilization of DAC followed by storage in depleted reservoirs. • Commitment to developing blue hydrogen with CCS. • Plan to develop early demonstrator projects for the expansion of CCUS technology, with a targeted timeline post-2030.	• Plans to reduce 15% of CO_2 abatement through CCUS initiatives by 2050. • A Terms of Reference (TOR) has been signed between MEM and Petroleum Development Oman, Oman Shell, OQGN and Occidental Oman to establish the CCUS and Blue Hydrogen Framework. The objective is to create a conducive regulatory environment that encourages investments in CCUS technologies [32]. • At COP28, it was publicly announced that Petroleum Development Oman was working with the Global CCS Institute on developing a regulatory framework for deploying CCS projects in the country [33].
Bahrain	• Support for CCU and DAC under Technology Innovation and Deployment section.	• Plans to develop investment institutions for low-carbon initiatives. • Initiated CO_2 capture demonstration projects with public funding [34].
Egypt	• CCS is not mentioned.	• Currently exploring the deployment of CCUS hubs to reduce industrial CO_2 emissions. Egypt has substantial onshore storage capacity in saline aquifers, allowing cost-effective CO_2 storage without offshore infrastructure [17]. • Egypt's National Climate Change Strategy (NCCS) 2050 outlines five primary goals and 22 objectives to achieve these goals. One objective is to reduce emissions from fossil fuel use, for which exploring CCUS technologies is a proposed direction [35]. • An amendment to the Investment Law in August 2022 offers a pathway for CCUS projects to fall under a unified approval system, provided they meet specified criteria. The amendment allows the Cabinet of Ministers to grant a single approval for companies undertaking national or strategic projects encompassing the entire project lifecycle, including permits, land allocation, and potential incentives outlined in the Investment Law [36].
Algeria	• CCS is not mentioned.	• There are currently no policy commitments for CCS.
Morocco	• CCS is not mentioned.	• Morocco aims to become a leading Power to X producer, where it plans to use DAC or BECCS to produce synthetic fuels from captured CO_2 [37] .

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In addition to national policy commitments, Saudi Arabia is spearheading the Middle East Green Initiative to foster a united regional effort in addressing climate change. The goal is to attain a substantial 60% reduction in emissions from hydrocarbon production within the region [38]. As a key component of this initiative, a project named the Regional Carbon Capture, Utilization, and Sequestration Hub (Gulf Cooperation Council (GCC) with Iraq) is under development. Although specific details are yet to be unveiled, this endeavor is expected to facilitate a comprehensive strategy for implementing CCS projects throughout the region.

In addition, under the Middle East Green Initiative (MGI), the Circular Carbon Economy Regional Collaboration (CCERC) Initiative was launched in 2021. This serves to be a regional collaborative platform for MENA countries to support each other to achieve their climate ambitions. Since its launch, the CCERC has supported CCUS implementation in the MENA region through different activities, workshops and deliverables that focused on various enablers such as capacity building, policy dialogues, technical knowledge building, joint investment opportunities, and studies [39].

2.1.5 High-level overview of domestic legal and regulatory architecture that may support CCUS activities.

The widespread deployment of CCS in the MENA region faces significant obstacles due to the absence of robust legal and regulatory frameworks. Many of these nations lack specific laws or regulations dedicated to CCS, reflecting an early stage of development in this field. To overcome this regulatory gap, some countries have adopted a strategy of state ownership of CCS facilities through state-owned enterprises. Given the expertise, subsurface knowledge, capability and economic significance of regional state-owned enterprises, it is likely these entities will remain at the forefront of CCS activities. In addition, the sensitivity of subsurface rights in the MENA countries may result in regulatory models that differ from those observed in other regions, where exclusive storage services offered to emitters rather than the license-based storage models common in the US and the UK [40].

Moreover, there is a lack of market-driven incentives such as mechanisms for carbon price discovery, and government-backed support measures like contracts for difference or tax allowances, aimed at stimulating demand for CCS.

Establishing effective laws and regulations is crucial for the successful delivery of CCS facilities and to align with climate mitigation goals. The In Salah CO_2 capture and storage project in Algeria serves as an example of the negative consequences that can arise in the absence of a regulatory framework. The project was suspended due to concerns about seal integrity and potential leakage, issues that could potentially have been addressed with a regulatory regime mandating measurement, monitoring, and verification by the operator [41].

There are some early indications of policies and regulations emerging to facilitate CCS deployment. Egypt, for instance, amended its Investment Law in August 2022 to provide a streamlined approval process for CCUS projects that meet specified criteria. This amendment expands the scope of the Investment Law to cover the entire lifecycle of national or strategic projects, including permits, land allocation, and potential incentives, thereby establishing a regulatory framework to encourage the development and operation of such projects in Egypt [36].

Additionally, Oman is collaborating with the Global CCS Institute to develop regulatory frameworks for commercial-scale CCS projects in the country [42]. The UAE has submitted a long-term net-zero strategy to the UNFCCC, outlining plans for CCS policy and regulatory frameworks, economic incentives, and addressing regulatory issues such as long-term storage liability [43]. Despite these promising signs, these plans are in the preparatory phase and as such, it may require time for the practical implementation of CCS initiatives.

2.2 CO_2 storage potential

The CO_2 storage analysis presented in this report provides a high-level examination to identify this region's storage potential.

The approach categorizes sedimentary basins according to their suitability for CO_2 storage, using the Institute's Basin Suitability Tool. The tool is a criteria-based initial filter to identify those basins with early opportunities and the highest potential for success in the initial characterization phase. The tool's strength is its standardized approach using global datasets. Therefore, using this consistent method, the same analysis can be produced for every global basin, enabling local-to-global comparisons between basins.

Each basin is scored against eight weighted criteria for a total score. The weighting of the criteria is based on the criteria's overall impact on the viability of a basin to host a commercial-scale storage project. For example, a mature, hydrocarbon-producing basin is more important than a basin hosting a pilot CO_2 storage facility. Although the latter indicates a viable storage option in a basin, a hydrocarbon-rich basin will have an extensive, comprehensive subsurface dataset, geological knowledge, and known viable reservoirs and seals. These three factors increase the likely success rate of identifying CO_2 storage resources in further characterization studies. For a description of the criteria, see APPENDIX A – STORAGE ANALYSIS.

Basins fall into four categories with these general characteristics:

1. Category I: High confidence in identifying viable storage resources due to suitable geology, an existing comprehensive dataset, mature hydrocarbon production and existing CO_2 storage projects. CO_2 storage characterization could move rapidly in this basin.
2. Category II: Moderate confidence in identifying viable storage resources due to suitable geology but generally less comprehensive datasets as a minor hydrocarbon producer. CO_2 storage could advance in key areas of the basin where the geology is well known.
3. Category III: Low confidence in identifying viable storage resources. Generally, geological knowledge and data are restricted to a few areas of the basin. Basin CO_2 storage characterization would require extensive data collection and analysis.
4. Uncategorized: the geology is poorly understood due to a lack of hydrocarbon exploration.

The categorization of each basin is presented in the maps below.

There are two major caveats to this basin-scale approach. Firstly, the entire basin is categorized under one value. In reality, a basin's category (and individual criteria scores) is based on the most prospective area within each basin, and other parts of the basin will be unsuitable for storage. Therefore, for this analysis, areas of interest (AOI) are provided to show the optimal areas within each basin clearly. For this analysis, an AOI generally hosts:

- Mature oil and gas fields, with a bias towards giant fields.
- Abundant well data.
- Well intersections with one or more extensive and thick saline formations.
- Avoid populated regions, prohibited zones (marine parks, etc.), and places of social interest.
- Adjacent to emission source clusters (within 100 km).

The second caveat is that this analysis represents a point-in-time, first-pass analysis using a standardized approach. A high-scoring basin may not ever host a CO_2 storage operation due to a myriad of reasons. Conversely, a new study in a low-scoring basin may show highly prospective geology, improving that basin's overall score.

The scope of this analysis precludes detailed site characterization, resource calculations, or de-risking opportunities. However, these three areas of study are the critical next steps and present a much larger body of analysis.

2.2.1 Gulf Coast

The geological storage potential of the Gulf Coast region is well understood in terms of oil and gas production. However, knowledge of geological storage is limited to a few key studies.

Category I basins underlie the entire emissions-rich eastern margin of the Gulf Coast, including Saudi Arabia, Bahrain, Qatar, UAE and Oman (Figure 2). The high potential is due to the multiple, high-quality saline formations (sandstone and carbonates) and numerous depleted and near-depleted fields. The basins are also subsurface data rich as the region is well-explored and has a long hydrocarbon production history. These extend onshore through to the offshore.

The basins in this region have early opportunities in giant depleted oil and gas fields, which could host CCS hubs. The OGCI [44] estimated a theoretical volumetric total of 41.5 Gt storage in depleted gas fields across the region or over 200 years of the region's emissions. These fields are early-mover prospects and could be rapidly developed. The fields are distributed across the Gulf Coast, with concentrations in the UAE.

Much of the eastern margin of the Gulf Coast is also underlain by highly suitable saline formations – including continental sandstones (western and north-central) and carbonates (central and southeastern). The OGCI [44] estimated a theoretical volumetric total of 150 $GtCO_2$ in the Rub'al-Khali Basin. The reservoirs are also vertically stacked (multiple reservoirs, separated by sealing units), providing multiple opportunities for storage and expanding the resource potential from a limited surface footprint. Stacked saline formations also reduce risk due to the multiple options available. The saline formations are sealed by Hith and Arab formations, containing evaporite deposits that seal the world's largest hydrocarbon accumulations.

Away from the eastern Gulf Coast, the options are more limited (Figure 2). There are limited options in northern Saudi Arabia and in the west along the Red Sea. There are only minor hydrocarbon fields, so subsurface data is restricted. Ye et al. [45] stated very few saline formations exist and are of moderate quality. Despite finding limited storage options in the Red Sea Basin, the authors still identified a total theoretical storage resource estimate of over 7 $GtCO_2$ in the Red Sea saline formations and over 18 $GtCO_2$ in northern Saudi Arabia's Widyan Basin (Figure 2).

In addition to sedimentary storage, Oman hosts the Semail ophiolite. This igneous rock is highly suitable for mineral carbonation and hosts Project Hajar [48]. The OGCI predicted a storage estimate of 8.2 $GtCO_2$, although there is very low confidence in that value due to their methodology.

Overall, in the Gulf Coast, the highest opportunities are in the eastern margin's giant depleted fields, onshore Saudi Arabia and UAE. The OGCI [44] analysis is comprehensive for initial characterization but is restricted to the Rub'al-Khali Basin. The Gulf Coast region would benefit from this level of analysis across the entire area, including formation and site-scale analysis with supporting data published.

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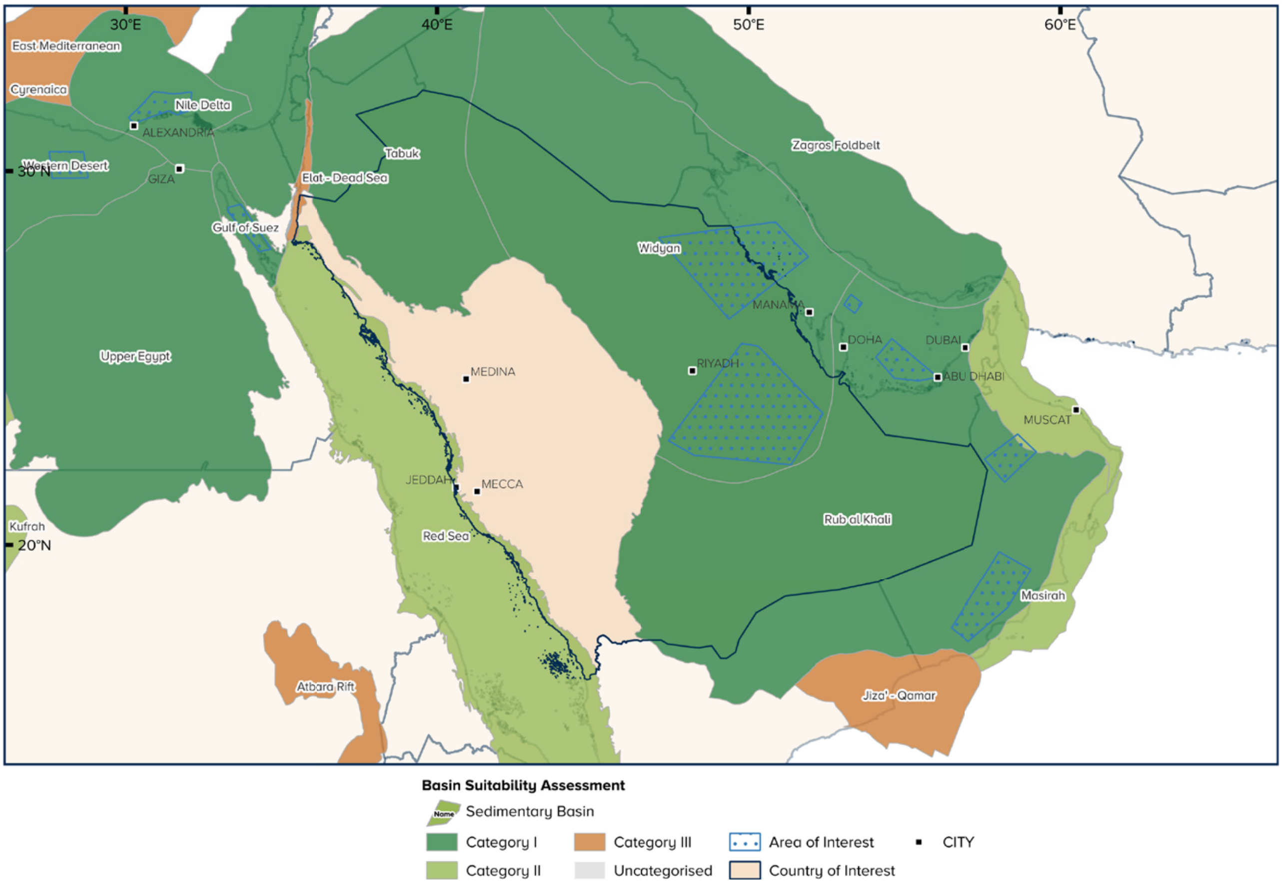
Figure 2: Basin suitability and areas of interest (AOI) for storage in the Gulf Coast region. Note: the Oman ophiolite is not shown but extends across much of the northern extent of Oman. Source: GCCSI.



2.2.2 Egypt

The geological storage potential of Egypt is poorly understood – no comprehensive studies have been published to date.

The basin suitability assessment tool identifies Category I basins across the country (Figure 3). However, the areas of interest are restricted to the northern basins – the Western Desert and Nile Delta along the coast and nearshore regions.

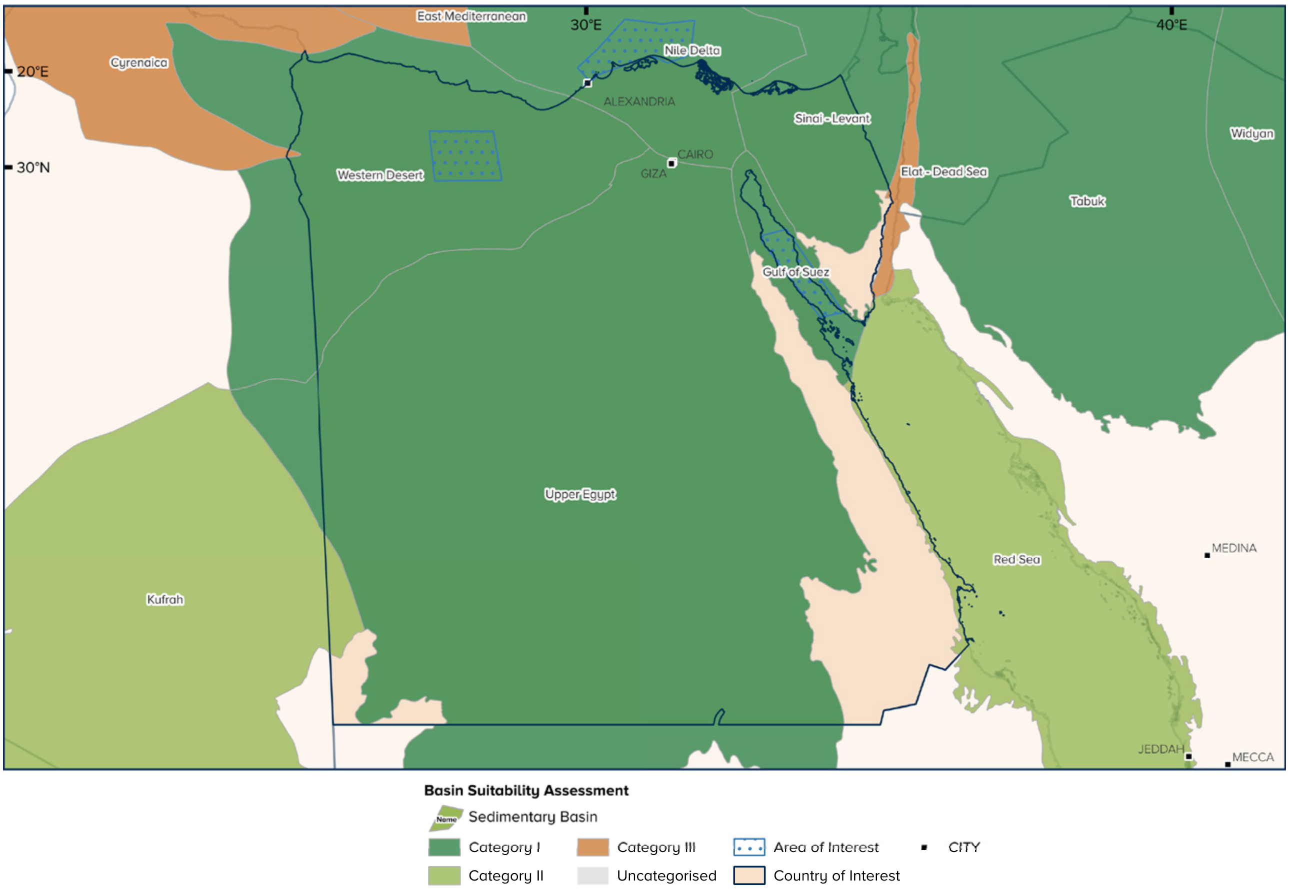
In contrast to the GCC, there are limited opportunities for storage in depleted fields. The primary reason is the majority of large gas discoveries are still early in their production lifecycle and therefore will not be available for decades. Potential near-depleted or abandoned fields that could host early opportunities for smaller CCS deployment are present in the offshore and onshore Nile Delta and the Western Desert.

High-level internal analysis of total theoretical storage resources estimates between 1-2 Gt in hydrocarbon fields of Egypt. More work is required to understand the storage potential of depleted fields in Egypt.

According to well intersections in producing gas and oil fields, several thick and extensive saline formations are available across northern Egypt, from the Western Desert to the Gulf of Suez. Thick regional formations covered by a regional seal and hosting hydrocarbon fields have a higher chance of success as they are proven to host hydrocarbons, indicating that viable reservoirs and seals are present. Specifically, the Nile Delta hosts several stacked saline formations onshore and offshore, with the Western Desert and Gulf of Suez basins comprising two to three potential formations each. Stacked reservoirs offer multiple opportunities for characterization in a single region, potentially leading to greater storage resources. A high-level internal analysis of Egypt's total theoretical storage resources is 150-200 Gt in saline formation.

Further work is required to determine the suitability of Egypt's saline formations for CO_2 storage.

Figure 3: Basin suitability and areas of interest (AOI) for storage in Egypt. Source: GCCSI.



2.2.3 Algeria

Algeria hosted one of the first dedicated CCS facilities – In Salah in the Ahnet-Timimoun Basin in the Algerian Central Sahara, which ceased operations in 2011. Despite the early deployment, Algeria has not progressed CCS in that country since. Only one comprehensive study reviewed the geological storage potential [46].

Basin suitability analysis indicates that the majority of the central and western portions of the country host suitable basins (Figure 4). This analysis matches the findings of [46].

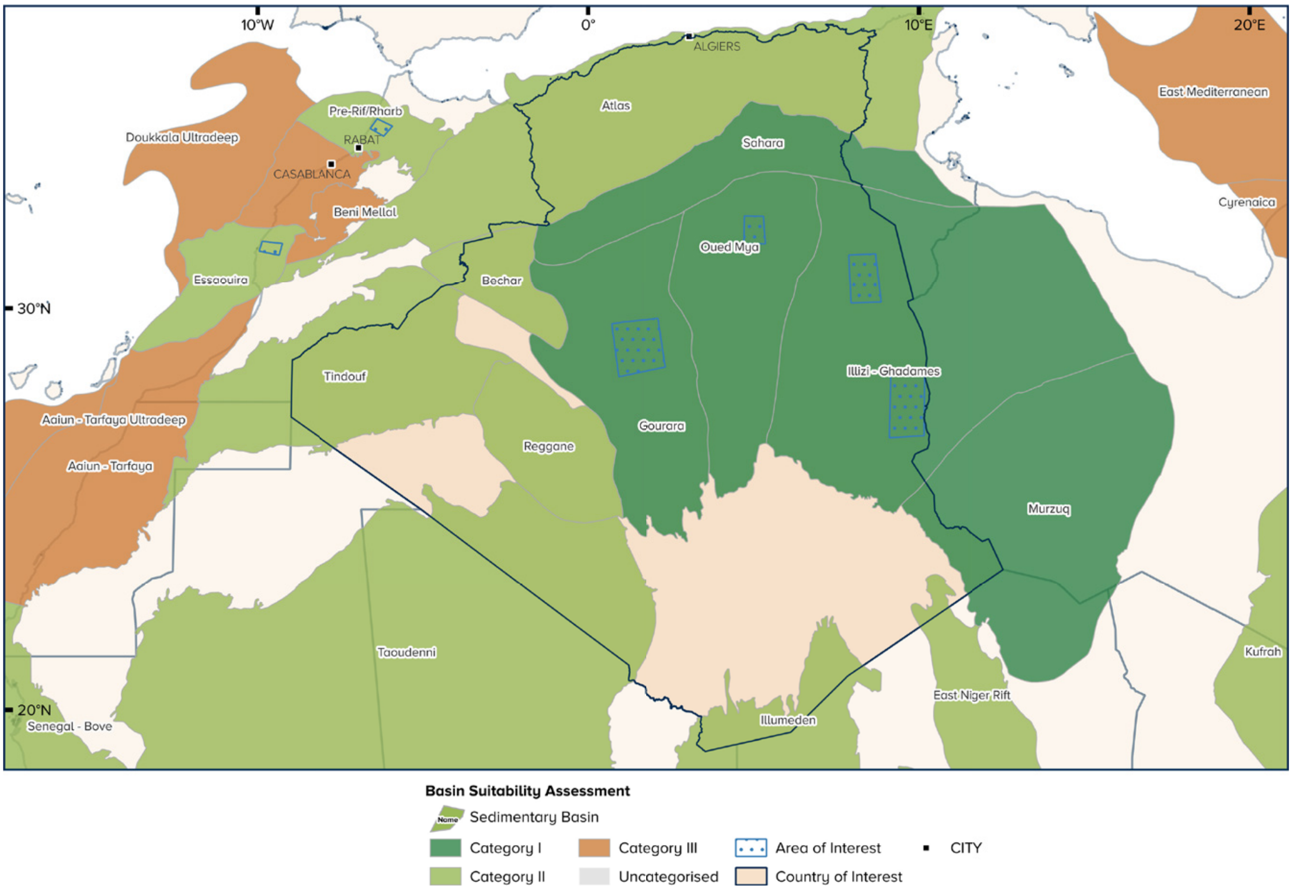
The AOI selected for Algeria is over 500 km from the emission sources along the coastline, where most emissions are located (Figure 4). The geology of northern Algeria indicates limited opportunities for CO_2 storage due to compression tectonics and shallow basins that are unsuitable for storage. The AOI for Algeria are located in hydrocarbon-producing regions with a high density of well data and saline formation intersections.

The current depleted fields of Algeria are unlikely to host a major CCS hub. However, further characterization work is required to understand the full potential of saline formations surrounding the data-rich fields. There are also producing giant fields that could host future CCS hubs. They are primarily located along the central eastern border of the country.

According to well intersections in gas and oil fields, several thick and extensive saline formations are available. In particular, the Argilo-Gréseux Inferieur formations in the northern Illizi-Ghadames Basin. Despite being extensive, the formation was deposited in a fluvial environment, and storage reservoir management could be an issue due to the compartmentalization of reservoirs. The saline formations of the Gourara Basin, according to [46], have better reservoir properties and in-place stacked opportunities. Stacked reservoirs offer multiple opportunities in a single area, reducing the risk of failure and increasing success through increased storage resources at the site. The volumetric theoretical storage resource estimate of those saline formations in the Gourara Basin, according to [46], is between 1-5 $GtCO_2$ depending on the storage efficiency factor used (1-5% of total pore space occupied by CO_2).

Basic characterization work is required to determine the suitability of Algeria's saline formations and hydrocarbon fields for CO_2 storage at a national scale; this includes de-risking storage options and completing resource estimations.

Figure 4: Basin suitability and areas of interest (AOI) for storage in Algeria. Source: GCCSI.



2.2.4 Morocco

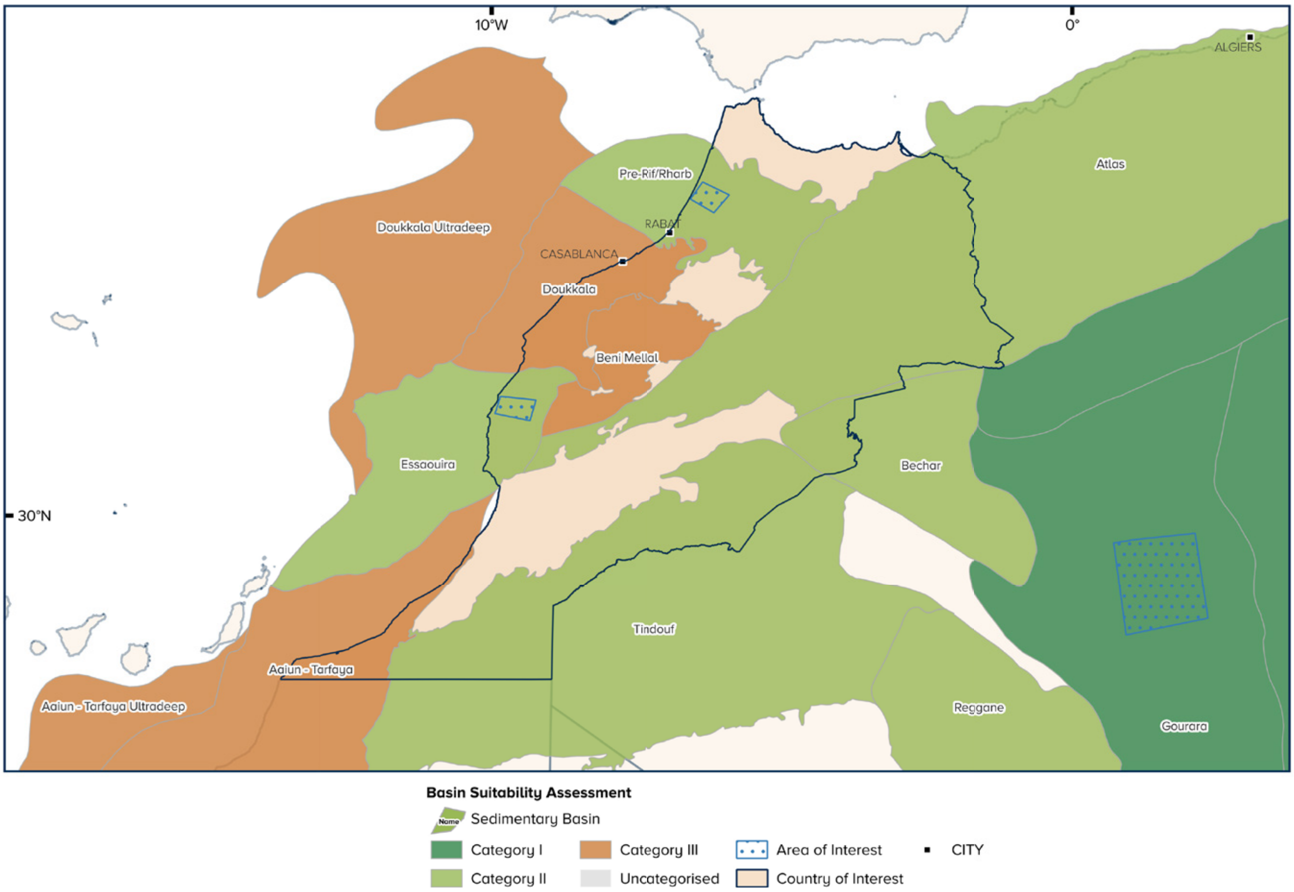
The geological storage potential of Morocco is very limited, with two Category II basins (Figure 5). Within those two basins, the Rharb and Essaouira, the AOI selected in this study, are potentially the only storage areas nationwide. This analysis is supported by one publication in 2015 as part of a Western Mediterranean CCS study [47]. Those authors also identified the same general areas for storage as the AOI for this study (in addition to one offshore). The authors completed a storage resource estimate of structures in those AOIs, estimating a total storage capacity of 4 $MtCO_2$ for the northern AOI and 266 $MtCO_2$ for the southern AOI. There is limited confidence in these values due to their methodology and a lack of published supporting data.

A few hydrocarbon fields in Morocco are generally too small to host a significant CO_2 storage hub. However, further characterization work is required to understand the full potential of saline formations surrounding the data-rich fields.

Basic characterization work is required to determine the suitability of Morocco's saline formations and hydrocarbon fields for CO_2 storage at a national scale; this includes de-risking storage options and completing resource estimations.

The mineral carbonation potential for Morocco has not been considered. The country hosts two ophiolitic units (comparable to those used in Project Hajar, Oman. See [48]) and several mafic and ultramafic units that could be viable storage targets. These are proximal to emission sources. Given the lack of sedimentary storage options, a characterization study is a critical next step.

Figure 5: Basin suitability and areas of interest (AOI) for storage in Morocco. Source: GCCSI.



2.3 Projects Overview

Three commercial CCS facilities in the MENA region operate with a total capture capacity of 3.8 Mtpa. Eleven commercial facilities are also in development, with the projected commissioning years between 2025 and 2027. The CCS facilities are mainly associated with emissions from natural gas processing and blue ammonia production. One CCS facility in the specialty chemical industry in KSA captures CO_2 from a mono ethylene glycol (MEG) plant that will supply CO_2 for various other industries. Several feasibility studies are also ongoing to investigate CCS project opportunities in different industry sectors in UAE, Oman, and Bahrain.

Table 3 gives further details on the projects the Institute has identified in the MENA region.

Table 3: Various CCS projects in the MENA region

COUNTRY	PROJECT NAME	CAPTURE CAPACITY	PLANT PROPONENT	OPERATION YEAR	CATEGORY	STAGE
KSA	Jubail CCS Hub	9 Mtpa	Owned by Aramco, partnering with SLB and Linde	2027	Commercial CCS Facility	Advanced Development
KSA	Uthmaniyah CO_2-EOR	0.8 Mtpa	Aramco	2015	Commercial CCS Facility	Operational
KSA	United Ethylene Glycol CCU	0.5 Mtpa	SABIC	2015	Capture-only Facility- No Storage	Operational
KSA	Gulf Cryo MEG Plant	0.1 Mtpa	Gulf Cryo, in partnership with Petro Rabigh	2024	Capture-only facility- No Storage	Early Development
KSA	KAUST Cryogenic Carbon Capture technology	30 tons per day	KAUST in collaboration with ENOWA, NEOM's Energy & Water company, and the Saudi Electricity Company (SEC)	-	Pilot CCS Facility	Early Development
UAE	Habshan	1.5 Mtpa	ADNOC	2025	Commercial CCS Facility	In Construction
UAE	Shah Gas Processing Plant	2.7 Mtpa	ADNOC	2025	Commercial CCS Facility	Advanced Development
UAE	Al Reyadah	0.8 Mtpa	ADNOC, Masdar, and Emirates Steel Industries	2016	Commercial CCS Facility	Operational
UAE	Hail and Ghasha	1.5 Mtpa	ADNOC; Eni; Wintershall Dea; OMV; LUKOIL	2025	Commercial CCS Facility	Advanced Development
UAE	TA'ZIZ Blue Ammonia	-	Abu Dhabi Chemicals Derivatives Company R.S.C. Ltd (TA'ZIZ), Fertiglobe, GS Energy Corporation, and Mitsui & Co., Ltd	2025	Commercial CCS Facility	Early Development
UAE	SNOC Sharjah	-	Sharjah National Oil Corporation (SNOC) and Sumitomo Corporation	-	Commercial CCS Facility	Early Development
Qatar	Ras Laffan CCS	2.1 Mtpa	QatarEnergy	2019	Commercial CCS Facility	Operational
Qatar	QatarEnergy North Field East	4.3 Mtpa	QatarEnergy	2025	Commercial CCS Facility	In Construction
Qatar	QAFCO Ammonia-7 Blue Ammonia Facility	1.5 Mtpa	Qatar Fertilizer Company and QatarEnergy Renewable Solutions	2026	Commercial CCS Facility	In Construction
Oman	44.01 Project Hajar	500 tpa	44.01 and Aircapture	2024	Pilot CCS Facility	In Construction
Oman	Study CCUS opportunities in Oman	-	Petroleum Development Oman (PDO) and Shell	-	Study technical, regulatory, and fiscal aspects of CCUS	-
Oman	Study implementing a CCS facility for the Sur ammonia-urea fertilizer production plant	-	Omani state-owned energy investment company (OQ) and Oman India Fertilizer Company (Omifco)	-	Study	Early Development
Bahrain	-	-	Mitsui O.S.K. Lines (MOL) and Bapco Energies Collaboration	-	Cross-border carbon dioxide (CO_2) transport and sequestration	Early Development
Bahrain	Feasibility study of KM CDR technology for CCS in one of the aluminum smelting plants of Alba	-	Mitsubishi Heavy Industries (MHI) and Aluminium Bahrain B.S.C. (Alba)	-	Feasibility study – CO_2 Capture	-
Egypt	Idku	1 Mtpa	Shell, Energean	Under Evaluation	Commercial CCS Facility	Early Development
Algeria	In Salah	0.8 Mtpa	A joint venture between Sonatrach, BP, and Statoil	2004	Commercial CCS Facility	Completed

2.3.1 KSA

2.3.1.1 Jubail CCUS hub / Accelerated Carbon Capture and Storage

Aramco is working with SLB and Linde to build one of the world's largest CCUS hubs comprising compression, injection, and onshore pipelines in the Jubail industrial zone in the eastern province of Saudi Arabia. In the first phase, the Jubail CCUS hub will capture up to 9 Mtpa of CO_2 starting in 2027. Aramco's share is 6 Mtpa from the Wasit, Fadhili, and Khursaniyah gas plants, and the remaining 3 Mtpa will be from neighboring industrial emitters [49], [50].

2.3.1.2 Uthmaniyah CO_2-EOR

The project launch was announced in July 2015. It involves capturing 0.8 Mtpa CO_2 from the Hayiwah Natural Gas Liquids (NGL) Recovery Plant and transporting it to the Uthmaniyah oil field via an 85 km pipeline in the Ghawar oil field for enhanced oil recovery [51].

2.3.1.3 United Ethylene Glycol CCU

SABIC built a CCU plant in 2015 at their affiliate United in Jubail. This facility captures up to 0.5 Mtpa of CO_2 annually from ethylene glycol production and utilizes it to produce methanol and urea fertilizers [52].

2.3.1.4 Gulf Cryo M.E.G. Plant

Gulf Cryo, in partnership with Petro Rabigh, will implement a carbon capture and utilization (CCU) facility with the capability to capture 0.1 Mtpa at the MEG plant in Rabigh in western KSA.

Gulf Cryo purifies the captured CO_2 to a high-purity, food-grade level. Some of the CO_2 is utilized internally by Petro Rabigh, while the remainder is supplied to various industries across the KSA, including water desalination, food preservation, agriculture, and concrete [53].

2.3.1.5 KAUST Cryogenic Carbon Capture technology

KAUST has partnered with ENOWA, NEOM's Energy & Water company, and the Saudi Electricity Company (SEC) for a pilot project on Cryogenic Carbon Capture that aims to capture 30 tonnes of CO_2 per day from SEC's Green Duba Integrated Solar Combined Cycle (ISCC) power plant at NEOM. The project completed pre-FEED study in June 2021 [54], [55].

2.3.2 UAE

2.3.2.1 Habshan

Habshan CCS Project has been announced by ADNOC, aiming to capture and store 1.5 Mtpa of CO_2 within geological formations deep underground in ADNOC's Bab Far North field, located approximately 240 km southwest of Abu Dhabi. Petrofac was awarded $615 million for the EPC contract for this project, with the expected commission in 2026.

The project will include carbon capture units at the Habshan gas processing plant, pipeline infrastructure, and a network of wells for CO_2 injection. These include CO_2 mineralization and carbon sequestration in saline formations [56], [57], [58].

2.3.2.2 Shah Gas Processing plant

ADNOC aims to recover 2.7 Mtpa of CO_2 from the Shah gas plant operated by ADNOC Sour Gas for injection into existing fields for EOR.

The Shah gas terminal, located in the Liwa area about 200 km southwest of Abu Dhabi, is expected to integrate the Shah CO_2 recovery project into its upcoming expansion [59], [60]

2.3.2.3 Al Reyadah

The Al Reyadah is a CCS facility in Abu Dhabi with a capture capacity of 0.8 Mtpa. It is currently the only fully commercial CCS facility for the iron and steel industry in the world.

In September 2013, the project was awarded as EPC contract to Dodsal, with Tebodin contracted for detailed engineering design. Construction of the project started in February 2014 and was completed and commissioned in the third quarter of 2016. The project was formally launched in November 2016. Since its launch, the project has been capturing approximately 0.8 Mtpa of CO_2 [61].

2.3.2.4 Hail and Ghasha

The CCS project, through a combination of innovative decarbonization technologies, is integrated into the overall design of the Hail and Ghasha development, which is ADNOC's offshore gas processing facilities. The project is expected to capture 1.5 Mtpa of CO_2 [62].

2.3.2.5 TA'ZIZ Blue Ammonia

Abu Dhabi Chemicals Derivatives Company RSC Ltd (TA'ZIZ) signed a shareholder agreement with Fertiglobe, GS Energy Corporation (GS Energy), and Mitsui & Co., Ltd. (Mitsui), to develop an anticipated 1 Mtpa low-carbon ammonia production facility at the TA'ZIZ Industrial Chemicals Zone. The expected commission year is 2025 [63].

2.3.2.6 Feasibility of a CCS project for Sharjah National Oil Corporation (SNOC)

SNOC has signed a memorandum of understanding (MoU) with Sumitomo Corporation Middle East FZE to conduct a joint feasibility study on carbon capture and storage potential in Sharjah and beyond [64].

2.3.3 Qatar

2.3.3.1 Worley's FEED Project for QatarEnergy LNG

Worley is developing a FEED study, to be completed in 2024, for a CCS facility with a capacity of 4.3 Mtpa from QatarEnergy LNG's LNG train. This study includes compression trains, pipelines, and injection into new wells. The EPC scope of work will be developed upon completion of the study and based on the selected concept by QatarEnergy LNG [65].

2.3.3.2 Qatargas Qatar LNG

This project captures 2.2 Mtpa of CO_2 from a gas processing plant at the north field of Ras Laffan and stores it in the Arab Formation saline formation for EOR in the Dukhan oil field. It is projected to expand to 5 Mtpa by 2025 and 9 Mtpa by 2030 [66].

2.3.3.3 North Field East (NFE)

The NFE project, operated by QatarEnergy on behalf of Qatar Petroleum, is expected to capture and store 2.9 Mtpa of CO_2. It will be integrated with QatarEnergy's Ras Laffan CCS facility [67].

2.3.3.4 Qatar Fertilizer Company (QAFCO) Ammonia-7 Blue Ammonia Facility

QatarEnergy Renewable Solutions & QAFCO plans to build Ammonia-7, the world's largest blue ammonia facility with 1.2 Mtpa of Blue Ammonia capacity, in Mesaieed Industrial City. It is expected to be operational in 2026 [68].

2.3.4 Oman

2.3.4.1 44.01 Project Hajar

44.01, a developer of carbon mineralization technologies, and Oman's Ministry of Energy and Minerals have agreed on a CO_2 in-situ mineralization project in the Hajar mountains in Oman planned for 2024. 44.01 has partnered with Aircapture, a leading DAC technology company, to capture and liquify 500 tonnes of CO_2 annually through a DAC pilot facility. 44.01 will mineralize the captured CO_2 in a peridotite underground formation site in the Al Qabil region, northwestern Oman [69].

2.3.4.2 Study CCUS opportunities in Oman

In collaboration with Petroleum Development Oman (PDO), Oman Shell has been studying CCUS opportunities in Oman. They have signed an MOU to jointly assess the technical, regulatory, and fiscal aspects of CCUS projects in the country [70].

2.3.4.3 Oman India Fertilizer Company (Omifco) Ammonia

The Omani state-owned energy investment company (OQ) has signed an agreement with Omifco to conduct feasibility studies on implementing a carbon capture facility at the Sur ammonia-urea fertilizer production plant operated by Omifco [71].

2.3.5 Bahrain

2.3.5.1 Mitsui O.S.K. Lines (MOL) and Bapco Energies Collaboration

MOL and Bapco Energies have signed an MoU to develop a cross-border CO_2 transport and sequestration project, where MOL provides shipping of liquified CO_2 to an offshore storage site in Bahrain owned and operated by Bapco Energies [72].

2.3.5.2 Mitsubishi Heavy Industries (MHI) and Aluminum Bahrain B.S.C. (Alba)

In March 2022, MHI in the Europe, Middle East, and Africa (MHI-EMEA) and MHI Engineering (MHIENG) signed an MOU with Alba to examine the feasibility of applying KM CDR Process™, CO_2 capture technologies developed by MHI and Kansai Electric Power Co., at an aluminum smelting plant in Bahrain. This collaboration aims to support Bahrain's sustainable development goals and enhance MHI's presence in the Middle East. No updates have been published [73].

2.3.6 Egypt

2.3.6.1 Eni's Carbon Capture and Storage Project

As part of Egypt's effort to contribute to carbon emission reduction, Egypt's Ministry of Petroleum and Resources has employed Eni to build a pilot CCS facility in Meleiha with a capacity of 25,000 to 35,000 tonnes per annum with a prospective expansion to 1.2 Mtpa depending on the successful results of the first phase [74].

2.3.6.2 Idku

Shell and Energean are collaborating on a CCS project at the LNG terminal in Idku. The project aims to capture CO_2 from the terminal and store it in a depleted reservoir in the Abu Qir offshore concession Energean operates [75], [76].

2.3.7 Algeria

2.3.7.1 In Salah

In Salah CCS Project, a joint venture between Sonatrach, BP, and Equinor, is located in Algeria's Krechba field, a gas-producing field. The project commenced in 2004 and finished in 2011, during which approximately 4 million tonnes of CO_2 were stored.

2.4 Key CCS research centers and centers of excellence in the region

In the MENA region, several prominent research centers are actively involved in research and development in CCS technologies.

In KSA, institutions like King Abdullah University of Science and Technology (KAUST) work on the technical aspects of CCS, while King Abdullah Petroleum Studies and Research Centers (KAPSARC) focus on the policy and economic sides of CCS and both have engaged in knowledge dissemination through global forums. Energy and Sustainability initiatives by King Fahd University of Petroleum & Minerals (KFUPM) and King Abdulaziz City of Science and Technology (KACST) further strengthen the region's research landscape in CCS.

In the UAE, Khalifa University's Research and Innovation Center on Carbon and Hydrogen (RICH) and the Masdar Institute drive sustainable technology research. At the same time, United Arab Emirates University (UAEU) focuses on CCS modelling and assessment.

Qatar Carbonates and Carbon Storage Research Centre (QCCSRC), Qatar University, and the Qatar Environment & Energy Research Institute (QEERI), lead collaborative research on characterizing carbonate reservoirs and advancing CCUS technologies.

In Oman, Sultan Qaboos University (SQU) supports CCS-related research and promotes energy transition initiatives.

While direct involvement in CCS research is not evident, the Egyptian Petroleum Research Institute (EPRI) in Egypt conducts significant research on energy and environmental technologies, including CCS, often in collaboration with international partners.

The following summaries provide further details on the areas of interest for each research center and center of excellence in each country.

2.4.1 KSA

2.4.1.1 King Abdullah University of Science and Technology (KAUST)

KAUST is a leading research university located in Thuwal, Saudi Arabia. A number of centers and research groups of the university, including Advanced Membranes and Porous Materials Center, and KAUST Catalysis Center have strong focus on various aspects of CCS such as material development for efficient carbon capture. The Clean Combustion Research Center (CCRC) conducted a successful installation of a cryogenic carbon capture demonstration plant through partnership with national and international industries and universities. The university's Ali I. Al-Naimi Petroleum Engineering Research Center (ANPERC) also conducted several research on geological storage assessments and CO_2 EOR and published their outcomes in journal articles [76], [77].

2.4.1.2 King Abdullah Petroleum Studies and Research Centers (KAPSARC)

KAPSARC have been actively involved in research on CCS technologies. They held a side event at the Global Clean Energy Action Forum (GCEAF) in Pittsburgh in September 2022 to advance knowledge on carbon capture technologies and their widespread applications.

In 2023, they co-hosted the second International Energy Forum (IEF) with the IEF committee and the Clean Energy Ministerial with the aim of building momentum behind carbon CCUS projects [77].

2.4.1.3 King Fahd University of Petroleum & Minerals (KFUPM) and King Abdulaziz City of Science and Technology (KACST)

KACST has established a Technology Innovation Center (TIC) on CCS at KFUPM, aiming to achieve world-class excellence in strategically relevant research areas related to CCS through collaboration with national and international universities and research organizations.

2.4.1.4 Saudi Aramco Research and Development Center

Research & Development Center (R&DC) and the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC-ARC) are Aramco Global Research Center headquarters in Dhahran, where CCS is one of the key research areas [78].

2.4.1.5 Saudi Aramco-Korea Advanced Institute of Science and Technology (KAIST) joint CO_2 Research Center

The joint CO_2 Research Center in South Korea aims to develop new technologies and economically feasible solutions for CCUS [79].

2.4.1.6 SABIC Technology and Innovation Centers

SABIC is a leader in CCU technology, focusing on capturing CO_2 and reusing it for industrial processes rather than storing it underground. SABIC Technology & Innovation Centers support their plans and commitments to reducing carbon emissions and advancing sustainability in their operations.

2.4.2 UAE

2.4.2.1 The Research and Innovation Center on Carbon and Hydrogen (RICH)

RICH is one of the centers of Khalifa University of Science and Technology that is dedicated to research on decarbonization and sustainable fuels. It is the only dedicated center in the country, and the first one in the region, focused on carbon capture, utilization and storage, hydrogen and its derivatives, and sustainable fuels.

2.4.3 Qatar

2.4.3.1 Qatar University

Qatar University is actively involved in research and development efforts related to CCS. They have carbon capture and storage in their research portfolios [80].

2.4.3.2 Qatar Environment & Energy Research Institute (QEERI)

QEERI, part of Hamed Bin Khalifa University (HBKU), focuses on research and development in CCUS technologies. Their research activities include CO_2 mineralization, electroreduction, and absorption, with a focus on developing sustainable and efficient scrubbing systems [81].

2.4.4 Oman

2.4.4.1 Sultan Qaboos University (SQU)

SQU is one of Oman's leading research universities and has been actively involved in supporting CCS-related research.

In 2011, SQU supported a workshop on geological carbon mineralization in mafic and ultramafic rocks. The workshop aimed to raise the profile of research on geological CCS, focusing on the potential for storage in ultramafic and mafic rocks. SQU also hosted the first International Conference on Earth Sciences and Energy Transition (ICESET-23) in February 2023 about energy transition and low-to-zero carbon energy.

2.4.5 Bahrain

Nothing identified.

2.4.6 Egypt

2.4.6.1 Egyptian Petroleum Research Institute (EPRI)

EPRI is a leading research institution in Egypt's petroleum sector. While not exclusively focused on CCS, EPRI researches various energy and environmental technologies aspects, including carbon capture and storage.

2.4.6.2 International collaborations

Egypt has been involved in international collaborations and partnerships related to CCS research and development. For example, Wintershall Dea, a German E&P company, has been involved in major CCS projects in the North Sea and has expressed interest in implementing CCS in Egypt.

3.0 BUSINESS MODELS FOR CCS

CCS business models vary by the type of industry, the specifics of the policy framework, market conditions, site-specific and other regional considerations.

This section describes the business models identified by the institute supporting CCS development globally.

3.1 Business models deployed globally

3.1.1 Emissions Clusters, CCS hubs and Networks deployed globally

Before discussing CCS business models, it is best to understand the evolution of CCS infrastructure and transport methods that are being observed to connect emissions sources to CO_2 storage.

3.1.1.1 Clusters

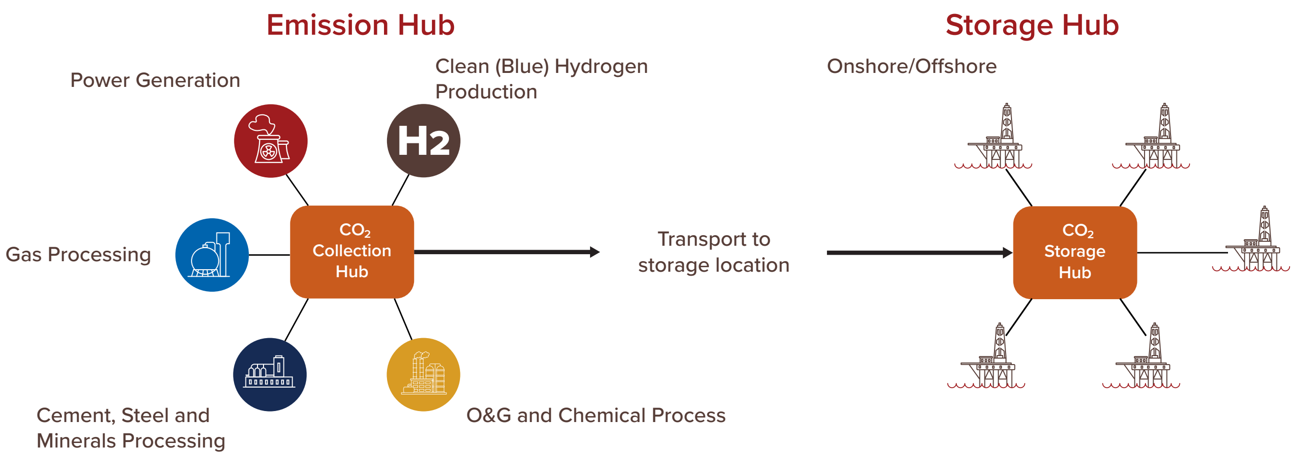
Many emissions-intensive industrial and power generation facilities globally are located in close proximity to each other. These facilities are often closely located for several reasons including supply of energy, common power generation facilities, common feedstocks or common product distributions networks. This close proximity of emission sources, or clusters, creates the potential for CCS projects to share infrastructure and resources, reducing costs for the transport of CO_2 to the desired storage location.

Comparable to emission clusters, there can also be storage clusters where the captured CO_2 is distributed among multiple CO_2 injection and storage sites within a defined geographical area. This can leverage synergies and economies of scale to enhance the efficiency, safety, and cost-effectiveness of CO_2 storage operations.

3.1.1.2 Hubs

CCS hubs act as centralized facilities for capturing and transporting CO_2 from multiple sources within the emission clusters or storing the CO_2 in storage clusters. CCS deployment is more economically viable through economies of scale.

Figure 6: CCS emissions and storage hubs



3.1.1.3 Transport methods

Pipelines and specialized vessels, such as ships, tankers, or barges, are used to transport CO_2 from capture facilities to storage sites or utilization facilities. This infrastructure is designed to safely transport CO_2 in either gaseous or liquid form, depending on the transportation method and distance.

3.1.1.3.1 Pipelines

Pipeline transport is a commonly used method for transporting captured CO_2 from industrial facilities to storage sites or utilization facilities within CCS networks.

CO_2 is transported as a gas or in dense-phase or supercritical conditions. Gas-phase pipelines are often considered for transport over shorter distances, whereas dense-phase or supercritical transport is typically considered for longer distances as it is more cost effective.

3.1.1.3.2 Shipping

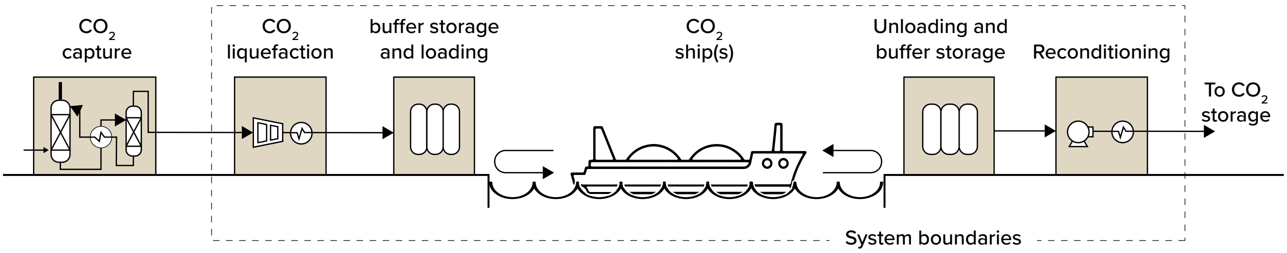
Ship transport involves transporting captured CO_2 via ships or vessels from capture facilities to offshore storage sites or utilization facilities.

CO_2 is liquefied under pressure and low temperatures, typically below -56.6 °C at atmospheric pressure, resulting in a dense liquid. The liquefied CO_2 is then stored in insulated tanks or cylinders to maintain its low temperature and prevent evaporation during transport.

There are loading and unloading facilities and buffer storage at ports to ensure continuous flow and safe transfer of CO_2 between ships and onshore infrastructure.

After unloading CO_2 from a ship and before subsequent transport to storage facilities, the CO_2 often undergoes conditioning to the CO_2 up to the required transport conditions (pressure and temperature) for ongoing transport to the storage location.

Figure 7: Main components for shipping logistics for CCS [82]



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3.1.1.3.3 Trucks and rail

Both rail and trucks are alternative means for transporting captured CO_2 from capture facilities to CCS networks. They are equipped with cryogenic systems, similar to shipping, and are suitable for remote locations inaccessible by pipelines or ships.

Truck transport is more suitable for short-distance transport and smaller scale. In contrast, rail transport is generally more cost-effective over longer distances, larger volumes, and when the infrastructure is available.

3.1.1.3.4 Barges

Barges for CO_2 transport are specialized vessels designed to carry CO_2 in liquid form along inland waterways, rivers, or coastal routes. These barges provide an alternative mode of transportation for CO_2, particularly for shorter distances or when access to ports or infrastructure is limited.

Barges are similar to ships but can operate in shallower waters and may utilize existing inland waterway infrastructure such as docks, jetties, or river terminals for loading and unloading. In contrast, ships require access to deepwater ports with suitable infrastructure for loading and unloading operations.

Barges may also be equipped with onboard pumping and storage systems for self-loading and unloading operations.

3.1.1.4 Networks

CCS networks connect CCS hubs, capture facilities, transport infrastructure, and storage sites across vast geographical areas. Networks can continue to grow as new emissions sources or storage locations are added, enabling access to CCS infrastructure for emissions sources that may otherwise be more challenging technically or cost-prohibitive.

Areas with a high density of CO_2 emitting industries and nearby suitable storage are considered excellent sites for hub and cluster developments supporting CCS network growth.

3.1.1.5 Strategic benefit of CCS networks

CCS networks are essential to secure the future of emissions-intensive industries and encourage future investments. This will be especially important as CO_2 emission reduction strategies become increasingly more necessary as a result of mechanisms such as climate protection policies or the introduction of a price on carbon emissions.

CCS networks offer several advantages for network participants, compared with vertically integrated CCS projects.

3.1.1.5.1 Cost reductions through shared infrastructure

Industrial clusters create an opportunity to reduce cost by allowing multiple parties to share the often-expensive infrastructure for CCS. Larger capacity infrastructure also delivers economies of scale reducing the unit cost of CO_2 transport and storage.

Shared infrastructure with sufficient proven storage capacity can also allow facilities to separate their investment decisions from the development of the network. This is important to maximize the deployment and exploitation of CCS and its benefits at scale.

3.1.1.5.2 Enabling the use of CCS for smaller emissions sources

Many industrial facilities, including refineries, gas processing, hydrogen and fertilizer production and other chemicals generate CO_2 either through the conversion of feedstocks to products, or the use of high-temperature heat. The volume of emissions from these industrial processes can be small and d. Dveloping vertically integrated CCS projects at this small scale often comes at a considerable cost. However, when these facilities are situated in close proximity to one another, the emissions from numerous small sources can be aggregated. This aggregation enables the utilization of shared infrastructure for CO_2 compression, transportation, and storage, thereby accessing economies of scale that would otherwise be unattainable for individual emission sources.

It is important to understand that the number of smaller industrial facilities worldwide contribute significant cumulative CO_2 emissions that are unavoidable as long as the facilities continue to operate. The development of large-scale and strategically located infrastructure will enable the lower cost and full-scale deployment of CCS in industrial clusters, reducing cost and risk to smaller emissions sources.

3.1.1.5.3 Enabling CCS in regions without access to suitable local storage

Networks offer an avenue for reducing emissions for industries in regions that do not have locally available storage. Regions with limited to no storage can leverage CCS networks to provide lower-cost transport either by pipeline or shipping to access storage in regions with abundant storage.

3.1.1.5.4 Enabling low-carbon industrial production

In numerous sectors like steel, cement, and chemicals, CCS stands out as a key technology capable of severing the tie between production and greenhouse gas emissions. Companies linking their facilities to CCS hubs and clusters stand to shield themselves and their investments from potential increases in carbon prices. Moreover, regions leveraging CCS to establish themselves as 'low carbon industrial zones' stand poised to gain significant advantages in attracting and retaining investments.

In an increasingly carbon-constrained world, the development of emissions clusters will attract investment, increase industry engagement, and encourage the development of further projects in each location, thereby accelerating the development of a broader CCS industry.

3.1.1.5.5 Reduced exposure to resource constraints

Resource constraints can manifest in many different ways for CCS. The supply of raw materials for the CCS equipment, equipment manufacturing and the workforce resources required to build and operate the infrastructure necessary to transport and store CO_2 may all be constrained given the potential demand for CCS in meeting global net zero commitments.

CCS networks may require additional resources during development and construction due to their scale versus a single vertically integrated CCS project; however, the workforce resources and equipment on a total number basis will be less when compared to the number of vertically integrated CCS projects that would be required to transport and store CO_2 from each of the emissions sources that could contribute to a CCS network.

This benefit will also extend to land availability and managing congestion in existing or new pipeline or shipping corridors, which could be limited for some existing emissions clusters located in densely populated areas or a highly congested shipping region.

3.1.1.5.6 Enhanced operational flexibility

The interconnected nature of CCS networks, while complex, can also provide more flexible and continuous CO_2 capture and storage operation. This flexibility allows CCS networks to adapt to fluctuations in CO_2 emissions from different sources, seasonal variations in energy demand, and unforeseen disruptions in CO_2 transport or storage infrastructure.

3.1.2 Business models

CCS business models fall into two main categories, either 'full chain' or 'part chain'. These categories describe the extent of the integration of the CCS value chain within the project.

Within the two business model categories, project ownership can either be public or state-owned, private or a public-private partnership (PPP). Financing of the project can either be through government sources such as grants, tax credits, loan support or through private financing such as revenue from direct use of CO_2 or low-carbon products and voluntary carbon markets.

A part chain model may be privately owned with government subsidies or fully government-owned and subsidized. A full chain model may also be either state-owned or privately-owned or consisting of a PPP depending on the approach a government has taken to establish a sustainable market for CCS.

Both full-chain and partial-chain models can be developed through a joint-venture structure, where ownership is shared by the participating stakeholders. A joint venture structure is usually the ownership model behind CCS hubs and clusters and applies to private as well as public stakeholders. In a joint venture, financial risk is usually shared between the participating stakeholders. Alignment and agreement are also required on where and how other risks are best tackled and essential to guarantee alignment among the various steps of the CCS chain.

3.1.2.1 Full chain model

Traditionally, most CCS projects followed a full chain model, in which a single organization owns and operates each element of the CCS chain. This model is typically applied to first of a kind projects or where suitable storage is nearby an emitter with no adjacent emitters to form a larger CCS hub.

This model benefits from a high degree of integration, which lessens the coordination risks associated with project development and operation of the entire value chain. However, it suffers from the requirement for a large upfront investment and liabilities that a single party must take on. This model is often limited to organizations with the necessary technical and operational expertise in all areas of the value chain.

Uthmaniyah EOR in KSA and Yanchang and Sinopec's Shengli Power Plant CCS Projects in China are examples of CCS projects that used this business model.

Shell's Quest project in Alberta, Canada is an example of a successfully completed operational project that implemented the full CCS value chain [83], [84]. In the Quest project, CCS was used to reduce the environmental impact of extracting bitumen and heavy crude oil in the Athabasca Oil Sands Project (AOSP). Started in January 2011 and since completed, CO_2 was captured from Shell's Scotford Upgrader. The Scotford Upgrader and the Albian Sands mining and extraction projects from the Muskeg and Jackpine mines make up the AOSP. The captured CO_2 was transported via an 80 km pipeline for storage 2 km below ground level in the Basal Cambrian Sands formation. CO_2 was injected into two injection wells, with three additional deep monitoring wells. Quest captured and stored over 6 $MtCO_2$.

3.1.2.2 Part chain model

There is a shift towards part chain business models focusing on specific aspects of the CCS value chain, such as capture, transport, or dedicated storage particularly as CCS hubs and networks grow in scale and complexity.

For effective implementation of a part chain model, maintaining segment expertise within the sector is crucial. While several private sector entities will need to collaborate and invest, they do so within their areas of expertise. Emitters or capture technology developers will need to construct capture plants to recover CO_2 for transport. Transportation and storage developers will need to construct and develop pipelines/trucking/rail/port facilities, compression facilities, marine vessels, and injection wells. This can be accomplished either independently or through joint ventures. This business model presents opportunities for cost reduction through economies of scale and project risk reduction as each element of the value chain represents a smaller, separate project.

3.1.2.2.1 Capture as a service (CaaS)

Instead of investing and managing their own carbon capture facility, the emitter industries can outsource this activity to CaaS providers, typically a technology developer, for a fee. The expertise rests with the CaaS provider who would design, build, and operate the CO_2 capture system allowing the emitter to continue with their primary activity. This model also presents opportunity for cost reduction through economies of scale if multiple sources of CO_2 can be aggregated for capture, although these sources would typically need to be in very close proximity to each other.

Aker Carbon Capture is an example of the CaaS business model. Aker's amine solvent based technology can be applied at industrial to existing point source emission sources or to new ones [85].

3.1.2.2.2 Transport as a service (TaaS)

TaaS providers offer transportation services for captured CO_2 from emission sources to storage or utilization sites through different means of transport, including pipeline, shipping, rail, and barges.

TaaS providers could operate one component of a transport network or integrate different transport modes depending on their expertise. For example, CO_2 captured from industrial facilities may be transported by trucks or pipelines to a nearby shipping port, which is transferred onto ships for long-distance transport to offshore storage sites.

TaaS providers can implement monitoring systems to monitor the movement of CO_2 during transportation from source to destination.

3.1.2.2.3 Storage as a service (StaaS)

StaaS providers deliver storage services of CO_2 following receipt of CO_2 from TaaS providers. The storage solutions that StaaS providers offer include site selection, injection well design, reservoir management, safety and environmental compliance, liability management, and insurance.

The Alberta Carbon Trunk Line (ACTL) in Canada is a significant infrastructure project utilizing TaaS and StaaS. It involves constructing and operating a large-scale CO_2 pipeline network to transport captured CO_2 from industrial facilities in Alberta to suitable storage sites for permanent geological storage. Wolf Carbon Solutions is the transportation service provider of this project and is responsible for the design, construction, and operation of the CO_2 pipeline network. Enhance Energy acts as the storage service provider and is responsible for design, construction, and operation of the storage infrastructure, including injection wells, monitoring equipment, and surface facilities.

The Abu Dhabi CCS Project, also known as the Emirates Steel CCS Project, is a notable example of utilizing TaaS and StaaS. The project captures CO_2 emissions from the Emirates Steel Industries (ESI) complex, located in the UAE, and transports the captured CO_2 to an offshore oil field for EOR and permanent storage by ADNOC. This aspect of the project can be considered as employing StaaS, where ADNOC provides storage services to the Abu Dhabi CCS Project under a contractual agreement. ADNOC manages the injection wells, monitoring systems, and other infrastructure required for safe and secure CO_2 storage.

3.1.2.3 Impact of carbon pricing

Full value chain - Due to the high level of integration and typically single-party ownership, the cost of full-chain CCS projects is substantial. For these projects to be economically viable, carbon prices would need to be high enough to provide sufficient financial incentives for deployment.

Part value chain - An increase in carbon prices can incentivize emitters to pay for CCS services. This can lead to the aggregation of multiple emitter sources into clusters/hubs, resulting in cost efficiencies and economies of scale as a result of shared infrastructure and expert operators for each respective part of the value chain."

3.2 Deployed financial models globally

3.2.1 Policy tools utilized in other regions to increase demand for CCS

3.2.1.1 Carbon pricing - EU Emission Trading Scheme

The EU ETS is the world's first and largest carbon market system, with jurisdiction over all 27 EU member states and Norway, Iceland, and Liechtenstein. The EU requires mandatory participation for companies that operate in energy-intensive sectors and especially those that generate GHG emissions as part of their operations. The ETS cap and trade works by setting a cap on the total GHGs that can be emitted by all the entities under its jurisdiction. The cap is dynamically reduced over time to reduce annual emissions over time. Entities can trade allowances within the ETS that are allocated through auction sales or allocated for free. The free allocation of allowances is meant to address high risk sectors and those sectors that are deemed to be at risk for carbon leakage [86].

The EU's legal framework states that the EU ETS considers captured CO_2 that has been geologically stored (or safely stored) to be "not emitted". Environmental Impact Assessments and storage permits are required, in addition to stringent requirements for site selection according to the CCS Directive [87].

3.2.1.2 Carbon import tariff

In October 2023, the EU implemented a Carbon Border Adjustment Mechanism (CBAM), imposing a carbon price on emissions generated during the production of carbon-intensive goods entering the EU. Upon full implementation, CBAM is expected to cover over 50% of emissions in the sectors included in the ETS. The CBAM is the EU's regulation to prevent carbon leakage. The CBAM helps the EU level the playing field between local manufacturing and imports, by allocating a price to carbon-intensive goods imported into the EU. The price or tariff is also aimed to incentivize lower carbon operations outside of the EU. Addressing carbon leakage will enhance the motivation to invest in clean technologies, including CCS [88].

While the full effects of the CBAM are yet to be seen, its implementation could induce several negative implications. For instance, developing countries, which often have lower financial capacity to invest in cleaner technologies, may be disproportionately affected by CBAM. This could exacerbate economic disparities and hinder their development efforts. Additionally, the introduction of CBAM might lead to retaliatory trade measures, creating barriers to free trade and escalating trade tensions."

A particular study has identified that CBAM may have limited effects on carbon leakage. For example, a significant portion of EU imports consists of intermediate inputs for production, which are less sensitive to price changes than final consumption goods [89]. Moreover, while CBAM improves the competitiveness of domestic carbon-intensive products by raising import prices, it does not address the increased fossil fuel demand in non-abating countries. This occurs because fuel prices may drop due to reduced demand in abating regions such as the EU, leading to higher fossil fuel consumption.

3.2.1.3 Sustainable taxonomies

The EU taxonomy stands as a pivotal element within the European Union's sustainable finance framework, serving as a crucial tool for enhancing market transparency. Its primary role is to guide investments towards economic activities that are vital for the transition, aligning with the objectives of the European Green Deal. This classification system sets out criteria for economic activities that contribute to a net-zero trajectory by 2050, encompassing environmental goals beyond climate considerations. Notably, CCS is identified as a sustainable activity within this framework, presenting an incentive for directing finance sector investment into these activities as part of green portfolios [90].

It's important to recognize that this is just one example of a sustainable finance framework, and there are numerous standards and taxonomies globally. As more of these schemes emerge, achieving a certain level of standardization will be crucial. Discrepancies where a company's economic activity is considered green by one taxonomy but not by another can create confusion and challenges for issuers trying to use green bonds across different markets.

3.2.1.4 Green procurement

Implementing policies that stimulate the demand for low-carbon or net-zero products serves as a powerful incentive for the widespread adoption of CCS. This is

particularly crucial for hard-to-abate industries such as the steel sector. A notable example is the Buy Clean California Act, a policy mandating state agencies to consider the embodied carbon emissions of construction materials, including steel, in public contract awards. The Act sets maximum acceptable global warming potential (GWP) values for various construction materials, encouraging the utilization of lower-carbon alternatives. This, in turn, can motivate steel producers to invest in CCS technologies, reducing the carbon intensity of production to comply with procurement standards [91].

3.2.1.5 International coalitions and agreements

Participation in international coalitions can serve as an effective strategy for countries to expedite the adoption of CCS technologies. The Carbon Management Challenge (CMC) serves as a global collaborative initiative and a unified call to action, bringing nations together to accelerate the implementation of carbon capture, removal, utilization, and storage technologies. The governments involved in the CMC may take various actions including advocating for supportive policies, showcasing progress in CCUS demonstrations, establishing national targets for carbon capture deployment and removal projects by 2030, and contributing resources/funding to carbon management initiatives. Being part of a coalition not only holds countries accountable for their actions but establishes a centralized platform for nations to exchange knowledge and expertise [92].

The London Protocol of 2009 is an international agreement designed to oversee the disposal of waste materials in marine environments. Through amendments in 2009, the protocol extended its scope to permit the cross-border transport of CO_2 for injection into subsea beds for storage purposes. By ratifying this amendment protocol, countries can gain access to opportunities for storage beyond their borders. This is especially crucial for nations lacking domestic storage resources [93].

3.2.2 Government funding with examples

In this subsection, we'll examine various government funding models from other regions that might offer potential opportunities for adoption in the MENA region.

3.2.2.1 Innovation Fund

The Innovation Fund aims to bolster the commercial implementation of innovative decarbonization technologies, including CO_2 capture and storage. It is sourced from revenues generated by the EU ETS. The Innovation Fund may amount to €40 billion for 2020-2030, depending on the EU ETS prices, awarded to projects in the European Economic Area (EEA) through calls for proposals or competitive tenders.

From 2020 to 2022, the European Commission launched three calls for proposals for large-scale projects and three others for small-scale projects. More projects with a CCS component applied with each new call. Some 20 CCS-related projects have been funded so far, which includes the Kairos@C project that aims to create the first and largest cross-border CCS value chain in the Port of Antwerp, Belgium, with the potential to avoid the emission of 14 Mt of CO_2 over its first 10 years of operation, starting from Q3 2025 [94].

3.2.2.2 UK CCS business models

The Industrial Carbon Capture Model is designed to incentivize existing industrial facilities to invest in carbon capture to decarbonize. This model will provide a contract of up to 15 years between emitter and counterparty that will pay emitters per ton of captured CO_2 to cover the additional costs of deploying carbon capture and offer risk protections in specific circumstances (e.g. transport and storage outages) if obligations are met. Contracts will be funded from the exchequer via the IDHRS scheme [95].

A second business model in development is the Power BECCS Business model, which aims to propel large-scale Bioenergy with Carbon Capture and Storage (BECCS). The model features a dual payment system, combining a 'Contract for Difference for electricity' with a 'Contract for Difference for carbon' ('CfDe + CfDc'). This innovative approach recognizes the significance of both negative emissions and low-carbon electricity

3.2.2.3 45Q tax credit

The US Federal Internal Revenue Code (Federal tax code section 45Q) provides a specific federal tax credit for geologically sequestered CO_2 [96], [97]. After the enactment of the Inflation Reduction Act in August 2022, the carbon capture provisions that provide incentives for CCS projects were significantly enhanced [98], [99].

The new law broadens the ability to transfer the 45Q tax credit. During the 12-year period mentioned above, the entity that originally receives the 45Q tax credit can transfer the entire amount or any portion of it to another tax-paying entity in exchange for a cash payment. Furthermore, this cash payment will not be taxed.

Other details are summarized below and in Table 4.

a. The new law provides entities an option to receive the 45Q tax credit as a direct payment. This is like the entity receiving a tax credit for overpaid taxes. The durations are different depending on the type of entity.
    i. Five years for for-profit entities after initiation of the project.
    ii. 12 years for tax-exempt entities.
b. More types of facilities can now qualify since the IRA reduced the annual CO_2 capture threshold to:
    i. 1,000 tons for DAC facilities.
    ii. 12,500 tons for industrial facilities.
    iii. 18,750 tons for power generation facilities (at least 75% of the CO_2 must be from a unit that generates electricity and has capture equipment installed).
c. Extends the deadline to begin construction by 1 January, 2033.
d. Continues allowing tax credits to be claimed for 12 years from the time the equipment begins service.

Table 4: Increases to the 45Q tax credit from the Inflation Reduction Act of 2022

ACTIVITY		BEFORE IRA (USD/TON OF CO_2)	AFTER IRA (USD/TON OF CO_2)
Geological storage of CO_2	From power generation and industrial facilities	50	85
	From direct air capture (DAC) facilities	50	180
Utilization of CO_2	From power generation and industrial facilities	35	60
	From DAC facilities	35	130

3.2.2.4 Powering the Regions Fund

The Powering the Regions Fund, an initiative by the Australian Government, is dedicated to bolstering regional areas as they transition towards a clean energy future. With a substantial total funding of AUD1.9 billion, this initiative aims to support regions in achieving net zero emissions. A key objective of the fund is to foster the development of new clean energy industries. CCS may qualify for funding under this program [100].

3.2.3 Private funding with examples

3.2.3.1 Aramis Netherlands

The Aramis project is a joint venture involving four key partners: Total Energies, Shell, EBN, and Gasunie. It aims to facilitate the transport of CO_2 for permanent storage, captured by industrial processes. The transport network is designed to link an onshore CO_2 collection hub at the Maasvlakte in the Port of Rotterdam to depleted gas fields located 200 km north. Industries facing challenges in reducing emissions, both within the Netherlands and neighboring countries, have expressed interest in utilizing this infrastructure.

A final investment decision is anticipated in 2024, with operational commencement as early as 2027. Initial operations are projected to involve transporting at least 5 Mtpa of CO_2 to storage locations beneath the North Sea. The overall estimated storage capacity is set to exceed 400 Mt [101].

3.2.3.2 Oman project (Shell blue hydrogen project)

Oman Shell is in the process of developing a project that intends to provide blue hydrogen and ammonia to both local and international markets. The project involves capturing and storing the associated CO_2 produced during the manufacturing process. In collaboration with Petroleum Development Oman, a suitable CO_2 storage facility for the project has been identified. Duqm has been chosen by Shell as the site for the manufacturing facilities, where the production of blue hydrogen and ammonia will take place. This location presents opportunities to supply low-carbon hydrogen to various local industries [102].

3.2.3.3 Quest Shell CCS project

The Quest CCS Project, developed by Shell as part of the Athabasca Oil Sands Project (AOSP) in Alberta, Canada, is the world's first commercial-scale CCS project for an oil sands operation. The Quest CCS project captures, transports and stores underground more than 1 Mt of CO_2 from Shell's Scotford Upgrader near Fort Saskatchewan, which was opened in 2003 to process bitumen from Muskeg River and Jackpine oil sands mines of the AOSP, a joint venture of Shell (60%), Chevron (20%) and Marathon Oil (20%). As the designer, builder and the operator of the Quest CCS, Shell started construction on the CAD1.35 billion project in September 2012. A funding agreement was signed between Shell and the Canadian and Alberta Governments to secure CAD865 million for the Quest CCS project in June 2011. The CCS project began operations in November 2015. It cuts down one-third of direct CO_2 emissions from the Scotford Upgrader [103].

4.0 OPPORTUNITIES FOR DEVELOPMENT OF CCS HUBS IN MENA

4.1 Current CCS hub potential

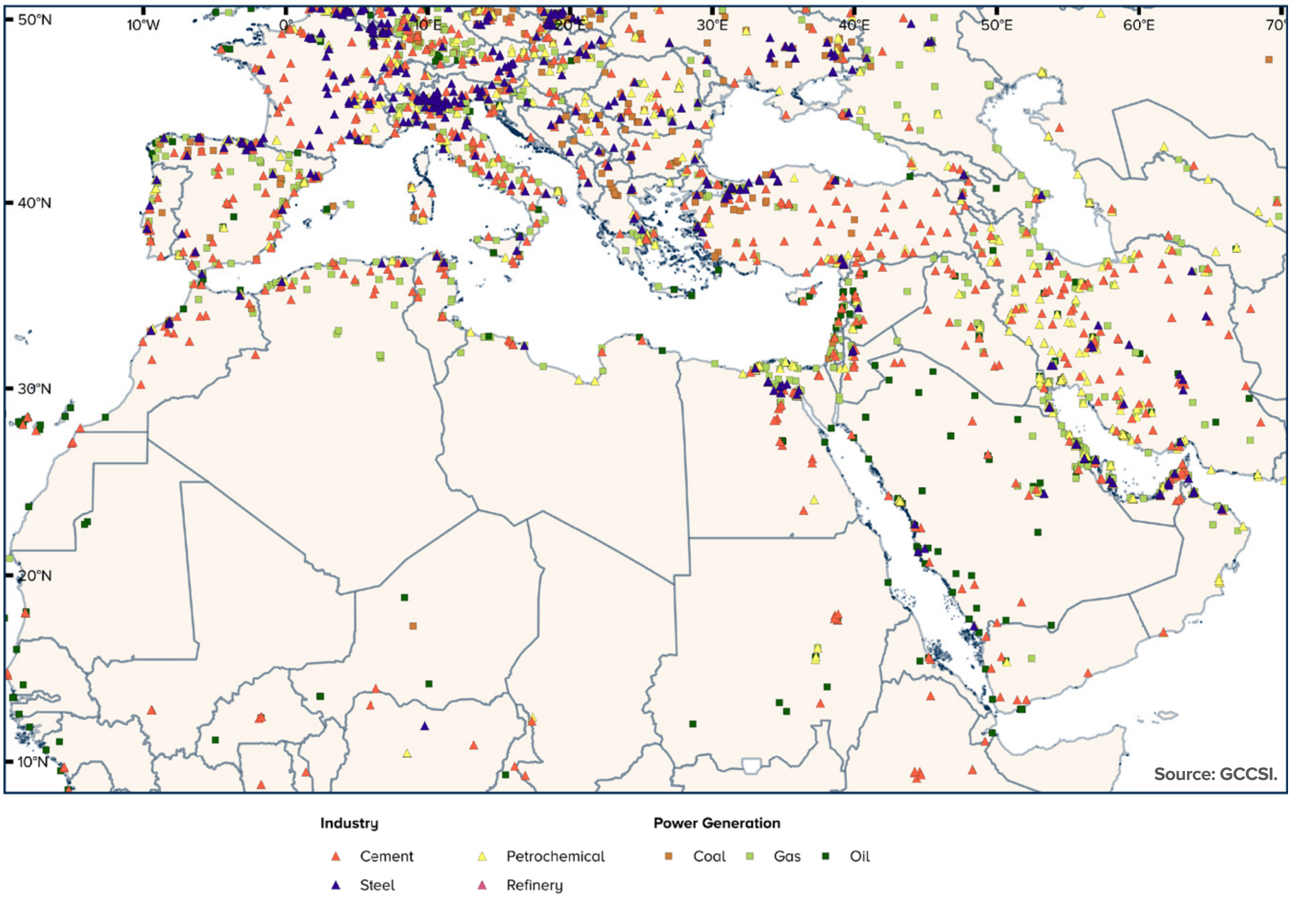
4.1.1 Overall emissions in MENA

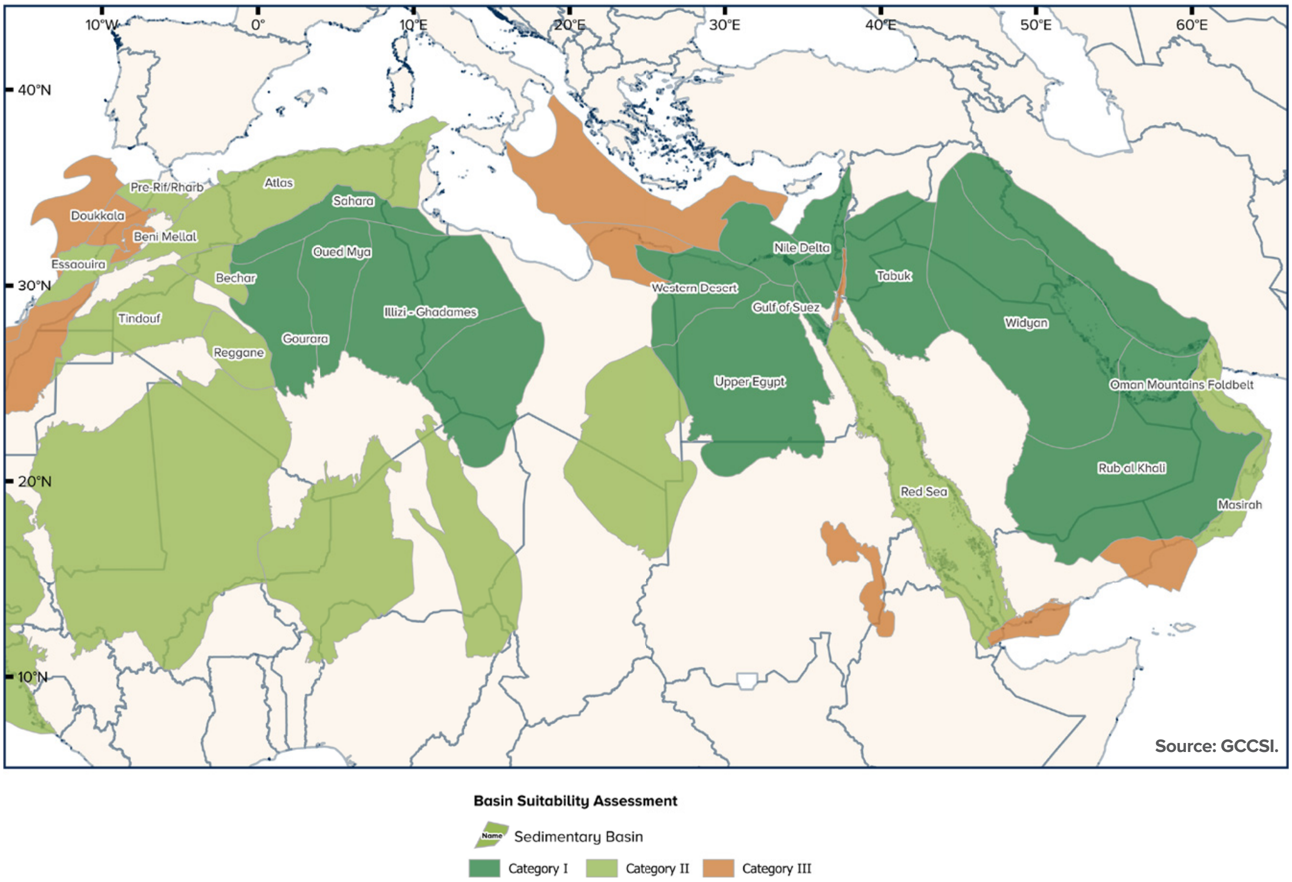
The MENA region consists of many emissions clusters in the countries investigated in this study that could support the development of CCS hubs and networks in the region.

The availability of sufficient storage is critical to any CCS project. The MENA region has excellent prospective storage opportunities, particularly the availability of onshore storage that often supports lower cost transport and storage costs for CCS hubs and networks.

For details on emissions data, see APPENDIX B – EMISSION DATA

Figure 8: MENA region emission sources (upper map) and storage basin suitability (lower map). Source: GCCSI.



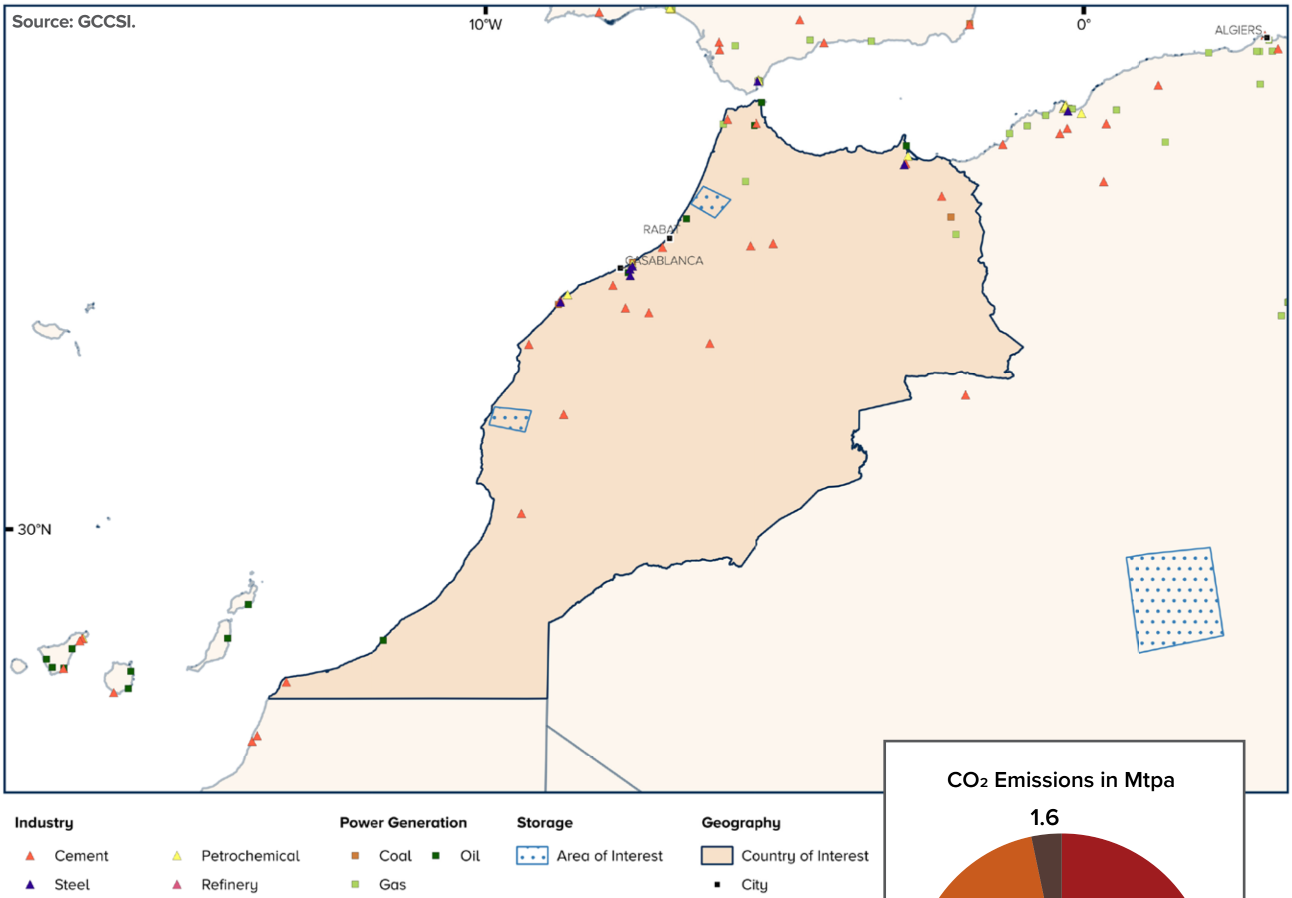


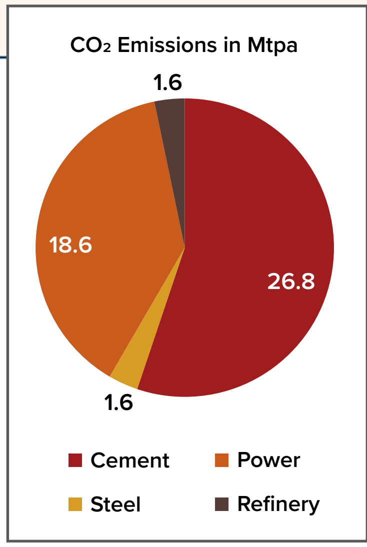
Generally, CCS hubs leverage lower the cost of capture sources to commence initial stages of CCS hub and network development. Fertilizer production, hydrogen generation and natural gas processing/LNG provide good starting emissions sources for CCS hub and network development, providing initial transport and storage infrastructure for more costly and harder to abate emissions sources such as cement, steel chemicals and refining, where CCS could be the most cost-effective or is the only technological solution for emissions reduction [104]. Figure 8 provides an overview of emissions sources and storage basin suitability across the wider MENA region. The subsequent maps in the following section focus on specific countries.

4.1.2 CCS hub current potential by country

The CCS hub current potential by country analysis presented herein is a high-level examination to identify this region's CCS hub potential. The assessment is qualitative in nature to assist in identifying potential early-mover CCS hubs that could support existing and new industry growth. The emissions sources identified in this study may not be exhaustive and are subject to the data available in the databases used to source plant types and locations.

4.1.2.1 Morocco





See Appendix B for details.

Emissions sources and storage areas of interest

- The majority of Morocco's identified emissions come from a significant cement and power generation industry.
- Phosphate fertilizer production likely accounts for similar if not greater emissions that could be easy to capture, however it is difficult to estimate and excluded from this analysis.
- Emissions are concentrated to along the coastline to the west, including phosphate mining and processing not visible on the map, near to onshore prospective storage
- Onshore prospective storage is located to the north and west of Morocco's coastline.

CCS hub and network potential

- Onshore prospective storage locations are an advantage allowing for less costly transport and injection infrastructure.
- Several small emissions clusters situated between (approx. 200km from) the storage location could facilitate CCS hub and network development to storage locations north and south of the cluster locations.
- Isolated facilities to the north and east of the upper most prospective storage location and facilities east and south of the lower most prospective storage location could consider CCS on a case-by-case basis.

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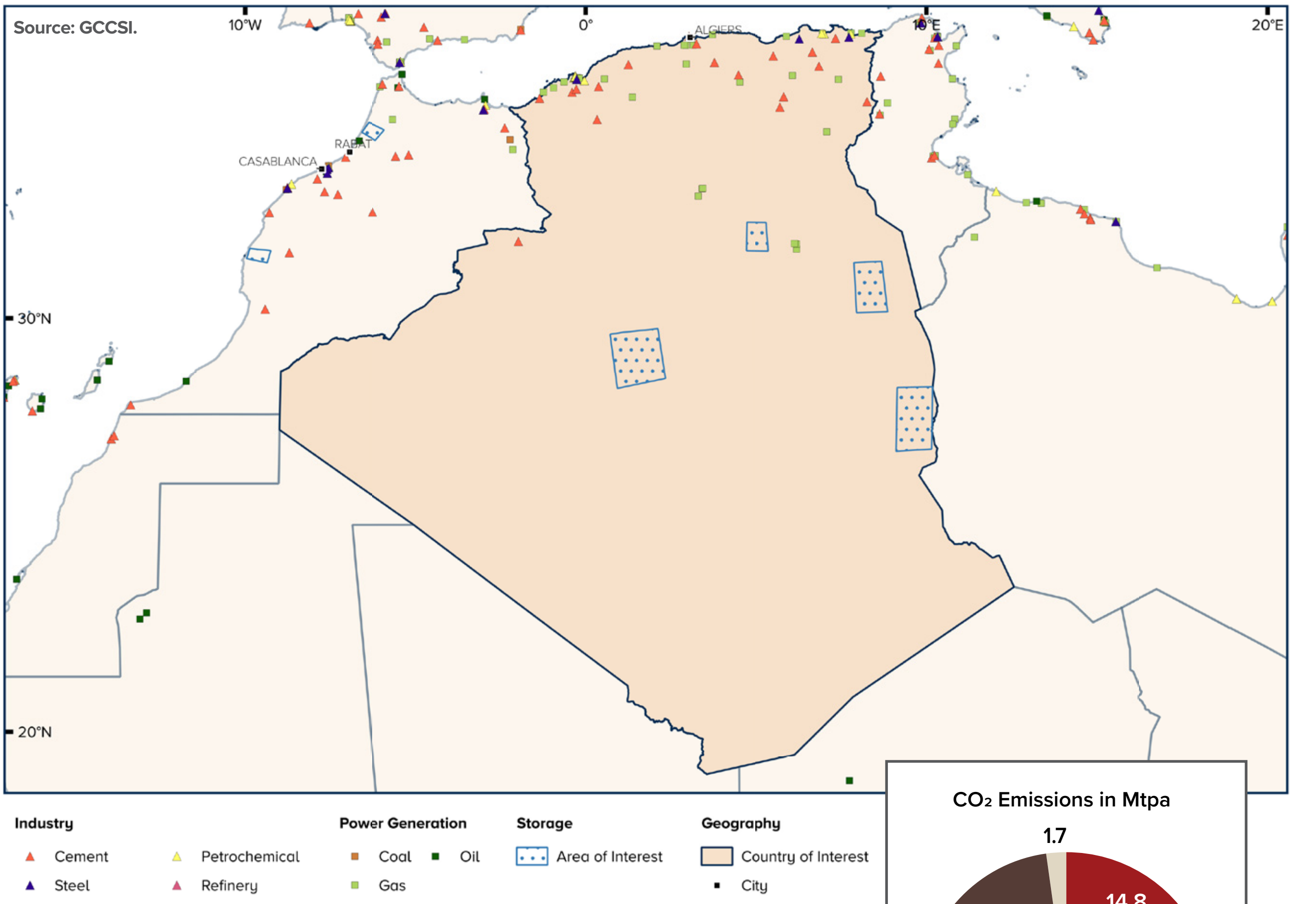
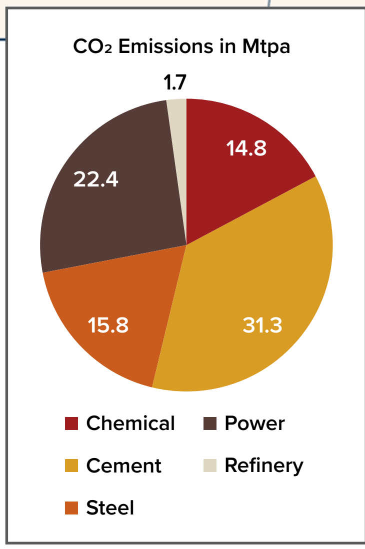
4.1.2.2 Algeria





See Appendix B for details.

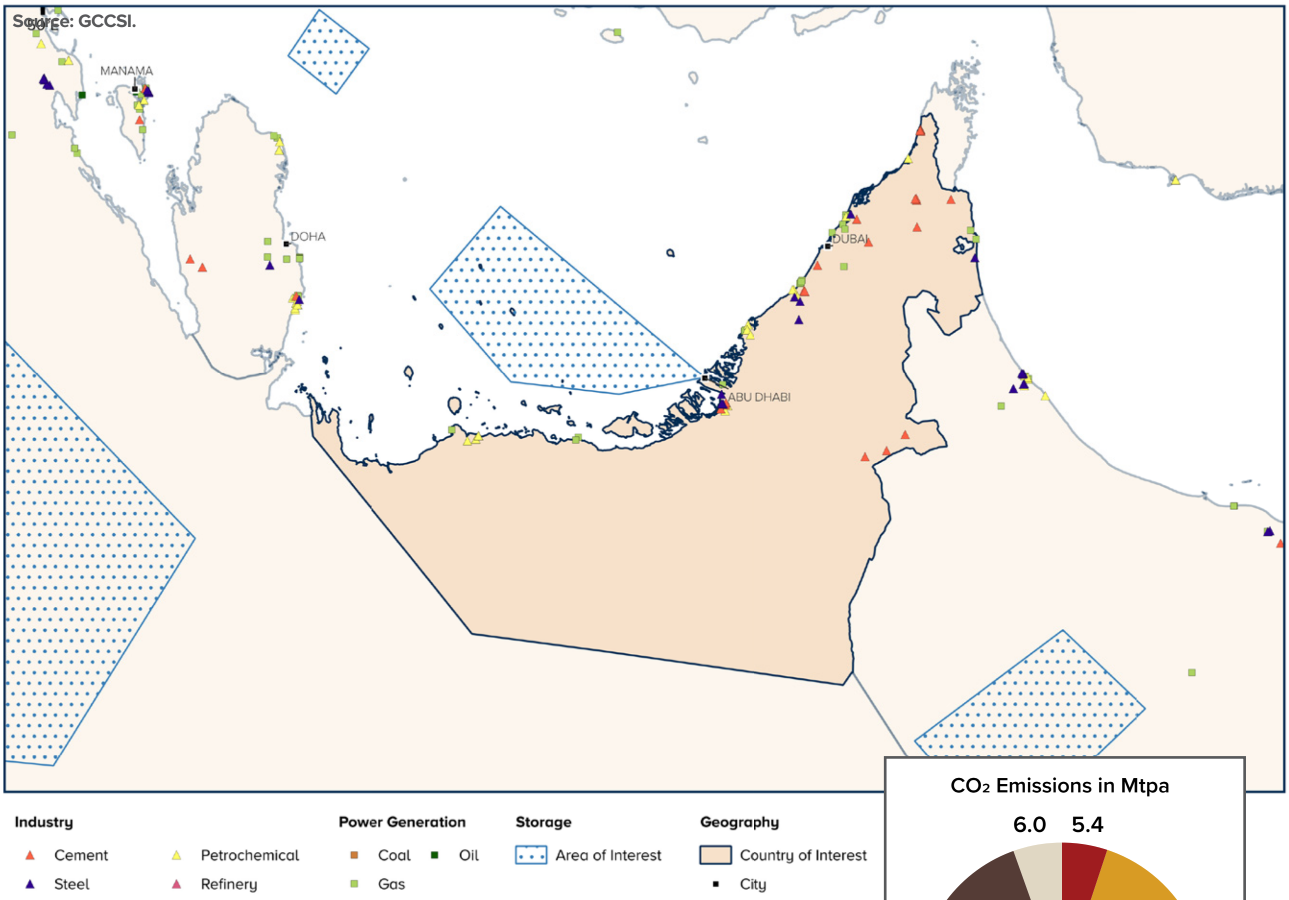
Emissions sources and storage areas of interest

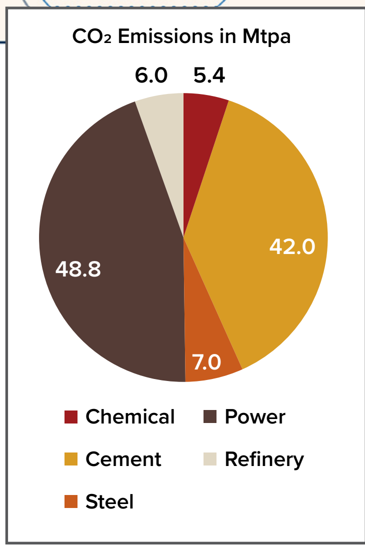
- The majority of Algeria's identified emissions come from significant cement, steel and coal fired power generation industries.
- Emissions are concentrated along the coastline to the north.
- A significant chemical industry cluster is located to the west of Algeria. A small number of other chemical facilities and refineries operate adjacent to larger cement and coal fired power industries to the north and northeast along the coastline.
- Onshore prospective storage locations are located to the south and east of Egypt

CCS hub and network potential

- Onshore prospective storage locations are an advantage allowing for less costly transport and injection infrastructure; however, the distances are significant for Algeria and CCS networks will be necessary to reduce transport costs
- Several emissions clusters along the northern coastline could act as CCS hubs enabling CCS network development to transport CO_2 the large distances needed to reach suitable storage locations to the south. Emissions sources further south from the coastline could leverage these larger emissions clusters for CCS network development providing transport of their CO_2.
- Smaller emissions clusters, such as that east of the central prospective storage location, would leverage either smaller independent CCS hub development or could leverage CCS network transport if pipeline routes from northern CCS networks were in close proximity.
- Individual facilities to the east and central Algeria would need to consider CCS on a case-by-case basis if main trunklines routes were in close proximity.

4.1.2.3 UAE





See Appendix B for details.

Emissions sources and storage areas of interest

- The majority of UAE's identified emissions come from cement and gas fired power generation with scattered clusters of chemical (fertilizer and petrochemicals) and refining facilities.
- The majority of emissions are concentrated along the coastline to the northeast the UAE near prospective storage. A small number of individual plants and smaller emissions clusters lie on the coast of central UAE.
- Prospective storage is located offshore to the north of central UAE.

CCS hub and network potential

- Offshore prospective storage may make transport more costly for the UAE compared to other countries in the region, however the distance offshore is not significant and dense clusters of emitters may assist in lowering transport and storage costs.
- Large clusters of emitters including cement, power and steel are located to the east of the UAE that could serve to develop CCS hubs and a CCS network to the offshore storage location.
- Smaller emissions clusters or individual facilities on the coast within a short distance may consider individual CCS projects given their proximity to other emissions sources.
- Isolated cement plants to the east of the UAE near the border of Oman could be supported by initial network growth to the north supporting reduced transport costs to reach the offshore prospective storage.

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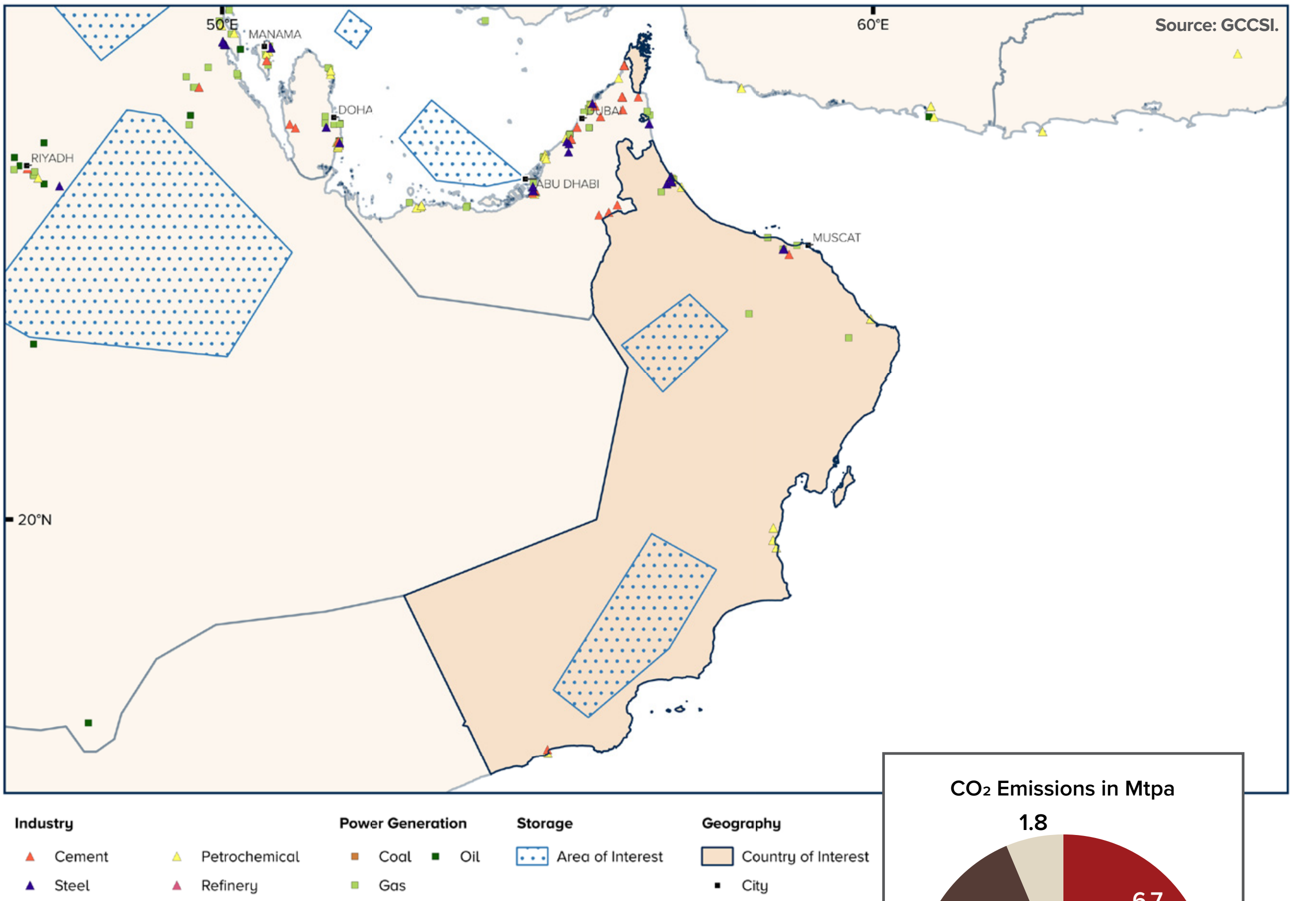
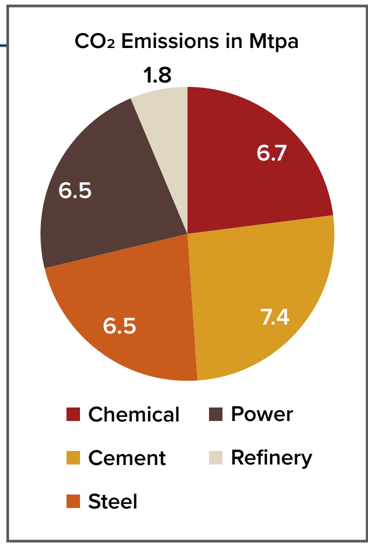
4.1.2.4 Oman





See Appendix B for details.

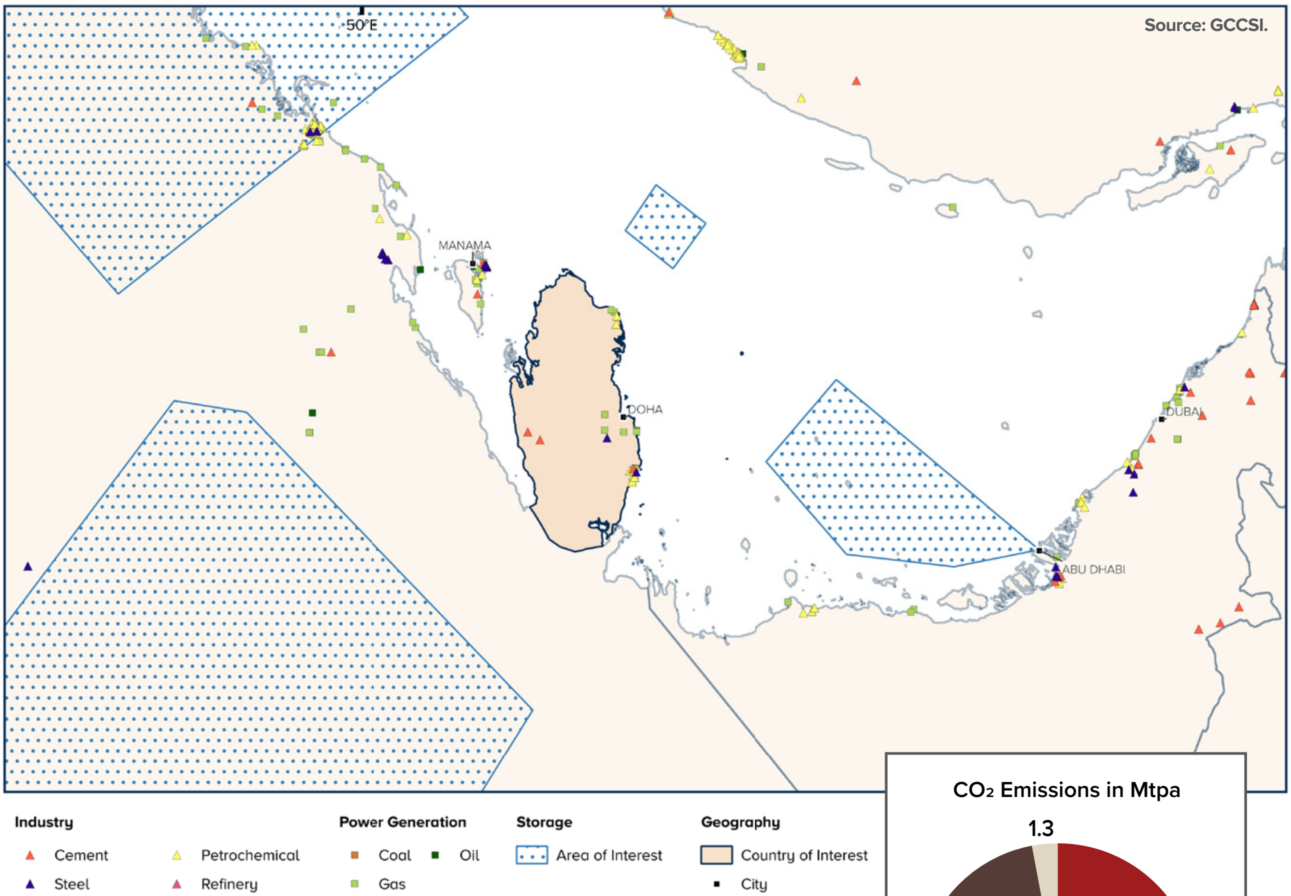
Emissions sources and storage areas of interest

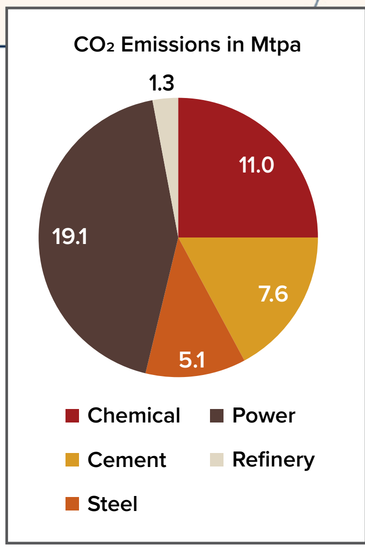
- The majority of Oman's identified emissions come from cement, steel, chemicals (fertilizer and petrochemicals) and coal fired power.
- coal fired power generation industry with scattered steel, cement and refining facilities.
- The majority of emissions are concentrated along the coastline to the north of Oman adjacent to the UAE. A small number of cement and chemical plants are located to the south.
- Onshore prospective storage locations are located to the south and central west regions of Oman.

CCS hub and network potential

- Onshore prospective storage locations are an advantage allowing for less costly transport and injection infrastructure.
- Emissions clusters to the northwest and central north of Oman could facilitate early CCS network development to storage in the central west region of Oman.
- Single facilities to the east could leverage CCS network infrastructure, however this would need to be on a facility-by-facility basis.
- The small emissions cluster to the south of Oman could serve to develop a small CCS hub with storage in the southern prospective storage location.

4.1.2.5 Qatar





See Appendix B for details.

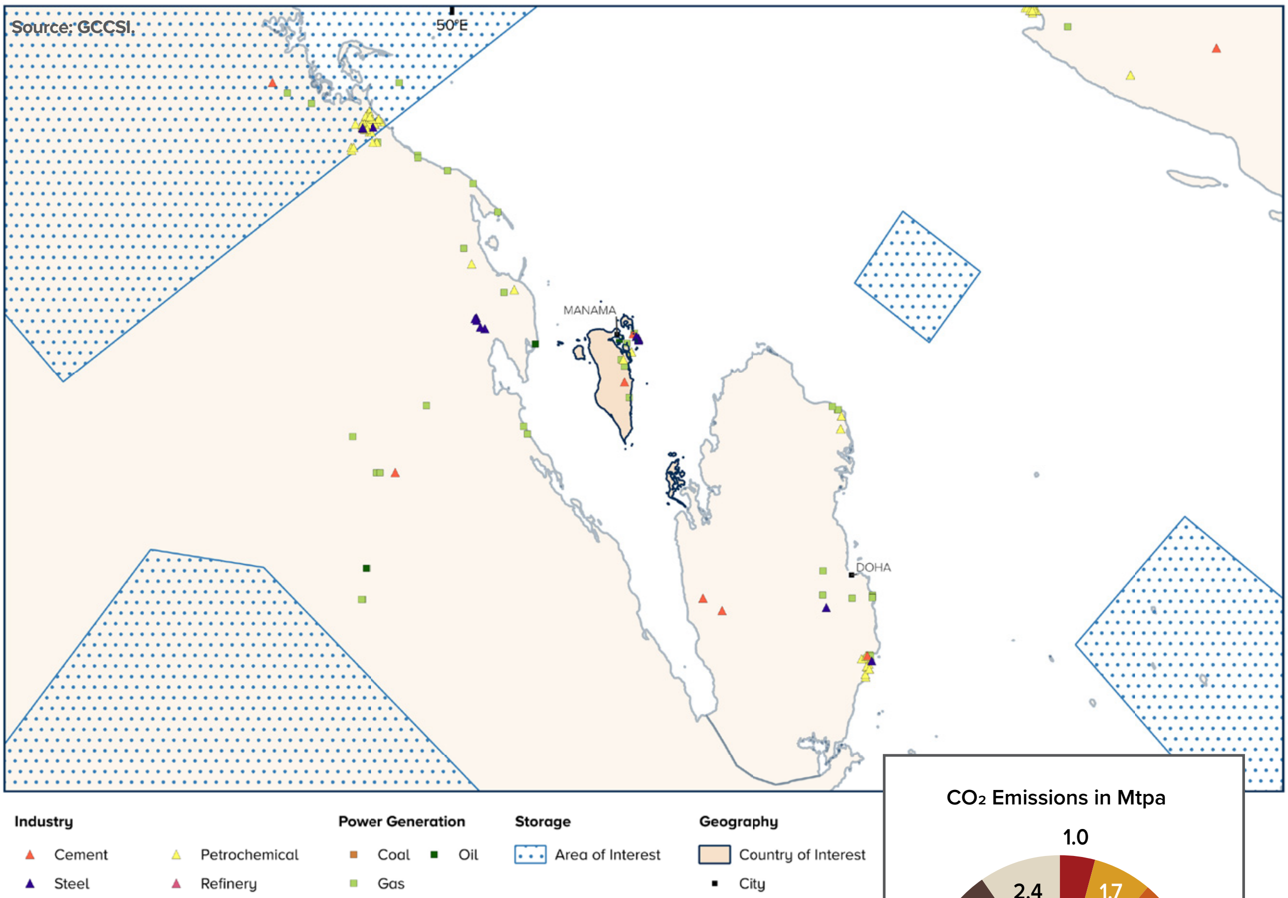
Emissions sources and storage areas of interest

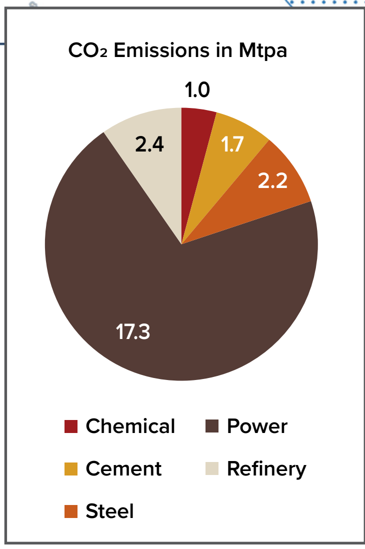
- Qatar has diverse industrial emissions with several hard to abate industries that could or will require CCS including cement, chemicals, and steel.
- Power generation is predominantly from gas fired power generation. Typically, lower CO_2 concentration for capture.
- The majority of emissions are located on the east coast.
- Offshore prospective storage is located to the north of Qatar. Onshore prospective storage is to the southwest in KSA and offshore to the east, north of the UAE.

CCS hub and network potential

- Emissions clusters to the northeast and east of Qatar could facilitate early CCS network development.
- The emissions cluster to the northeast could leverage nearby offshore prospective storage.
- The emissions clusters on the east coast could support network development north to the northeast emissions cluster for storage offshore. If storage capacity is limited, then transboundary transport to KSA or UAE would be required to reach suitable storage locations.
- Single facilities to the west could leverage CCS network infrastructure, however this would need to be on a facility-by-facility basis.

4.1.2.6 Bahrain





See Appendix B for details.

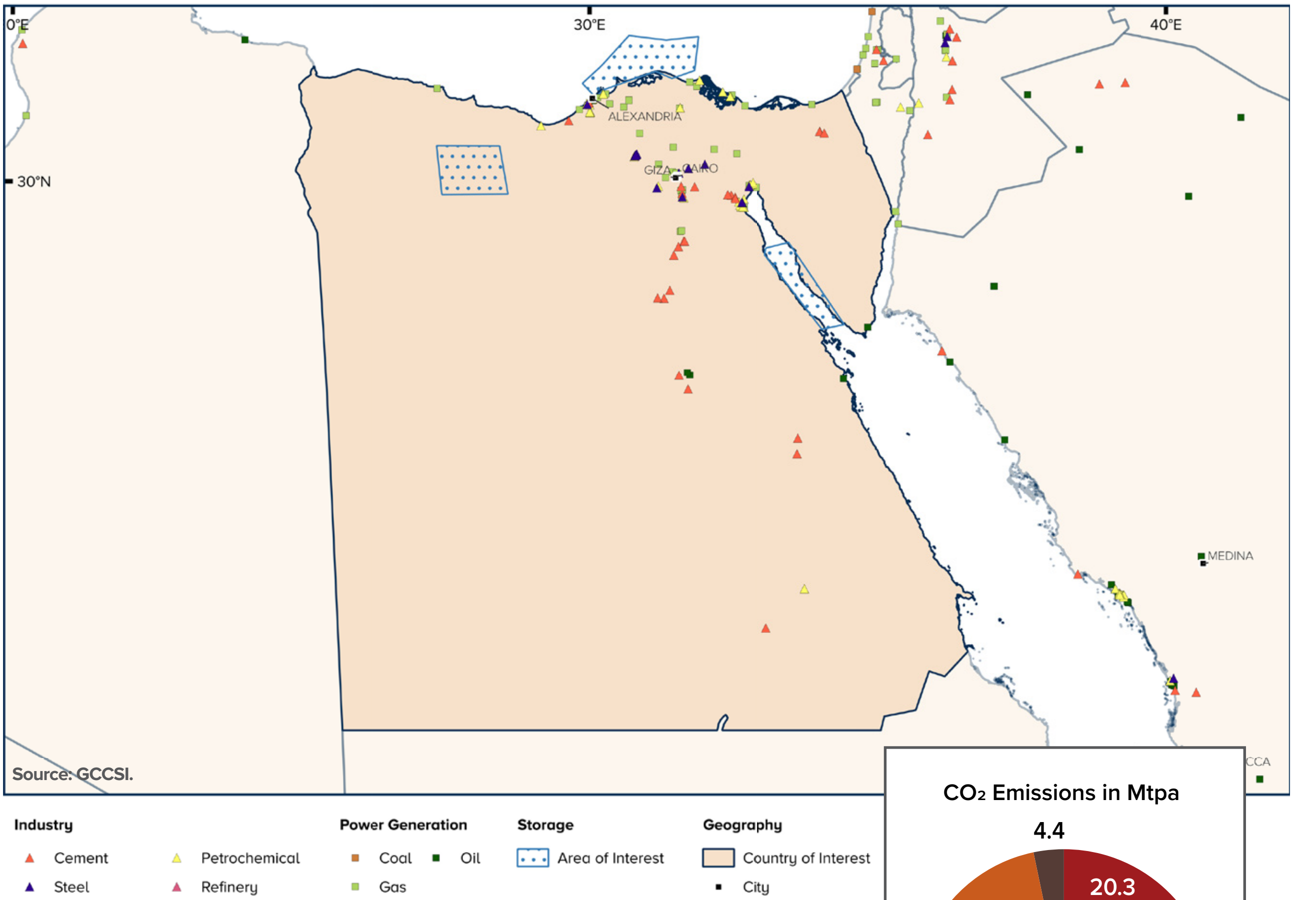
Emissions sources and storage areas of interest

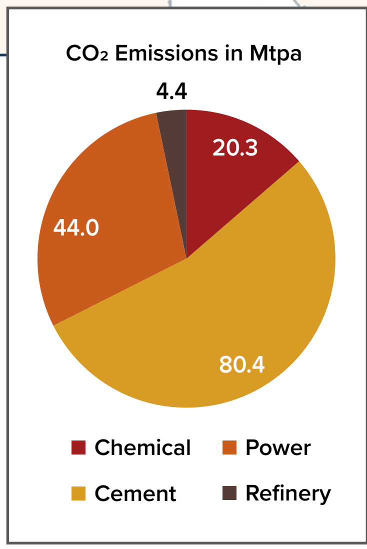
- The majority of Bahrain's identified emissions come from power generation with smaller refining, steel, cement and chemical emissions.
- The majority of emissions are concentrated along the east coast.
- Bahrain does not have identified prospective storage.

CCS hub and network potential

- Several small emissions clusters exist for Bahrain that could support at least one CCS network.
- The lack of prospective storage in Bahrain makes the development of CCS networks more challenging. Bahrain will need leverage prospective storage offshore of Qatar or in KSA to the north or southwest.

4.1.2.7 Egypt





See Appendix B for details.

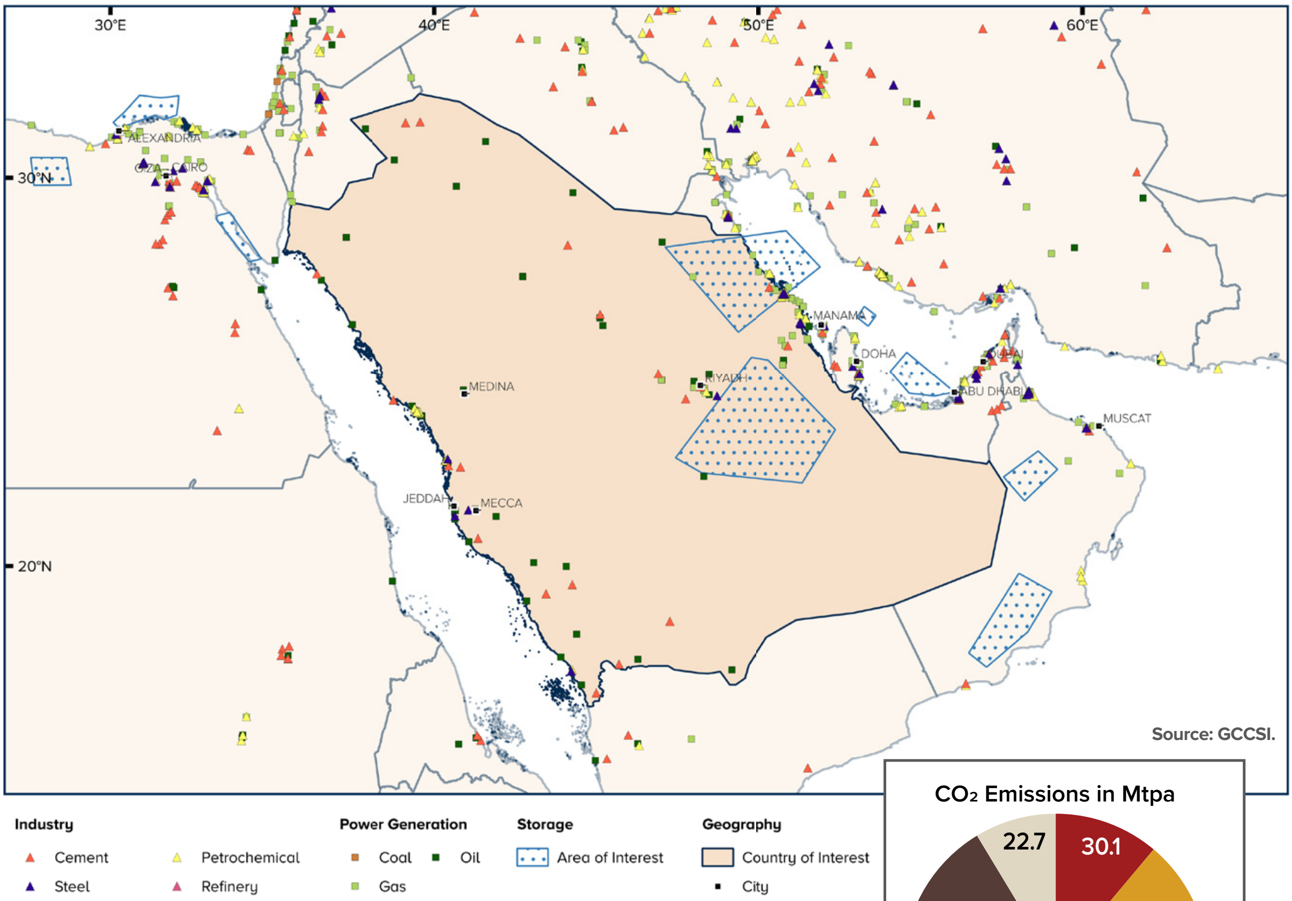
Emissions sources and storage areas of interest

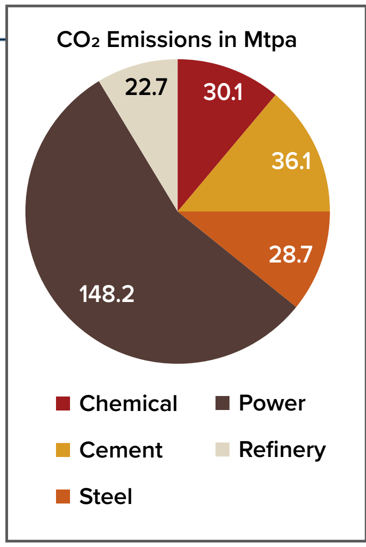
- Egypt has several large emissions intensive industries including cement and steel industries that would necessitate CCS.
- Emissions sources are in several larger clusters along the northern coastline, surrounding Cairo, south of Cairo along the Nile, and in the east towards Suez.
- A number of cement plants follow the Nile to the south of Egypt from Cairo.
- Prospective storage locations are located onshore to the west of Egypt, a significant distance from prospective emissions sources, and offshore off the northern shoreline and offshore in the red sea

CCS hub and network potential

- Offshore prospective storage in the red sea and northern coastline could be more expensive, however the distances are not significant to identified emissions clusters.
- Several clusters to the north of Cairo along the clusters along the northern coastline could underpin a large CCS network to the prospective storage location on the northern shoreline.
- Emissions clusters in Alexandria could also develop CCS hubs transporting CO_2 to the prospective storage location on the northern shoreline, however likely through an independent network to the aforementioned CCS network for Cairo and the northern shoreline.
- Several emissions clusters can be identified to near Suez and cement plants to the south of Cairo along the Nile could form two or more CCS networks transporting CO_2 to prospective storage in the Red Sea.

4.1.2.8 KSA





See Appendix B for details.

Emissions sources and storage areas of interest

- The majority of KSA's identified emissions come from power generation with refining, steel, cement and chemicals consisting of a relative even split of the remainder of emissions.
- The majority of emissions are concentrated along the east and west coasts with some dense clusters centrally located.
- Prospective storage locations are to the east of KSA.

CCS hub and network potential

- Onshore prospective storage locations are an advantage allowing for less costly transport and injection infrastructure; however, the distances are significant for significant for emissions sources to the west.
- Several emissions clusters along the east coast and central KSA could facilitate early CCS network development to storage in the two east prospective storage.
- Several emissions clusters can be found on the west coast of KSA. However, a detailed analysis to identify AOIs in the west was not completed in this analysis due to insufficient data. Further work is required.
- Single facilities to the east could leverage CCS network infrastructure, however this would need to be on a facility-by-facility basis.

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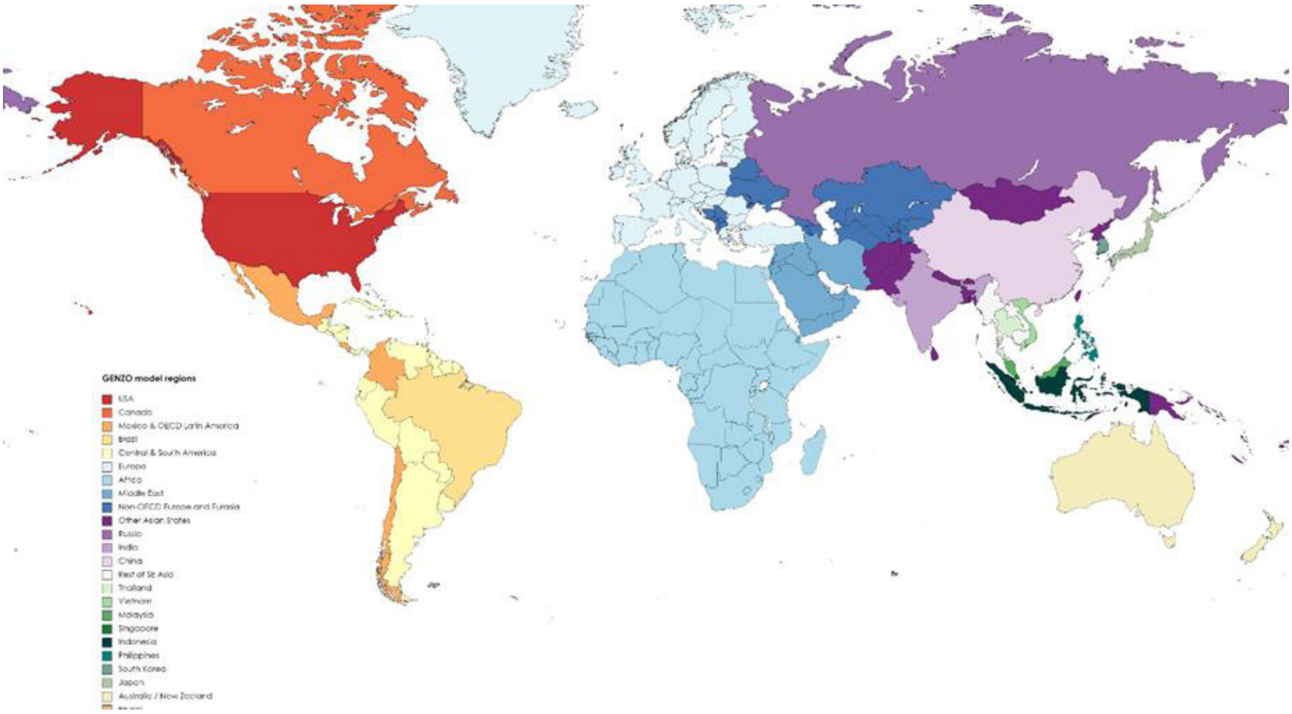
4.2 CCS growth opportunities

4.2.1 Global Economic Net Zero Optimization (GENZO) model methodology

The GENZO model is a bottom-up technology-focused model based on the Open Source Energy Modelling System (OSeMOSYS) framework. OSeMOSYS is similar to MARKAL and TIMES and is used widely in academia and in government for policy analysis and energy system planning [105], [106], [107], [108], [109].

GENZO consists of 24 regions as shown in Figure 9. We run GENZO with all 24 regions simultaneously to ensure that results reflect trade in energy and commodities across regions.

Figure 9: GENZO regions. Source: GCCSI.



GENZO solves for the lowest total cost whilst meeting emission trajectories and other constraints. GENZO is technologically rich and has good sectoral representation: 5 heavy industries plus other industry, 4 modes of passenger travel, 7 modes of freight transport, buildings, and agriculture. GENZO models trade in oil, LNG, coal, ammonia, Bio-LNG, synfuel, steel, aluminum, physical CO_2 for storage, and, optionally, CO_2 emission credits.

GENZO invests in and operates technologies over the entire energy system from energy resources to energy transformations to end-use technologies to satisfy final demands and to fall within constraints like net zero pathways.

In GENZO, future final energy service and commodity demands are exogenous[1], and everything else is endogenous . For example, we do not set oil prices or have an oil price forecast. GENZO models the supply of oil in each region, and the demand for oil that results from investment in technologies that require oil and the decision to operate those technologies. Oil prices result from the balance of supply and demand, along with trade of oil between regions. The same is true for all energy and commodity prices in GENZO.

The results shown in this report are not forecasts of what we expect will happen in the future. They should be thought of as "what if" analyses that highlight what, given a particular scenario assumption, is the least-cost structure of the energy system through 2065. This study can be seen as providing a roadmap for what would ideally be achieved. Achieving a particular least-cost path, however, does not happen automatically. It requires carefully crafted and implemented policies.

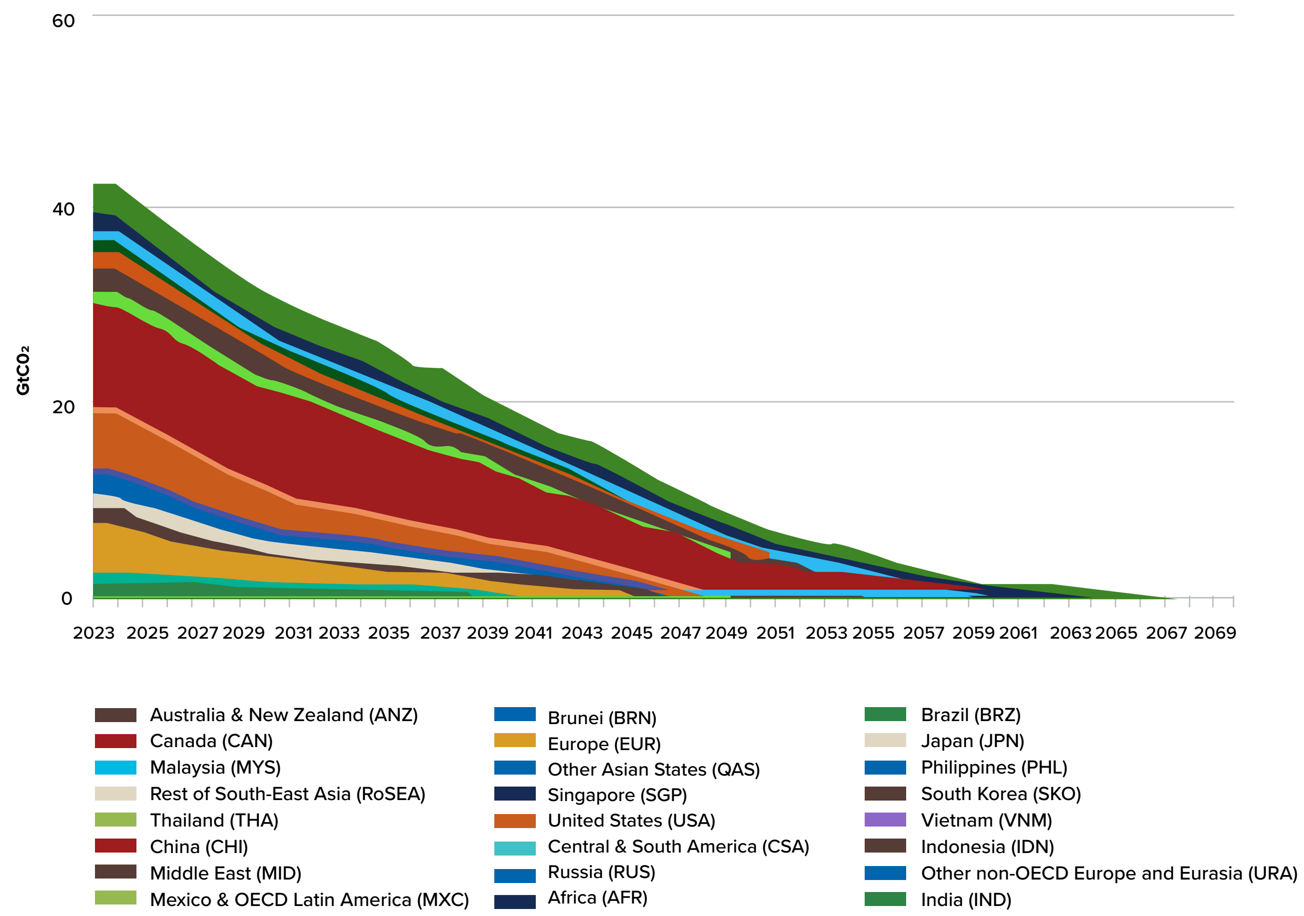
Further information about the GENZO model, its structure and key assumptions can be found in the GENZO model documentation: genzo1123.pdf (globalccsinstitute.com).

[1] Exogenous refers to an assumption that affects the outcome of a model and is not changed within the model. Endogenous refers to anything that gets determined within the model as a result of the model's optimization.

4.2.2 Scenario assumptions

In this analysis, we assume that all regions in GENZO reach their announced net zero targets.

Figure 10: Net zero targets



We consider two scenarios in which we assume different growth rates in the development of CO_2 storage as shown in Table 5. Based on geological assessments, we have assumptions for the total capacity of CO_2 storage available in each region, which does not change. What does change is the rate at which this potential capacity is developed with appropriate infrastructure to be ready for storing a given number of tons of CO_2 per year. These two scenarios – moderate storage growth and substantial storage growth – are growth rates that apply starting in 2031 based on what we know about the storage development project pipeline by that year. Rather than assuming a constant growth rate across scenarios, we assume that regions that are first movers in CCS and with announced intentions to vigorously develop CCS have higher growth rates in each scenario than other regions. Given the economic advantages afforded by pursuing CCS in reaching net zero and the investment capital and ability to mobilize large-scale projects in a relatively short period, we assume that the Middle East has the highest growth rates for CO_2 storage development in the substantial storage growth scenario.

Table 5: Scenario assumptions

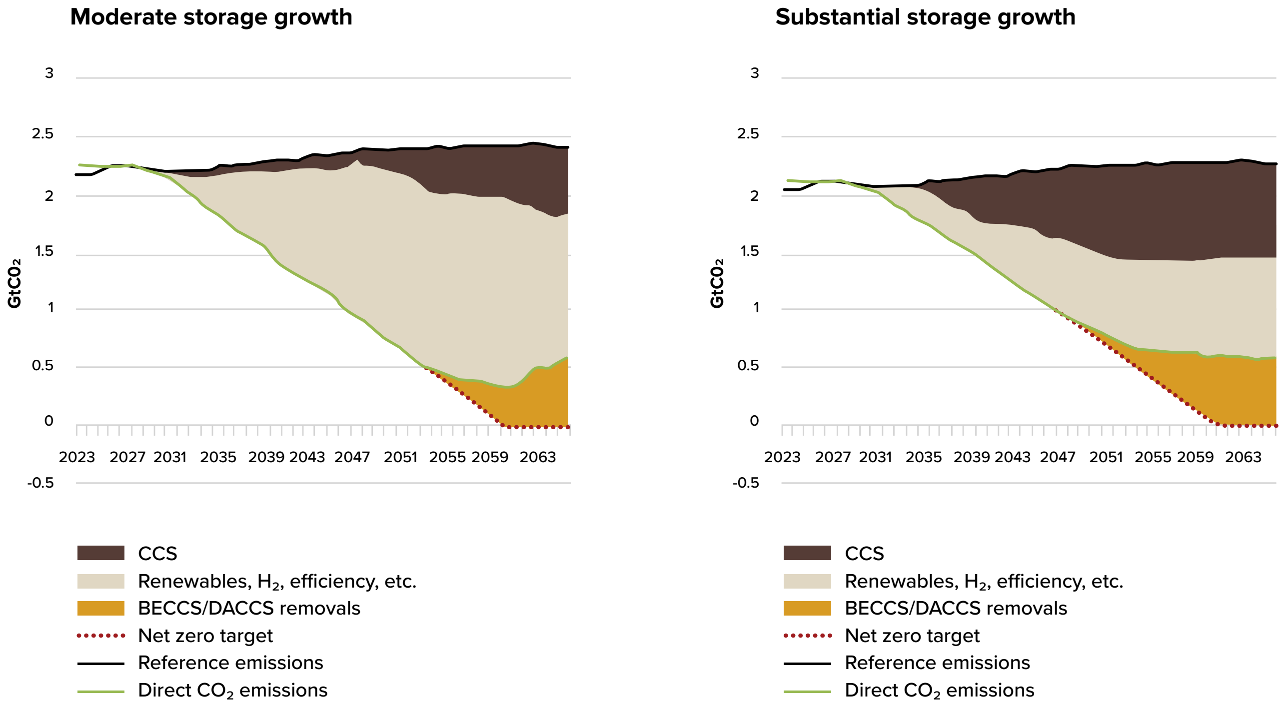
GENZO REGION	MODERATE STORAGE GROWTH	SUBSTANTIAL STORAGE GROWTH
Africa	5%	10%
Australia & New Zealand	10%	50% declining to 0% before 2060
Brunei	5%	10%
Brazil	5%	10%
Canada	10%	50% declining to 0% before 2060
China	5%	10%
Central and South America	5%	10%
Europe	10%	50% declining to 0% before 2060
Indonesia	5%	10%
India	5%	10%
Japan	5%	10%
Middle East	10%	60% declining to 0% before 2060
Mexico & OECD Latin America	5%	10%
Malaysia	5%	10%
Other Asian States	5%	10%
Philippines	5%	10%
Rest of SE Asia	5%	10%
Russia	5%	10%
Singapore	0%	0%
South Korea	5%	10%
Thailand	5%	10%
Other non-OECD Europe and Eurasia	5%	10%
USA	10%	50% declining to 0% before 2060
Vietnam	5%	10%

4.2.3 High-level results

We first run GENZO without any net zero targets to establish a reference case. Because of advancements in cost-effective, efficient and less carbon-intensive technologies, the CO_2 emissions in the reference case see limited growth even without a CO_2 target. We then run GENZO with all the same assumptions as the reference case except that we apply the net zero targets and the scenario assumptions described in the previous section.

Both scenarios reach the exact same net zero reduction pathway, but they do so in quite different ways. In Figure 11, the black line represents the reference emissions, the green line the actual direct emissions, and the red dashed line the net zero target. The brown area represents the number of $GtCO_2$ that are captured and stored with fossil-based CCS. The clay shaded area represents the $GtCO_2$ that are reduced through renewables, hydrogen, efficiency, fuel switching, etc. The orange shaded area represents the $GtCO_2$ that are removed from the atmosphere by biomass with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). These carbon removals are how the remaining direct emissions are offset to achieve the net zero target. The moderate storage growth scenario results in significantly less fossil-based CCS as well as less carbon removals than the substantial storage growth scenario.

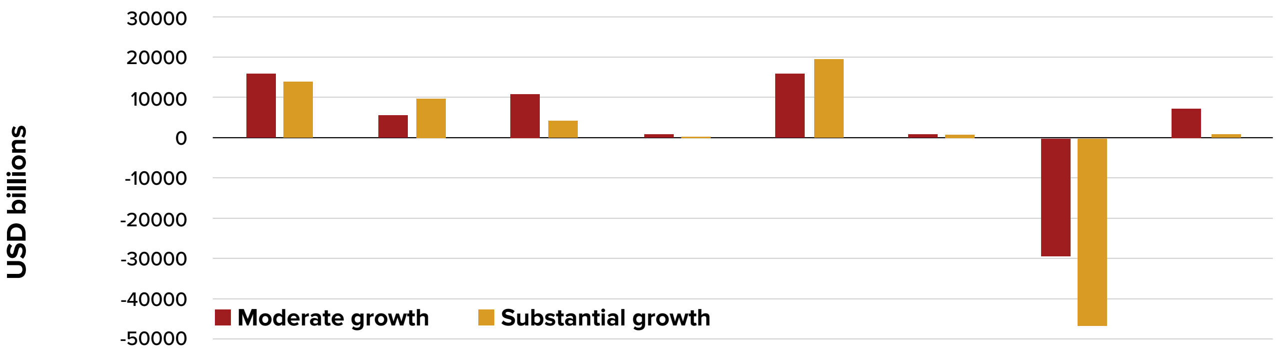
Figure 11: How the Middle East achieves net zero



The more limited development of CO_2 storage resources in the moderate growth scenario limits the opportunities to deploy cost-effective CCS and carbon removals, forcing higher cost decarbonization options. It also leads to higher energy system costs and, importantly for the region, significantly lower oil and gas export revenue. Figure 12 breaks out the total energy system cost for the Middle East through 2065 into its component parts. End-use CAPEX and non-energy OPEX costs are higher with the moderate growth scenario, largely because of this scenario's reliance on hydrogen for decarbonization in end-use sectors and the higher cost of technologies that can use hydrogen. The substantial storage growth scenario, as will be shown later, relies primarily on CCS and electrification to decarbonize end-use sectors, and this added reliance on electrification leads to higher CAPEX and non-energy OPEX costs in the electricity sector compared to the moderate growth scenario. The reverse is true for hydrogen. The moderate growth scenario's reliance on hydrogen leads to substantially higher costs of CAPEX and non-energy OPEX.

Fossil fuel production costs are also higher in the substantial storage growth scenario because the exports are so much higher in this scenario than in the moderate growth scenario. In fact, the difference in export revenue is the single biggest difference in dollar terms between the two scenarios (note that the export revenue in the figure is expressed as a negative value as import costs). The substantial storage growth scenario results in USD 17.8 trillion more in oil and gas export revenue over the time period. At the same time, the moderate storage growth scenario requires significantly more low-carbon fuel imports than the substantial storage growth scenario.

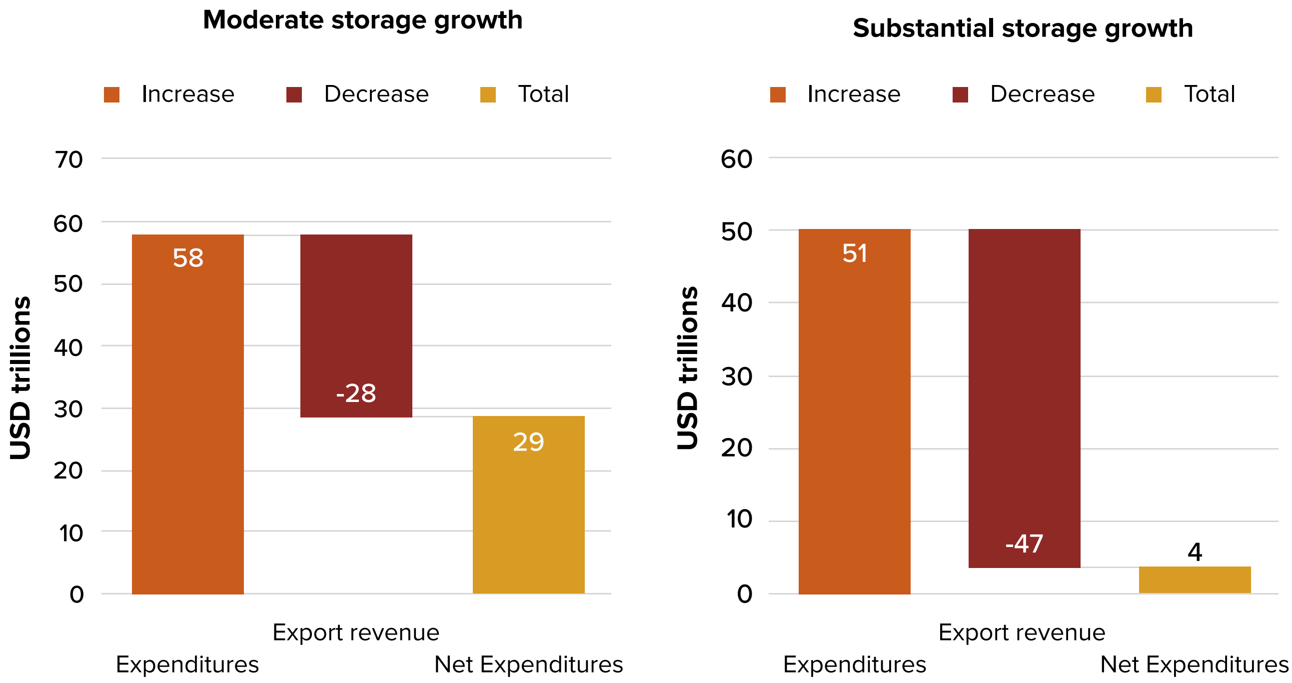
Figure 12: Components of system cost through 2065



	End-use CAPEX + non-energy OPEX	Electricity CAPEX + non-energy OPEX	Hydrogen CAPEX + non-energy OPEX	Fuels CAPEX + non-energy OPEX	Fossil fuel production	Biomass production	Oil & Gas imports	Low-carbon fuel imports
Moderate growth	16370	5989	10824	566	16184	201	-29293	7779
Substantial growth	14570	9659	4634	510	20082	197	-47008	930

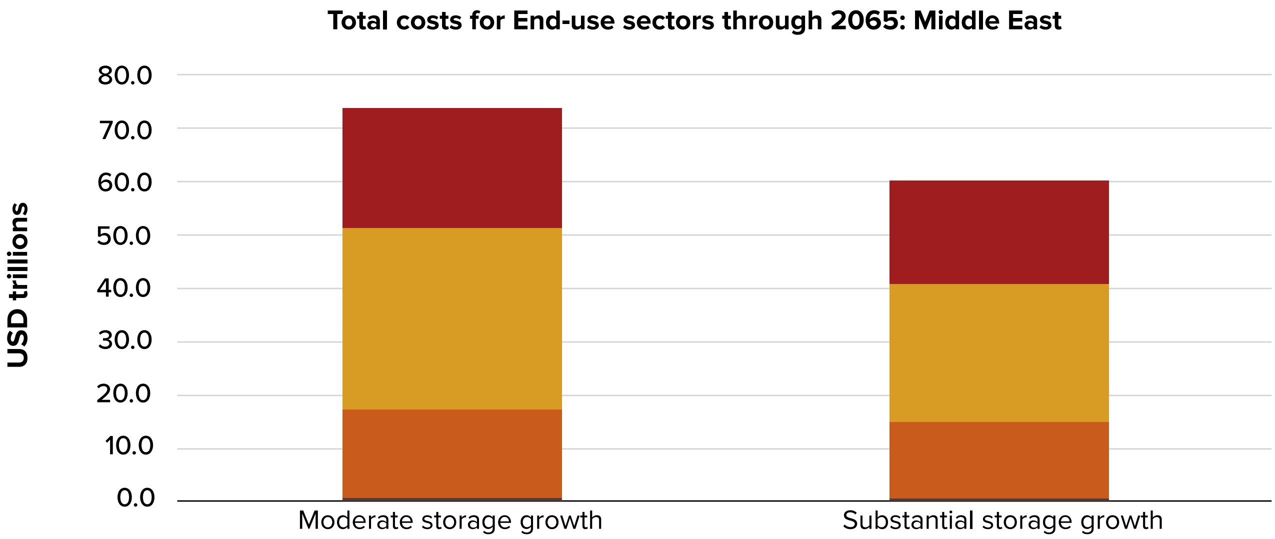
If we sum all the system cost expenditures and deduct export revenues (Figure 13), we see that the final net cost of the energy system is USD 29 trillion for the moderate storage growth scenario compared to USD 4 trillion for the substantial storage growth scenario. The direct cost, labelled "Expenditures" in the figure, is USD 51 trillion for the Substantial storage growth scenario versus USD 58 trillion in the Moderate scenario, but the most significant difference between the scenarios is that the Substantial storage growth scenario results in USD 47 trillion in export revenue versus only USD 28 trillion in export revenue in the Moderate growth scenario. Please note that while we refer to these costs as energy system costs, we model the full cost of commodities produced by energy-intensive industries, not just the energy required to produce them, so these costs implicitly include more than strictly the energy system.

Figure 13: Net costs for energy system



Looking at costs from the perspective of end-use sectors, which do not pay for energy at the cost of producing it but instead at market prices, we see how the scenarios are likely to affect individuals through buildings and transport and non-energy producing industries. End-use industries save USD 7.6 trillion with the substantial storage growth scenario. Buildings and transport together save an additional USD 6 trillion with the substantial storage growth scenario. Agriculture saves USD 0.1 trillion.

Figure 14: Costs to end-use sectors through 2065



	Moderate storage growth	Substantial storage growth
Transport	22.5	18.9
Industry	34.2	26.6
Buildings	16.6	14.2
Agriculture	0.7	0.6

The economic advantages of the substantial storage growth scenario for the Middle East are clear, but the export revenues in this scenario are possible by the rest of the world also pursuing CCS and enabling the continued use of oil and gas while still meeting climate goals. Nevertheless, there are still clear cost advantages for the Middle East in pursuing a substantial storage growth scenario regardless how of how CCS evolves around the world.

4.2.3.1 Carbon capture and storage

Drilling down into the results further, we see that the substantial storage growth scenario has carbon capture and storage options that are scaled up across the board compared to the moderate storage growth scenario (Figure 15). Most notably, the use of carbon capture and storage in industry and electricity is significantly higher in the substantial vs moderate storage scenario. However, much of the difference in CCS between the two scenarios is due to timing.

If we look at capital investment in carbon capture (Figure 16), not including transport and storage, we can see that, while the substantial storage growth scenario does require more investment in total, the difference is not as significant as the carbon capture results suggest. What is happening is that the higher storage growth in the substantial growth scenario allows for earlier investment and operation of CCS technologies, which leads to more tons of CO_2 captured over the period than the moderate growth scenario. However, in terms of total investment, the moderate storage growth scenario still requires 85% of the capital investment in carbon capture of the substantial storage growth scenario. The later timing of this investment means that the moderate storage growth scenario captures only 43% of the CO_2 that the substantial storage growth scenario does through 2065. But to continue meeting net zero targets, the moderate storage growth scenario also must invest much more in high-cost hydrogen infrastructure to produce, transport and use it than the substantial storage growth scenario.

Figure 15: Types of carbon capture and storage in the Middle East through 2065

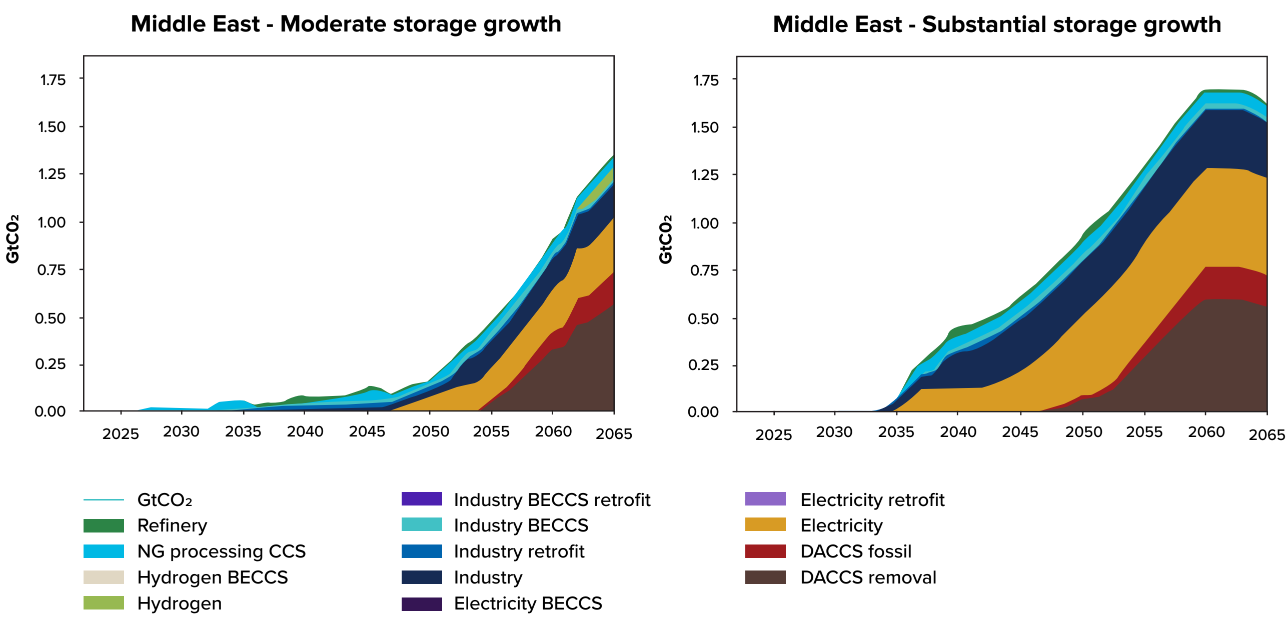
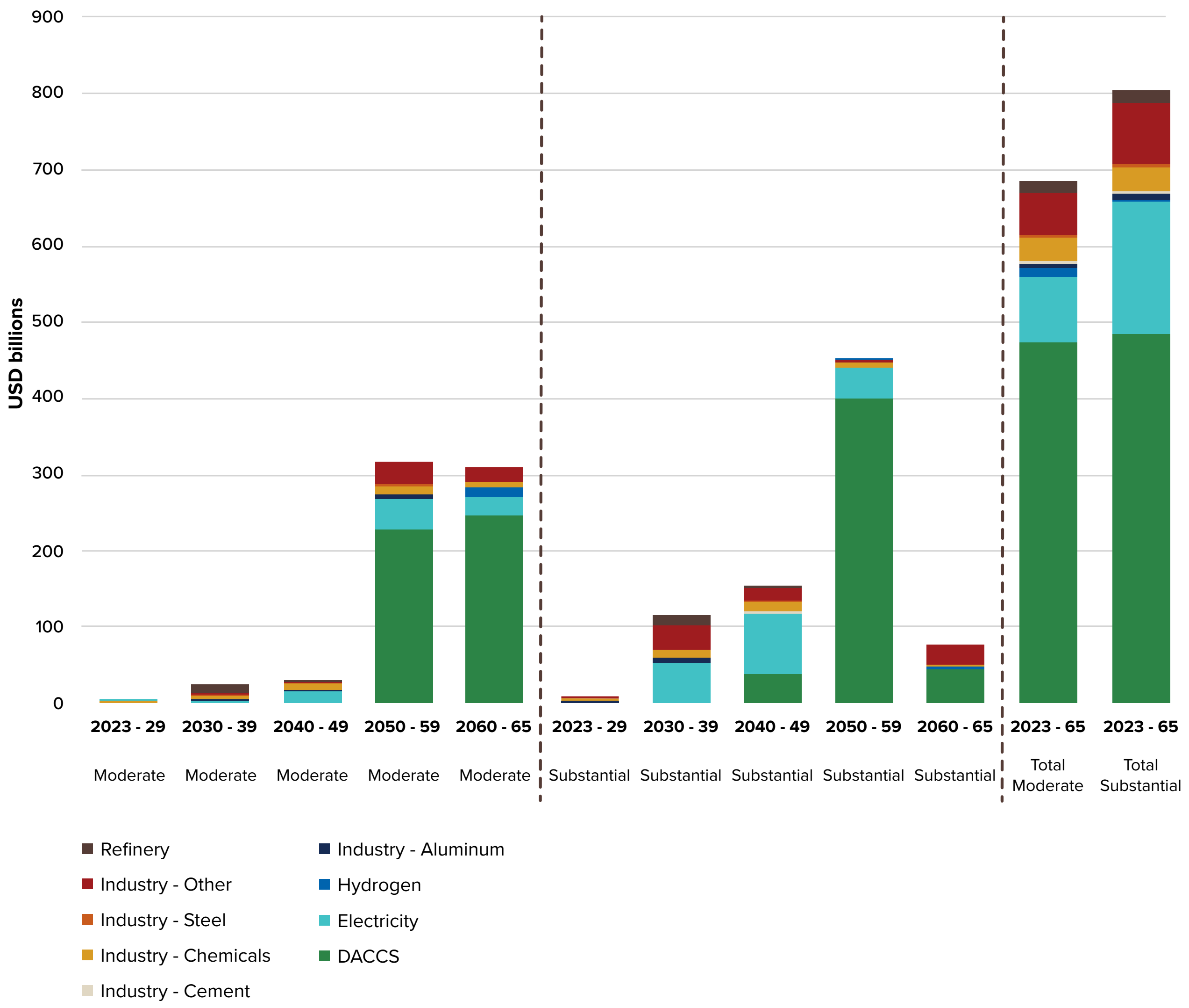


Figure 16: Capital investment for carbon capture, excluding transport and storage



The Middle East is well-positioned to be an option for other regions with limited storage potential or limited storage development to ship CO_2 for storage. In the moderate storage growth scenario, which applies to all regions, the Middle East has limited capacity to take in CO_2 from other regions. In this scenario, the aggregate region of Other Asian States starts shipping 3.9 $MtCO_2$ in 2036 that grows to a peak of 266 $MtCO_2$ in 2065 (Figure 17). The substantial storage scenario is in stark contrast. In this scenario, the Middle East develops significantly more CO_2 storage capacity than it needs for its own captured emissions and receives CO_2 primarily from India and Other Asian States plus a small amount from Vietnam, Thailand, Singapore, the Rest of South-East Asia and China. CO_2 stored in the Middle East imported from other regions peaks at 2.39 $GtCO_2$ in 2053 in the substantial storage growth scenario.

We do not have sufficient data to characterize the cost of storage by region. As a default, we assume that the cost of domestic storage within a region is USD 10 per ton, but the cost to store CO_2 in another region is USD 20 per ton (in addition to the cost of transport to deliver it). Assuming that every ton imported for storage generates a USD 10 profit, the cumulative 4.1 $GtCO_2$ stored from other regions in the moderate storage growth scenario would generate USD 41 billion in profit, while the 48.8 $GtCO_2$ stored from other regions in the substantial storage growth scenario would generate USD 488 billion in profit.

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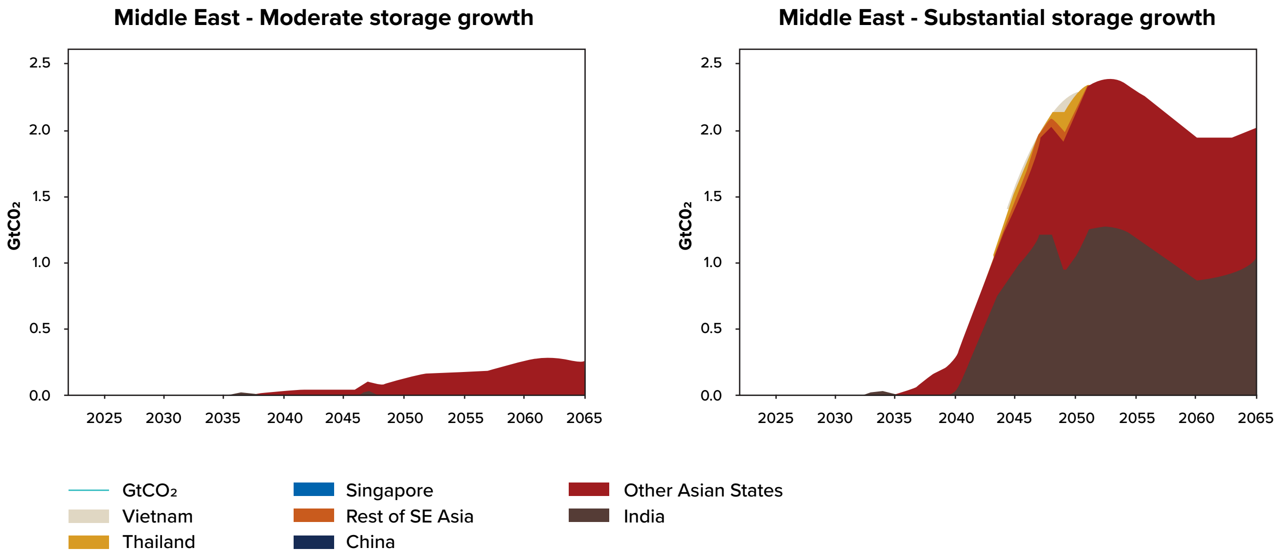
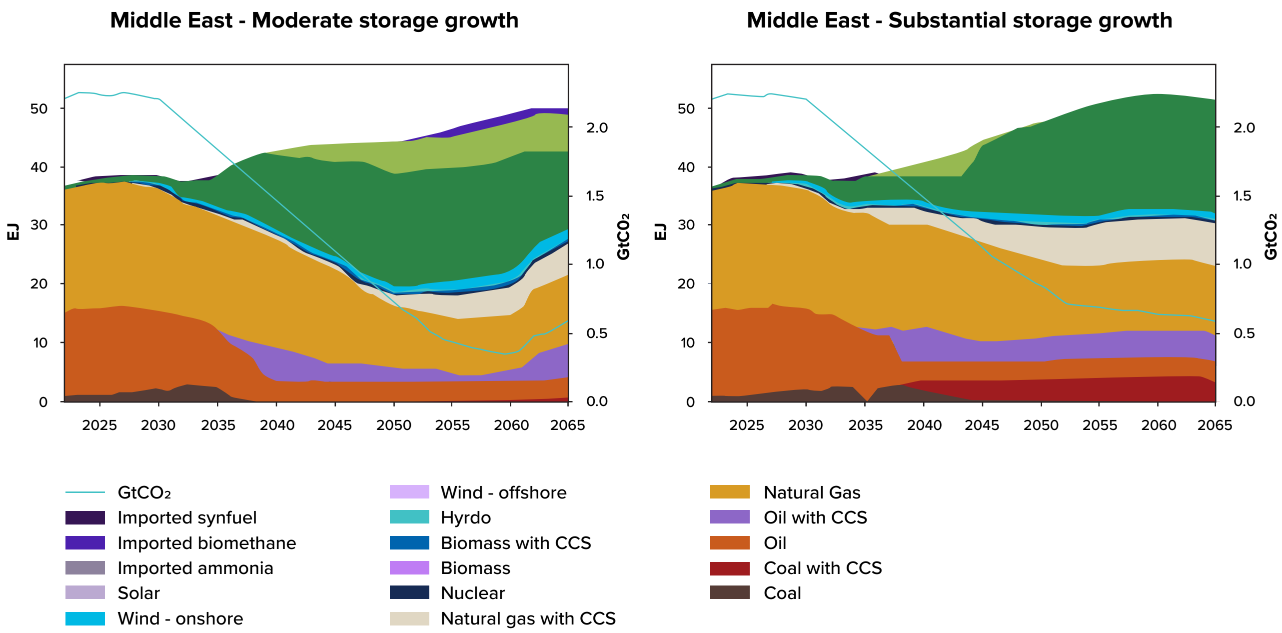
Figure 17: CO_2 imports from other regions to store in the Middle East



4.2.3.2 Energy

The growth of CO_2 storage development has a significant impact on overall primary energy use in the Middle East (Figure 18). In the moderate storage growth scenario, coal use declines to near zero by 2037, and oil and gas use begins to decline around 2030, with some CCS associated with them. Oil and gas use reach a low in the 2050s and then rebound somewhat through 2065. What primarily fills the gap is solar and a small amount of onshore wind. What is interesting is that in this scenario, the Middle East becomes a net importer of ammonia and biomethane as well. The substantial storage growth scenario also sees a decline in oil and gas use starting around 2030, but that decline is far less steep and has much more associated CCS. Coal use in this scenario continues but is almost entirely with CCS by 2045. Solar primarily fills the gap in the moderate reduction in oil and gas use and covers most remaining growth in primary energy use, except for some ammonia imports during the transition phase from 2035-2050 and a small amount of onshore wind.

Figure 18: Primary energy use



Electricity generation differs significantly between the two scenarios starting around 2035 (Figure 19). The more limited availability of CO_2 storage requires that the moderate growth scenario phase out natural gas-fuelled generation and instead to rely on hydrogen fuel cells for baseload generation beginning in the late 2030s because the developed CO_2 storage is insufficient to accommodate CCS in the electricity sector. Hydrogen fuel cells require a very costly and circuitous energy pathway, relying on a large amount of solar electricity generation to produce hydrogen, costly infrastructure to transport it, and costly fuel cells to then convert it back to electricity. By 2045, enough CO_2 storage is available for the moderate growth scenario to deploy far less costly natural gas combined cycles with CCS. The growth in electricity generation comes from a mix of solar, solar with battery systems, onshore wind, a small amount of nuclear, and distributed solar and energy efficiency.

The substantial storage growth scenario, overall, sees far more growth in electricity than the moderate storage growth scenario. The reason for this is that in this scenario, the industrial sector decarbonizes through a combination of CCS and electrification, whereas in the moderate storage growth scenario, industrial decarbonization is primarily through hydrogen with a small deployment of CCS. The substantial storage growth scenario can make possible the cost-effective expansion of electricity generation because sufficient CO_2 storage is available to enable a significant deployment of natural gas combined cycle with CCS. At the same time, far less solar generation is needed for hydrogen production compared to the moderate storage growth scenario, and solar resources can instead be dedicated to solar generation for general electricity use.

Figure 19: Electricity generation

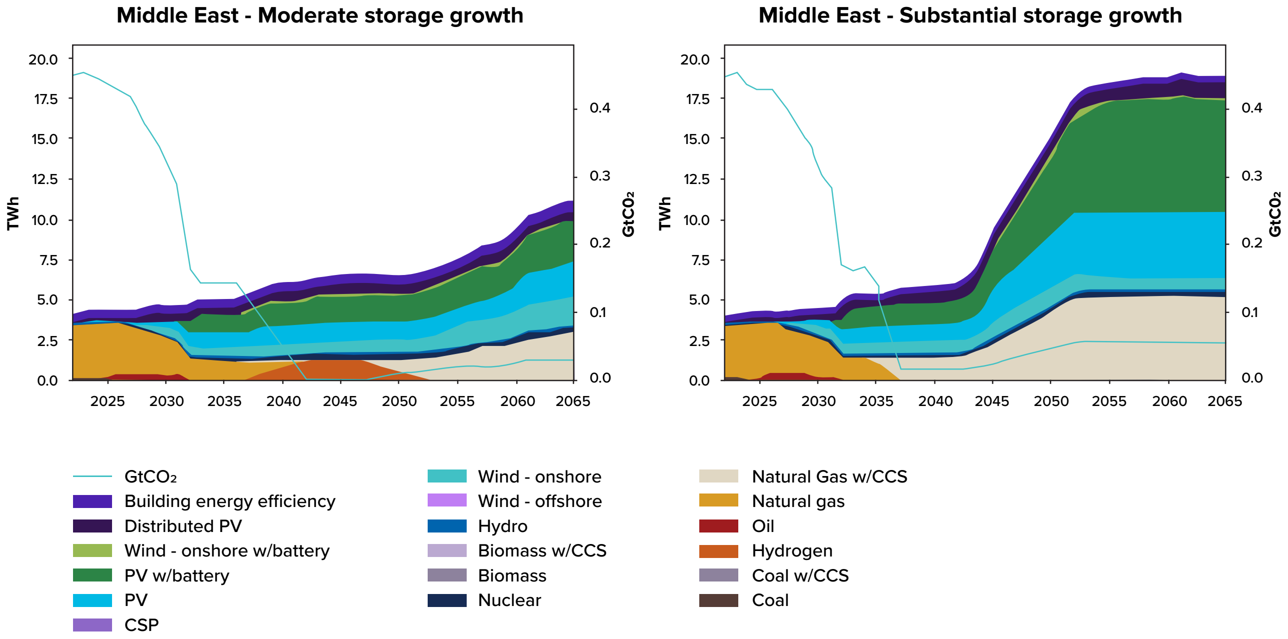
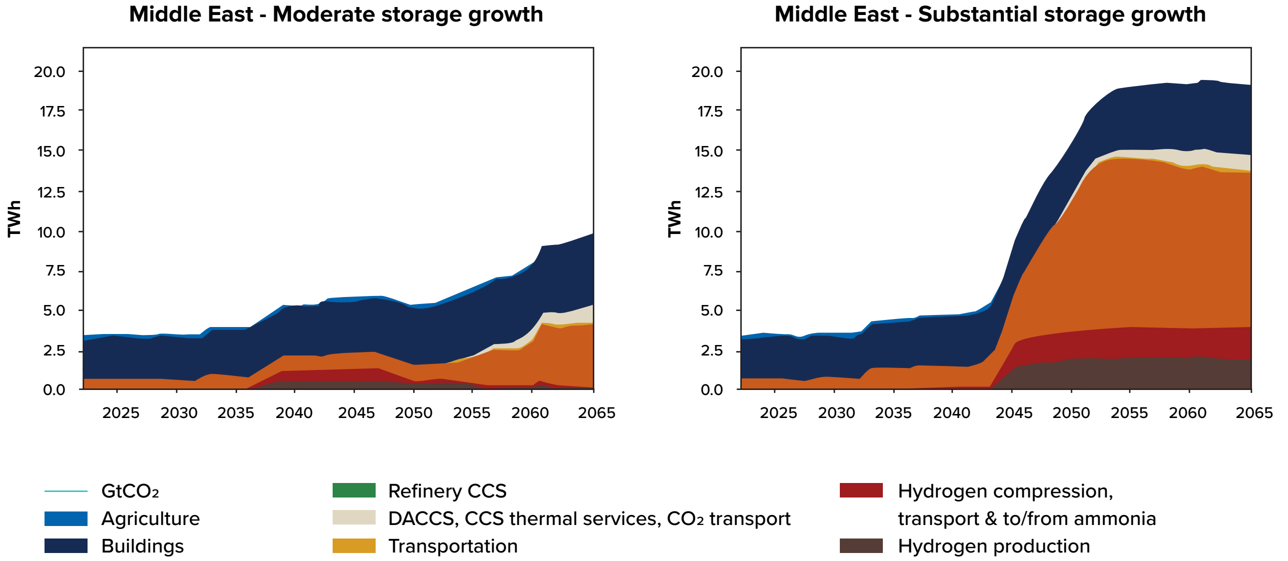


Figure 20 reveals where electricity is used in the two scenarios. Note that dedicated solar hydrogen production is not reflected in this figure as hydrogen production. Only electricity taken from the grid is counted as hydrogen production here. Use of electricity in buildings is similar in the two scenarios, as well as DACCS, CCS thermal services, and CO_2 transport. The significant difference, as discussed previously, is that the industrial sector in the substantial growth scenario decarbonizes to a significant extent through electrification in addition to CCS.

Figure 20: Electricity use



The moderate storage growth scenario produces an extraordinary amount of hydrogen – over 15 EJ by the late 2040s (Figure 21). The substantial storage growth scenario still produces a significant amount of hydrogen, but only about half the amount in the moderate growth scenario. The moderate growth scenario also imports another ~7.5 EJ of ammonia and synthetic fuel. The substantial storage growth scenario imports some ammonia during the transition phase from 2035 to 2050, but far less than the moderate growth scenario and does not import any synthetic fuel.

In both scenarios, the most cost-effective hydrogen production in the region is dedicated solar electrolysis, though a small amount of hydrogen in the moderate growth scenario is produced using electricity from the grid and in the last few years, oil with CCS.

Figure 21: Hydrogen production

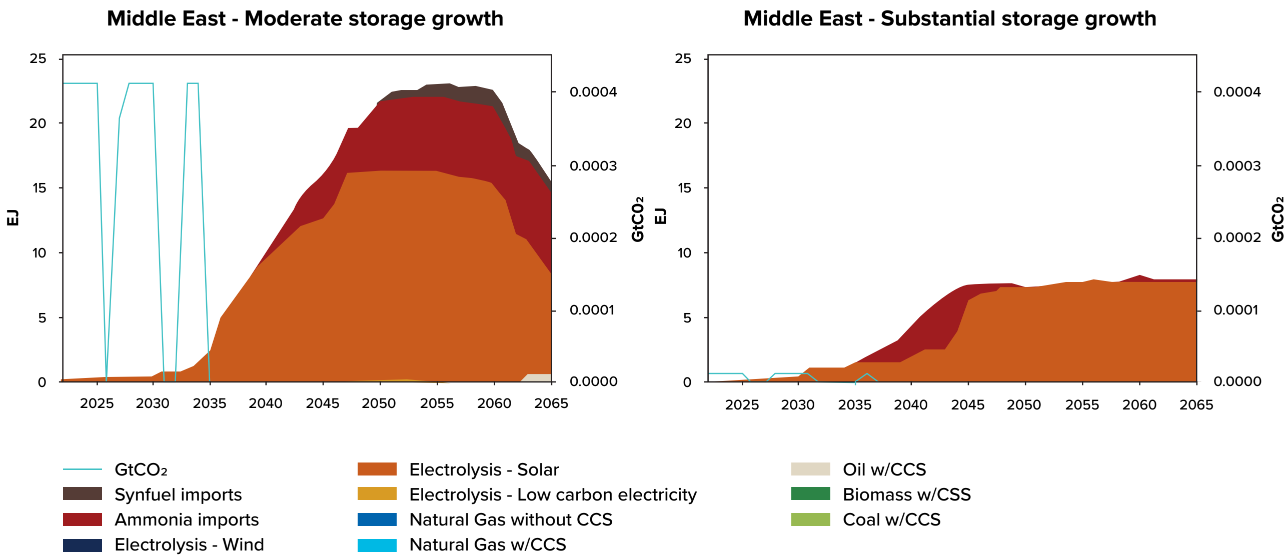


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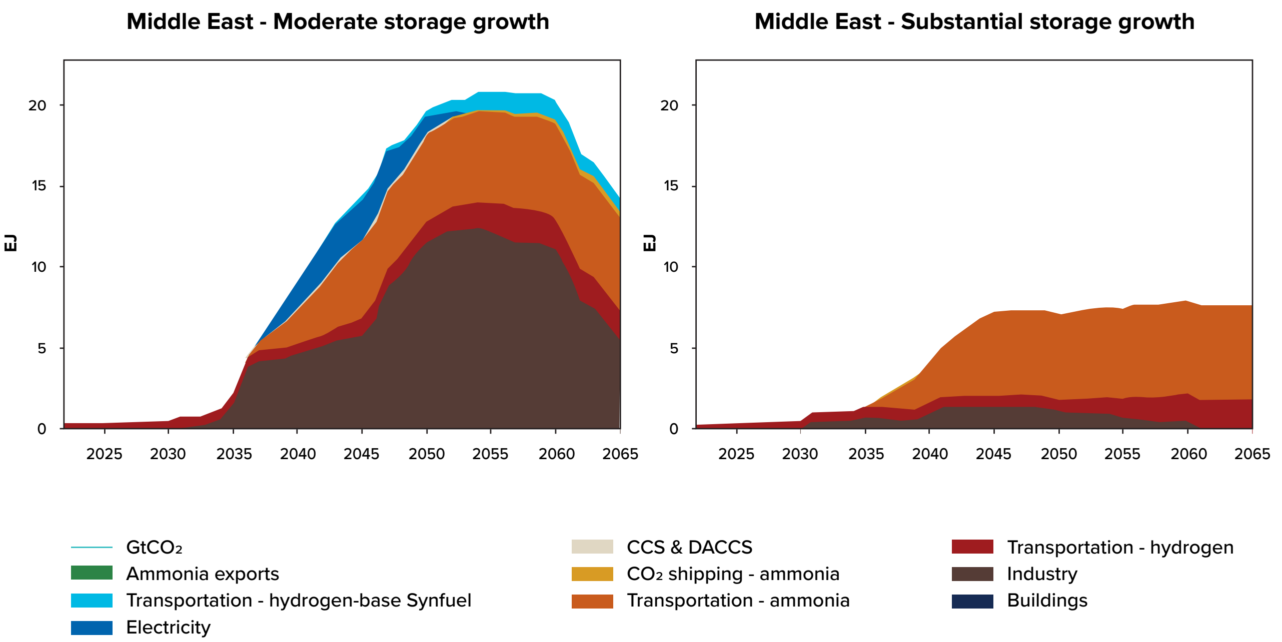
Figure 22 shows where hydrogen is used. Rather than CCS and electrification as the primary means of decarbonizing industry as in the substantial storage growth scenario, the moderate storage growth scenario relies primarily on hydrogen, peaking in industry alone at over 10 EJ in the 2050s. The moderate growth scenario also needs hydrogen for electricity from 2035 to 2050. The remaining hydrogen use is in transportation. The substantial growth scenario does use a modest amount of hydrogen in industry, but most of the hydrogen used is for transportation.

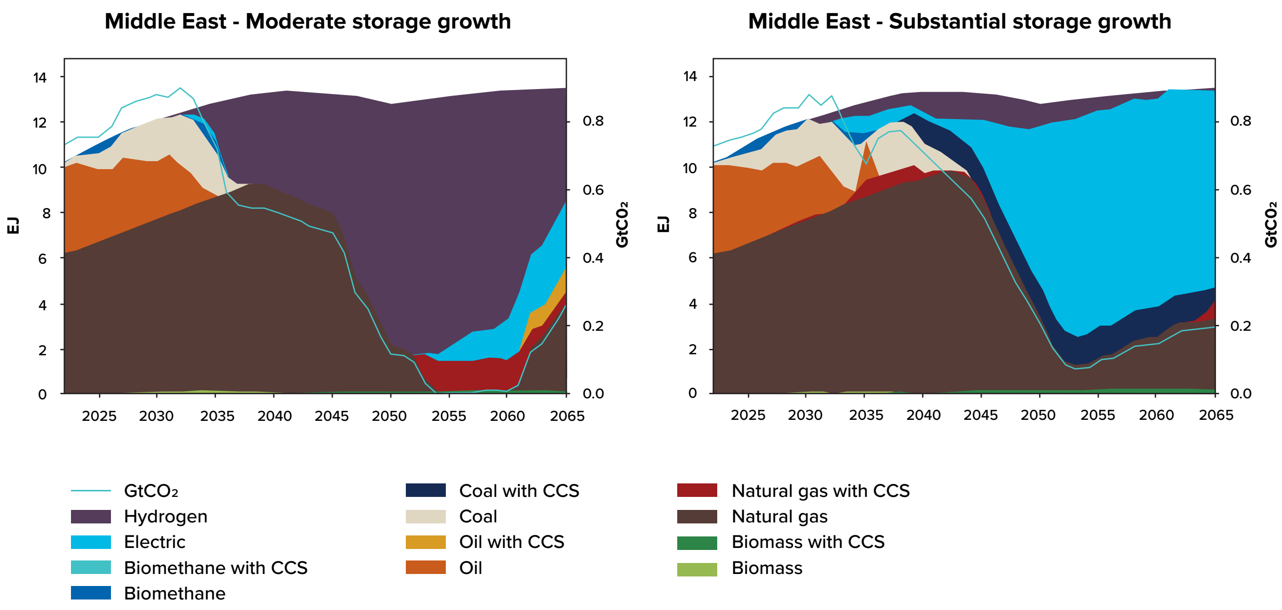
Figure 22: Hydrogen and derivatives use



4.2.3.3 End-use sectors

How industry evolves through 2065 depends on the specific industry and scenario. Figure 23, which shows the energy used for producing heat and steam for "other" industry, illustrates the trade-offs between hydrogen and electrification. Energy usage is quite similar until the late 2030s when the moderate storage growth scenario transitions significantly toward hydrogen. In the substantial storage growth scenario, hydrogen use begins in the 2030s as well, but at a slower rate and by the 2040s, electricity rapidly becomes the primary source for heat and steam.

Figure 23: Other industry non-electricity energy use by type



Aluminum production is almost the same between the scenarios.

In chemicals, both scenarios begin shifting away from natural gas toward natural gas with CCS for heat requirements in the late 2020s. In 2035, the substantial growth scenario begins deploying coal with CCS, thus accelerating the phaseout of uncontrolled natural gas in chemicals. The low cost of coal and ample CO_2 storage development enable coal with CCS to begin overtaking natural gas with CCS by the late 2040s in the chemical sector. In contrast, in the moderate storage growth scenario, natural gas with CCS continues to expand until 2050 when further growth is met with hydrogen in chemicals.

Steel in both scenarios sees a dramatic increase in domestic production. For the moderate storage growth scenario, DRI EAF and DRI EAF with CCS almost keep up with domestic demand for steel, leading to a significant decline in steel imports. For the substantial growth scenario, domestic steel production shifts to SR BOF with CCS, but roughly half of the Middle East's demand for steel is met from imports, which, nevertheless is far less than today in which the vast majority is met with imports.

Passenger transport, which includes air, rail, and light duty vehicles, is essentially the same in both scenarios until 2040, when synfuel begins displacing both aviation fuel and gasoline in the moderate growth scenario (Figure 24). In the substantial growth scenario, synfuel begins displacing gasoline in 2050, but aviation fuel remains. Both scenarios have a modest deployment of electric vehicles, entirely in the light duty vehicle sector.

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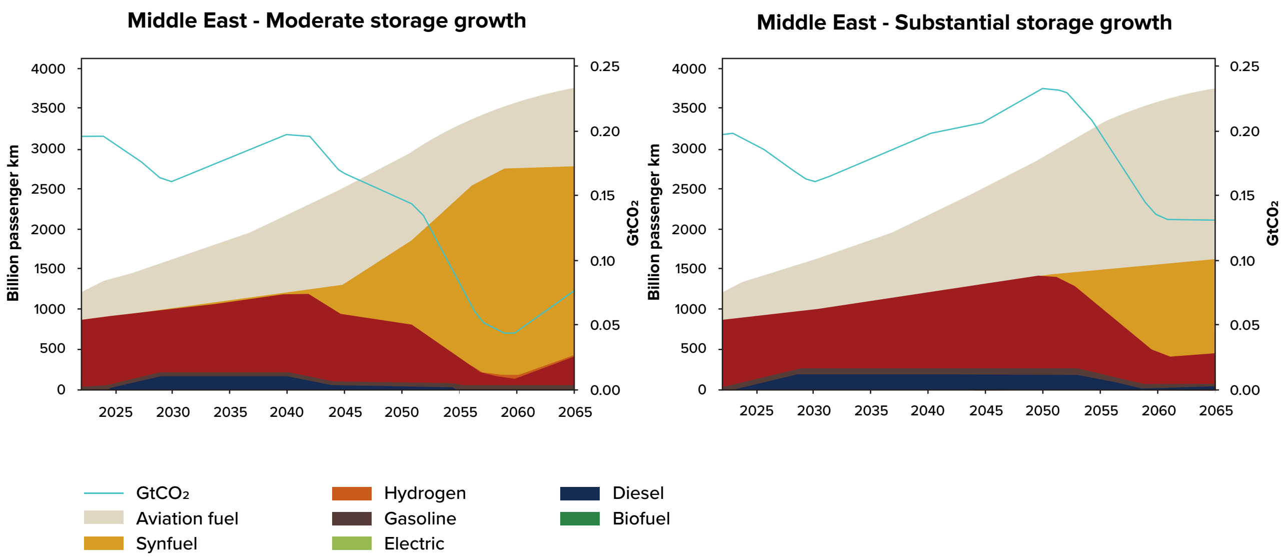
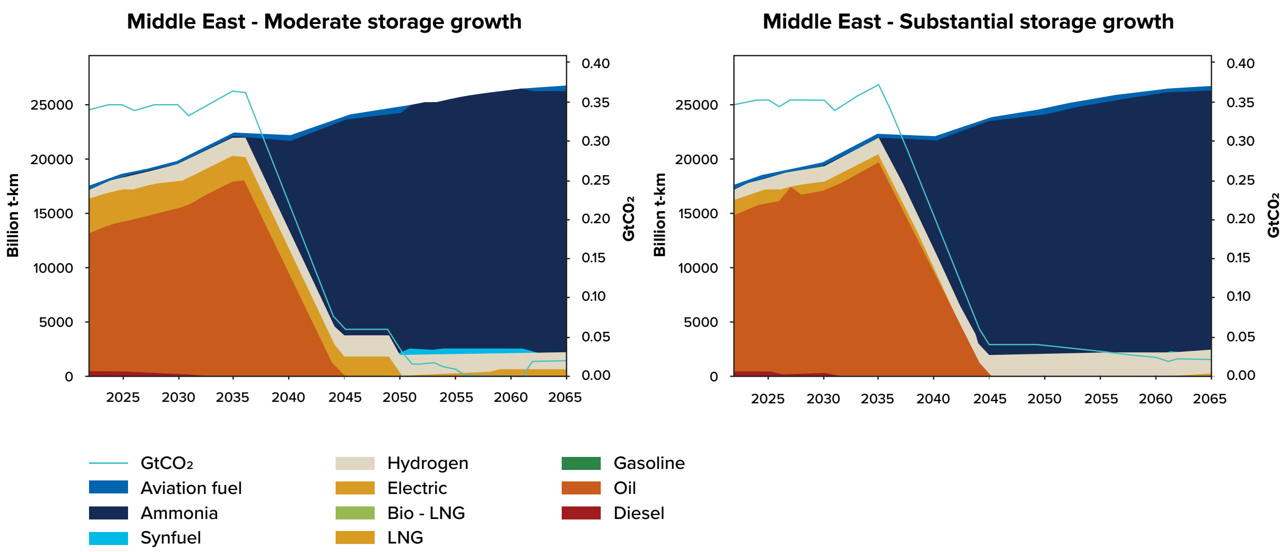
Figure 24: Passenger transport



Freight transport, which includes domestic and international shipping, air freight, rail freight, and light-, medium- and heavy-duty truck freight, is remarkably similar between the two scenarios. The moderate storage growth scenario sees more LNG in shipping and a small amount of synfuel use (displacing some aviation fuel), but the vast majority of freight moved in both scenarios shifts toward ammonia starting in 2035 and with the transition primarily to ammonia complete by 2045. The shipping industry shifts almost entirely toward ammonia, and the sheer volume of ton-kilometers moved via shipping compared to other freight modes is why ammonia becomes so dominant.

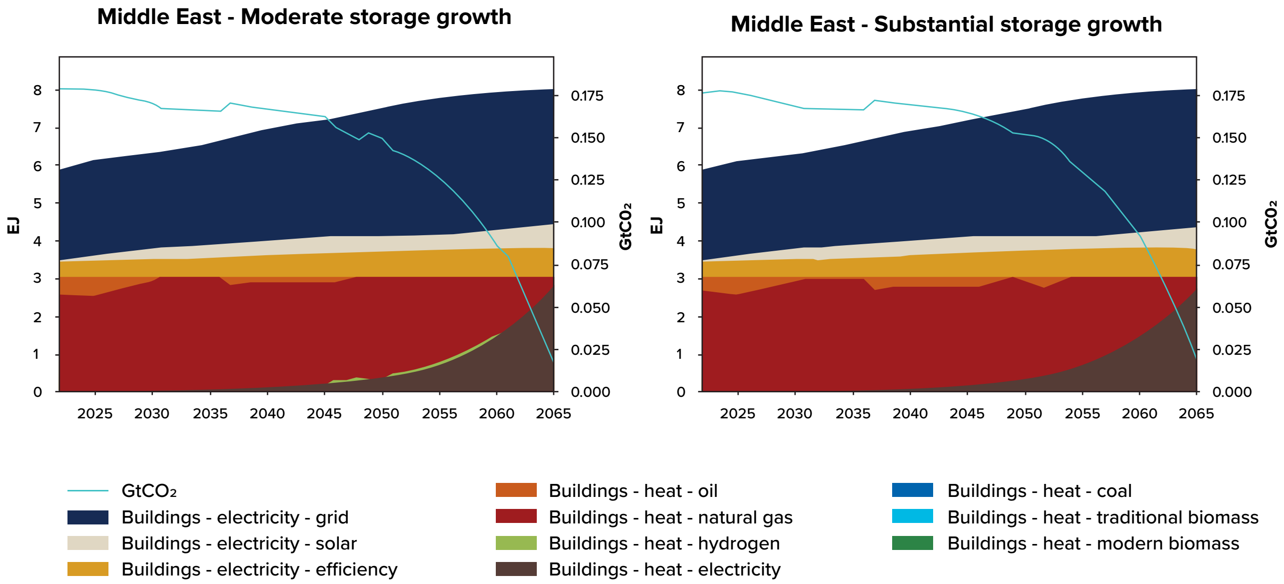
Figure 25: Freight transport



Finally, the buildings sector is almost the same in both scenarios, which energy efficiency and distributed PV growing in both. Heat from oil mostly gives way to natural gas. Starting around 2030, electricity-based heat gradually begins to cut into natural gas and almost displaces all natural gas by 2065. The one real difference in the scenarios is that from 2045-2060 a small amount of hydrogen is used for building heat in the moderate growth scenario.

Agriculture and construction are also essentially the same in both the scenarios.

Figure 26: Buildings



4.3 Summary

The MENA region has clusters of existing emissions sources coupled with nearby high potential geological storage making it possible to develop excellent CCS hub and networks. These networks can act as seeds for CCUS growth supporting the expansion of existing and new industries for MENA region countries.

The findings of the growth opportunities analysis present a compelling case for the strategic pursuit of an accelerated CCS growth scenario in the Middle East. The economic benefits of such an approach are evident when considering the potential for increased export revenues and cost savings across various sectors, though the export revenues depend on other regions also pursuing accelerated carbon storage development.

Furthermore, the analysis highlights the Middle East's advantageous position to act as a CO_2 storage hub for regions with limited storage potential. This ability to import and store CO_2 could become a significant economic activity for the region, with the potential to generate substantial revenues under the substantial storage growth scenario.

One of the primary drivers for higher costs for the moderate storage growth scenario is that this scenario results in almost three times the use of expensive hydrogen and hydrogen-based fuels compared to the substantial storage growth scenario. The industrial sector, for example, primarily sees a combination of CCS and electrification with a modest use of hydrogen in the substantial storage growth scenario. The moderate storage growth scenario, on the other hand, relies far more on expensive renewable-based hydrogen to decarbonize industry.

5.0 CHALLENGES FOR DEVELOPMENT OF CCS HUBS IN MENA

While there are strong opportunities for the development of CCS hubs in MENA there are challenges that need to be overcome to facilitate CCS growth, both specific to the region but also for CCS more broadly.

5.1 CO_2 storage resource development

There are several challenges to developing CO_2 storage resources in the MENA region. Oil and gas exploration and production mean the geological storage potential of the Gulf Coast, and to a lesser extent Algeria and Egypt, is promising. However, the challenge is a lack of publicly availability data and analysis across MENA. The limited access results in a lack of detailed geological and reservoir/seal data, particularly saline formations. In addition, due to the lack of transparency of data, there is low confidence in published results, and that storage knowledge is restricted to companies that acquire the subsurface data, primarily national oil companies, or through subscription services.

In most places across the region there is no data for deep saline formation away from oil and gas producing regions. Globally, deep saline formations will likely host the majority of CO_2 captured; therefore, without sufficient understanding of saline aquifer storage in MENA, the majority of storage resources may not develop in the region. This challenge will mostly impact Egypt, Algeria, Morocco and western Saudi Arabia where there are few giant hydrocarbon fields that could host CCS.

The storage potential in ultramafic and mafic igneous rocks to enable mineral carbonation operations is the final challenge for the MENA region. The full potential in these rock units is unknown in each country apart from a limited study in the Oman ophiolite. Mineral carbonation presents another storage option and additional resources. The limited analysis to date is because mineral carbonation as a commercial option only started with the deployment of the CarbFix project in Iceland in 2023.

5.2 CCS regulatory frameworks

As highlighted in Section 2.1.5, the MENA region faces obstacles to deploying CCS due to the absence of robust legal and regulatory frameworks. Many countries lack specific laws or regulations dedicated to CCS, reflecting an early stage of development in this field. Effective regulations are crucial for successful CCS delivery and aligning with climate goals. Despite promising developments in the region, practical implementation of CCS initiatives may take time as these plans are still in the preparatory phase.

The storage of carbon dioxide in the subsurface introduces concerns around potential liabilities in the event of a loss of containment leading to harm to human health, the environment or property. Risks associated with carbon dioxide storage can arise from either the migration of carbon dioxide within the subsurface or its leakage to the surface. While leakage incidents may occur at any stage of the CCS project lifecycle, challenges around liability often revolve around the post-operations phase, primarily due to the extended timeframes involved.

The extended timeframe associated with CO_2 storage makes it impractical to expect operators to maintain responsibility indefinitely. This expectation is unrealistic given the typical lifespan of commercial entities and the potential obstacles it creates for industry investment in the technology, due to the uncertainty and costs linked to long-term CO_2 storage risks. Consequently, many of the pioneering regulatory frameworks incorporate a provision for the transfer of site responsibility and associated liability to the state after a specified period.

However, it is crucial to distinguish between ongoing legal responsibilities, such as monitoring and corrective actions in the event of leakage, and legal liabilities to third parties resulting from such leakage. For instance, operators may still be held liable for leaks that occur during the operational phase but are only discovered years later.

5.3 Insurance coverage

The insurance sector is poised to play a crucial role in assisting operators in managing liabilities specific to CCS. Existing regulatory frameworks often mandate operators to secure insurance products that address the expenses and liabilities associated with their operations. This includes covering the costs of compliance with regulatory directives and addressing any potential environmental, human health, or property damage.

Some studies have emphasized that CCS faces challenges regarding the conditions of insurability, particularly concerning the predictability of risks and the establishment of well-defined time periods. Legal uncertainty is also a factor, with insufficient clarification of the risk exposure associated with CCS operators in different project lifecycle phases, especially during long-term stewardship. This highlights the significant impact of government regulations and laws on shaping the coverage provided by the insurance sector. This observation aligns with insights gleaned from interviews conducted by the GCCSI with representatives from the insurance sector. In these interviews, regulatory issues were identified as a contributing factor to challenges in the availability of insurance coverage.

In the context of carbon credit schemes, the financial risk linked to leakage is characterized by significant uncertainty, primarily driven by the unpredictable nature of future carbon prices. This uncertainty creates difficulties in accurately assessing the potential financial implications associated with leakage. However, there are promising initiatives that aim to address these challenges. As of the beginning of 2024, the global insurance company Howden has unveiled a pioneering insurance facility, focused on covering the leakage of carbon dioxide from commercial CCS facilities. This facility offers coverage for environmental damage and revenue loss resulting from the sudden or gradual release of CO_2 from CCS projects into the air, land, and water. Notably, this insurance encompasses liabilities associated with carbon credits and allowances, including those related to the UK and EU Emission Trading Systems [114].

Furthermore, based on prior project experience and research, it is argued that many risks associated with the CCS value chain are well-known and manageable. The industry acknowledges a widely accepted risk profile, where the risk of leakage increases during a project's injection phase before significantly decreasing when pressure in the storage site reaches its maximum upon injection cessation and site closure.

5.4 CCS incentives

As with the rest of the world, without policy-driven incentives, capturing CO_2 emissions in the MENA region has no direct economic value beyond revenue from EOR or utilization. The region lacks market-driven incentives and government-backed support measures to stimulate demand for CCS, such as carbon market mechanisms.

5.5 Social and cultural barriers to CCS deployment

The international CCS community has gleaned important insights from the widely publicized shortcomings of early CCS projects. These initiatives often faced significant delays, incurred high costs, and were sometimes abandoned altogether due to strong public opposition. This opposition arose largely because of inadequate consultation and engagement with influential stakeholders and local communities.

In contrast, projects that achieved greater success in terms of public engagement typically involved government participation during site selection and initiated collaboration with local stakeholders from the outset. A pivotal factor in gaining public approval was the opportunity for stakeholders to influence decision-making processes. Effective public engagement necessitates the involvement of all parties affected by the decision. By embracing a diverse group of stakeholders and employing participative methods, projects can markedly enhance the quality of risk identification, risk analysis, and decision-making processes.

A more inclusive approach to public engagement not only fosters improved relationships but also cultivates sustainable and innovative outcomes. This is particularly true when public concerns and values are integrated into decision-making processes at the project's inception stages.

5.6 CCS project scale

Given the location of emission sources to prospective storage in the MENA region countries analyzed in this study it is inevitable that CCS hubs and networks will be required to transport CO_2 the distances necessary to reach suitable storage.

CCS hubs and network projects can be increasingly more complex than historical full chain approaches. The addition of new industries including low emissions fuels, DACCS and BECCS and transport of CO_2 from one jurisdiction to another will only add to this complexity.

As projects increase in complexity so do the potential risks that could lead to challenges in CCS growth. Risks could include:

- Cross-chain risks associated with complex CCS network development. CO_2 emitters need CO_2 transport and storage infrastructure to be available before initiating projects, while transport and storage providers must secure CO_2 demand before investing in expensive CO_2 infrastructure.
- Multiple modes of transport and cross-border transport. This can involve shipping, rail and truck transport with the associated infrastructure introducing technical, regulatory and permitting risks.

5.7 CCS development duration

A typical full-chain CCS project can take upwards of 8 to 10 years to move from concept design to commissioning and operation. Accelerating project lead times will be necessary to see the MENA region to develop CCS projects for CCS growth. The development of hub structures, involving complex networks linking multiple facilities and storage sites, poses challenges, with initial hubs potentially taking much longer to develop than full-chain projects.

Durations can extend as a result of:

- Government permitting and licensing delays
- Delays during CCS hub and network development with coordination of multiple stakeholders
- Storage appraisal and development
- Complex fabrication and construction of CCS infrastructure
- Social opposition that could delay or prevent a project proceeding

5.8 CCS costs

One of the most significant economic challenges of CCUS is the high upfront capital costs associated with building carbon capture facilities and transport, and storage infrastructure. High upfront project costs mean that companies potentially need to take on large amounts of debt, which poses significant barriers. For many industries in the MENA region including the large cement and steel industries, CCS is currently a key or sole solution to decarbonization.

5.9 Technology innovation

While a range of capture, transport and storage technologies are mature and have been around for many years, the costs of current technologies may be too high for some applications and solutions may not necessarily be well suited to integration with existing facilities. New technologies will be needed to support the growth opportunities of CCS in the MENA region.

There is also an excellent opportunity for DACCS and BECCS growth in the MENA region. Current DACCS technologies are in their early stages of development and commercialization with the ORCA project being the first kiloton-scale demonstration project globally in 2021 [111]. DAC will necessitate a reduction in costs from upwards of USD 1,000 per ton currently to realize its potential [112]. BECCS plants are also at the demonstration scale, although associated technologies are more advanced than current DAC technology.

CCS technology innovation can be limited for several reasons:

- R&D can be expensive and comes with a risk that the technology may not reach commercialization
- Often technology demonstration projects come with a level of technical and financial risk that can deter private investment

5.10 CCS technology and cost knowledge

Many commentators often cite CCS as being too expensive and unable to compete with renewables given their declining costs. In countries and regions that are in the early stages of developing net zero strategies this commentary can often lead to the lack of consideration for CCS as a decarbonization solution. However, it is generally well understood that a portfolio of solutions are required to meet global net zero emissions targets. While renewables will be central solutions; other technologies, such as CCS, will also be required. CCS can be a lower cost technology for decarbonization for many industrial emissions sources and in some cases (for example for cement production) the only technological solution to reducing emissions. As MENA region countries and industries develop their decarbonization strategies an understanding where CCS could be applicable, the associated costs and advancements in CCS technology will be essential to ensure CCS is included where it can offer a cost-effective solution.

5.11 CCS water demand

Additional water requirements introduced by CO_2 capture processes can be of concern in areas where water is scarce such as the MENA region. Alternative solutions exist to overcome this challenge such as using less water-intensive capture technologies or optimizing the integration of the capture plant with the host plant. Some of the new-generation technologies for CO_2 capture currently under development can also bring improvements in terms of water demands, although it is not the primary target of developers.

6.0 KEY RECOMMENDATIONS

Based on the study analysis the following recommendations supporting the development of CCS regulation, policy, storage development and business models in the MENA region were identified. MENA region countries should consider these recommendations as they continue to develop the necessary frameworks and tools that will support CCS growth.

6.1 Policy, legal and regulatory

6.1.1 Creation of a regional knowledge hub

Establishing a regional knowledge hub dedicated to CCUS projects could promote alignment and clarity in approaches across countries. Such a hub would facilitate harmonization by providing guidelines and guidance to relevant stakeholders. Additionally, it could foster regional dialogue and collaboration, promoting knowledge sharing and technology transfer. The Middle East Green Initiative launched by Saudi Arabia has various initiatives that could facilitate this, such as the Circular Carbon Economy Regional Colllaboration.

6.1.2 Promotion of green procurement

The KSA government should seek to stimulate demand for low carbon and net zero products, particularly those that are produced by hard-to-abate industries. This could be enabled through its continued participation in activities undertaken by the Industrial Deep Decarbonization Initiative. This could involve the signing of the Green Procurement Pledge announced at COP28, to adopt time bound commitments to procure low emission steel, cement and concrete and setting emissions reduction thresholds for the entire project life cycle assessments.

6.1.3 Incentivizing CCUS investment

The KSA government should design and implement robust financial incentives to attract investment into CCUS projects. The government could develop a range of policy tools including tax credits, grants, operating subsidies, revenue support in the form of contracts for difference.

6.1.4 Strengthening public private partnerships/Boosting R&D investment

The KSA government could help to support public/private partnerships, leveraging the expertise, capacity and funding of the commercial sector to accelerate CCS project development. The formation of public private partnerships could support a CCS hubs and clusters model, where the government could invest and own the infrastructure, whilst private operators cover operation and costs associated with maintenance. The government should also seek to increase investment in R&D, to promote innovation across the CCS value chain, which serves to enhance technological efficiency, reduce costs and provide solutions that are highly suited to the MENA region.

6.1.5 Participation in international coalitions

Enhanced engagement in international coalitions that could stimulate CCS initiatives within the MENA region. The KSA government could encourage other countries in the region to participate in the Carbon Management Challenge, helping to build knowledge exchange and expertise. Moreover, wider participation in the CMC across the region could hold countries accountable in delivering CCS projects, through mandated targets.

6.1.6 Development of CCS specific law and regulations

KSA must establish dedicated laws and regulations to streamline the implementation of CCS projects. The government should explore different approaches to developing a regulatory framework, opting for those that best align with the nation's political landscape. This may involve creating new legislation tailored to CCS, fast track approval processes, or revising existing laws. These measures should effectively oversee CCS activities and tackle specific issues, such as long-term storage, liability transfer post-closure, financial assurances, and seal integrity.

In addition to domestic regulations, KSA should seek to ratify the 2009 amendments of the London Protocol, aligning with international marine pollution policies. This would expand available access to storage resources beyond national borders, enhancing the opportunities for CCS initiatives.

6.2 Storage

Regional and national atlas

The first recommendation is to produce regional (Gulf Coast and Northern Africa) or individual national storage atlases supported by public and open datasets (well, seismic, etc.). These do not exist in the region, yet they bolster commercial success.

An atlas identifies where storage resources are located and how much can be stored. An atlas will also enable a comprehensive mapping and characterization of specific sites, including hydrocarbon fields and saline formations. Although Saudi Arabia is the most advanced in storage development, details are limited and not site-specific.

The outcomes of the atlas confirm the potential for CCS in a country, highlight competition for resources, and enable nationwide planning, including hub infrastructure. An atlas also identifies data gaps and major risks, including the limitation of CCS in a nation based on its emissions profile and storage resources. An atlas will also enable a comprehensive mapping and characterization of specific sites, including hydrocarbon fields and saline formations. Although Saudi Arabia is the most advanced in storage development, details are limited and not site-specific.

Mapping these storage resources promotes a broader understanding of the overall CCS potential of the region, rather than that knowledge (and data) being limited to only the oil and gas industry as it stands today. In addition, new storage operators could rapidly progress initial screening analysis by using the outcomes and data of the atlas.

A proven example globally is the National Atlas of the USA in 2015 [113] and the subsequent programs (CarbonSAFE) that enabled national CCS planning. It helped expedite CCS as a decarbonization option for the USA's growing emissions. The following release of the 45Q tax credit and government investment in CCS was only possible if the government knew storage could meet emission demands. See Cevikel and Thomas [114] for more details:

Pre-competitive storage analysis

Based on the findings of the atlas, a government-led de-risking of storage resources through pre-competitive data acquisition can remove the initial risk and cost barrier to storage exploration. A program aims to fill data gaps, reduce risk, and improve confidence in the geology. The programwould vary from site to site but could include core analysis and modelling, seismic acquisition, or drilling a well.

The key focus areas should be:

- De-risking highly prospective regions with subsurface data adjacent to emission-intensive areas, such as the east coast of the Gulf Coast.
- Filling data gaps in areas with limited hydrocarbon exploration and production but likely have suitable saline formations, such as the Western Desert of Egypt.
- Greenfield regions with no data are strategically placed near emission-intensive regions, such as coastal Morocco and northern Algeria.

The most critical aspect of pre-competitive data acquisition is to make the data publicly available. Much like the atlas, this program enables a broader understanding of the storage potential of the region, rather than that knowledge (and data) being limited to only the oil and gas industry.

A proven example globally is the Australian Government, which funded the national geological survey to complete several pre-competitive data acquisition programs to support storage development. The programs varied from greenfield data acquisition through to de-risking storage sites. A CCS project has been announced in each area where data was acquired. (https://www.ga.gov.au/scientific-topics/energy/resources/carbon-capture-and-storage-ccs/geological-storage-studies).

Permitting

Building on a storage atlas and then a pre-competitive data acquisition program, the national regulator for CO_2 storage is then empowered to initiate a permit program for storage, as the permitted area's risks are known, data gaps known, and storage potential known. As the site is initially de-risked and data is gathered for the site, the acreage release system can move rapidly—the public availability of the data acquired, and subsequent permitting area increases confidence in the prospects. In addition, due to the conclusions of the atlas and data acquisition findings, the regulator can create a competitive permitting (acreage) system for highly prospective areas.

Following the Australian Government example above, the Australian offshore regulator subsequently released a series of competitive storage exploration permits across offshore Australia. After a competitive tender program, these permitted sites now host several active CCS hubs. These hubs are variably planning to decarbonize natural gas, LNG and other industries in Australia and globally via international CO_2 shipping.

6.3 Business models

Many of the above recommendations support business model development in KSA and the broader MENA region. Beyond the above recommendations the following could provide additional support to business model development.

6.3.1 Long term planning

KSA as well as other MENA region countries, should continue to develop long-term strategies for CCS deployment in the MENA region, considering factors such as energy demand growth, climate change mitigation goals, and technological advancements. This should involve identification of prospective CCS hubs and networks within each country through Government and industry collaboration and expand to consider CCS network opportunities regionally. This can support identification and selection of business models best suited to development of identified hubs and overcome risks that may arise with complex CCS networks.

6.3.2 Cross chain business models leveraging existing expertise

KSA and the MENA region countries should explore business models that focus on separate models for capture, transport, storage that decouple value chain risks and leverage specific expertise in each area. State owned oil companies should be leveraged to support transport and storage infrastructure given the expertise and knowledge they have; however, business models should not isolate potential service providers (such as alternative transport providers for shipping, trucks or rail) that could support more complex CCS network development aiding CCS growth.

6.3.3 Cross border transport

Business models in the MENA region will need to consider cross-border transport of CO_2 within the region and the opportunity to receive CO_2 imports from neighboring regions. Given the opportunity KSA has with potential storage availability, it could lead early negotiations across the region to develop a business model that will support cross-border transport and CO_2 imports.

6.3.4 Develop regional CCS expertise through project development

Each MENA country should develop pilot CCS projects to build local expertise, test technologies in various geological settings, and demonstrate viability to potential investors. Learnings from these pilot projects should be shared in the region to ensure lessons learned are quickly captured enabling rapid scale-up of commercial CCS projects.

7.0 CONCLUSION

This study provides a detailed summary of the state of CCS in the MENA region with the following observations being made:

- Countries in the MENA region have made diverse policy commitments regarding CCS in their NDCs and through public announcements.
- MENA region countries are yet to formally develop CCS regulatory frameworks and there are currently no CCS incentives allowing CCS growth.
- MENA hosts three commercial CCS facilities in the region with the ADNOC Al-Reyadah CCS project capturing CO_2 from steel production commencing operation in 2016. Eleven commercial facilities are also in development, with the projected commissioning years between 2025 and 2027 and several feasibility studies are underway.
- There is good storage potential for CCS with high confidence in identifying viable storage resources due to suitable geology in the Gulf Coast, Egypt and Algeria.
- There are several prominent research centers that are actively involved in research and development in CCS, particularly in KSA, UAE, Qatar and Oman, that could be leveraged to support CCS growth regionally.

The study analyses CCS business models that are being developed globally highlighting a focus on CCS hubs and networks that leverage expertise in each element of the value chain with business models for capture, transport and storage emerging.

In the MENA region, there is currently a lack of government funding sources for CCS projects with a perception that funding and development of such projects should be entrusted to the private sector. The study details several policies that have been used to increase demand for CCS and government and private funding examples from other regions that might offer potential opportunities for adoption in the MENA region.

A broader analysis on CCS hub opportunities in the region shows a number of current emissions clusters and storage areas of interest that could support CCS hub and network development. Modelling using the institutes GENZO model shows a compelling case for an accelerated CCS growth scenario considering the potential for increased export revenues and cost savings across various sectors. The modelling also highlights an opportunity for the region to act as a CO_2 storage hub for regions with limited storage potential. This ability to import and store CO_2 could become a significant economic activity for the region, with the potential to generate substantial revenues.

While CCS growth is an opportunity for the MENA region, there are challenges that will need to be overcome. The report highlights several challenges that are both specific to the region and more broadly related to CCS and that will need to be addressed to support these CCS growth opportunities.

The analysis concludes with several recommendations based on the study's analysis focused on the development of CCS regulation, policy, storage development, and business models in the MENA region. It is important that KSA and other MENA region countries consider these recommendations and work collaboratively with all stakeholders as they continue to develop the necessary frameworks and tools to support CCS growth.

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APPENDIX A: STORAGE ANALYSIS

The screening criteria and their weighting are presented in the table below. The screening and ranking of identified basins are conducted in two stages. In Stage A, basins undergo screening and ranking using criteria 1 to 8, weight factors, and scoring criteria defined in the table below. Each basin is assessed against specific criteria crucial for CO_2 storage feasibility, as outlined in the provided table. A numerical score is assigned to each basin for every criterion based on predefined scoring categories within the table. A score of 3 denotes the most suitable conditions, 2 signifies moderate suitability, and 1 indicates unsuitability. A score of 0 is reserved for cases where relevant data is unavailable.

Subsequently, each score is multiplied by the defined weight factor for the criterion, which assigns a weight to each criterion based on its importance. The total score for each basin is obtained by summing these weighted values, enabling the ranking of basins. Basins with a total score higher than 2.1 are categorized as ''Category I'' basins, presenting early opportunities for storage. Those with a net score between 1.2 and 2.1 fall into ''Category II'', providing contingent storage resources. Basins with a total score of less than 1.2 are assigned to ''Category III'', potentially offering prospective resources awaiting discovery. Notably, utilizing the defined scoring system, the minimum total score for a basin is 0.35. The defined scoring range is obtained by dividing the range between the minimum score (0.35) and maximum score (3) into three equal intervals.

SECTION		CRITERIA	SCORE			
			3	2	1	0
Geology	1	Sedimentary basin area	> 50,000 km2	25,000 - 50,000 km2	< 25,000 km2	
	2	Tectonic setting	Divergent	Intermontane	Convergent	
	3	Hydrocarbon production maturity (producing and abandoned fields)	>= 5 fields	3 <= n < 5	1 <= n < 3	No field
	4	Giant gas fields (400 bcf ≈ 20 $MtCO_2$)	>= 5 fields	3 <= n< 5	1 <= n < 3	No field
	5	Giant oil fields (500 MMbbl ≈ 20 $MtCO_2$)	>=5 fields	3 <= n < 5	1 <= n < 3	No field
CO_2 storage projects (Commercial)	6	Basin associated with commercial CO_2 storage projects	Project Operating & Completed	Advanced development /	Commercial CCS Facility	No project
CO_2 storage projects (Pilot)	7	Basin associated with pilot CO_2 storage projects	Project Operating & Completed	Advanced development / In construction	Early development	No project
Geology	8	Depositional system	Marine	Mixed	Non-Marine	NA- Unknown

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APPENDIX B: CO_2 EMISSIONS DATA

The emissions data in this study was derived using facility location and production data from several databases coupled with standard emissions profiles from publicly available engineering studies and GCCSI reports as presented in the table below.

SECTOR	TYPE/UNIT/SOURCE	SPATIAL DATA AND PRODUCTION CAPACITY	EMISSIONS INTENSITY / CONCENTRATION SOURCE
Steel	Electric Arc Furnace, Furnace-Basic Oxygen Furnace, Direct Reduced Iron	Global Steel Plant Database [115]	IEAGHG 2013 "Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)" [116]
Cement	Integrated - Kiln and Heating	Global Cement Plant Database [117]	IEAGHG 2008 "CO_2 Capture in the Cement Industry" [118]
Chemical and Petrochemical	Numerous – Ammonia, Urea, Ethylene, Propylene	GlobalData Petrochemical Plant Database [119]	GCCSI NT CCS Hub Study Data [117]
Refinery	Numerous – Crude Distillation, Hydro skimming, Cracking, Coking, Topping	GlobalData Refinery Database [119]	IEAGHG 2017 "Understanding the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery" [120]
Power Generation	Coal, Gas and Oil-Fired Power Generation	Global Power Plant Database [121]	GCCSI NT CCS Hub Study Data and IEAGHG 2014 "CO_2 Capture at Coal-Based Power and Hydrogen Plants" [122], [123]

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