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Perspective

Establishing leadership in bringing carbon capture, utilisation and storage to scale

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ABSTRACT

Carbon capture, utilisation and storage, often referred to simply as CCUS, refers to a suite of technologies to decarbonise many hard-to-abate industries. However, commercial-scale adoption of CCUS technologies faces critical barriers related to application scope, societal acceptance, and financing. Here we propose how fossil energy-exporting countries are uniquely situated to expedite CCUS deployment at scale. Using a sociotechnical systems perspective, we show how one such country, the United Arab Emirates, serves as an important case study for addressing eight different sociotechnical barriers to CCUS adoption. We evaluate the elements that are addressed by factors related to local context and those which represent opportunities for application in other geographies. We argue that scaling-up CCUS is both a duty and opportunity for countries like the UAE as they decarbonise their industries and economies.

1. Introduction

Global commitment to transitioning away from fossil fuels is recognized [1] as essential to meeting climate targets. Nonetheless, the continued role of fossil fuels in modern economies and the need for their responsible carbon management make accelerated action critical in the coming decade, in order to enable a just and equitable transition.

Further, given the stark realities of climate change, as outlined by the Intergovernmental Panel for Climate Change's (IPCC) Sixth Assessment Report (AR6) [2], this need for urgent action is clearer than ever. The report states that there is a more than 50 % chance global temperature rise relative to pre-industrial levels will reach or surpass 1.5 °C between 2021 and 2040 across various scenarios. In 2020, the IPCC estimated that the remaining carbon budget for the 1.5 °C target was between 300 and 900 Gt CO_2, with a central estimate of 500 Gt CO_2. However, since then, continued CO_2 emissions and rising global temperatures have drastically reduced this budget. We note that a large number of studies have been published with carbon budgets estimates, with varying values depending on assumptions, methodological and model differences [3]. As an example, in 2023, the remaining carbon budget is estimated to be around 250 Gt CO_2 – expected to be exhausted within around 6 years, under a business-as-usual scenario [4]. As of early 2024, an update to this model places the remaining carbon budget between 100 and 450 Gt CO_2, with a central estimate of just 200 Gt CO_2 [5]. This value is in line with the latest estimate from the Global Carbon Project, which places the remaining carbon budget for a 50 % likelihood to limit global warming to 1.5 °C at 235 Gt CO_2, as of January 2025 [6]. Limiting global warming will require aggressive emissions reductions, regardless of which cross-cutting solutions are embraced. These solutions include very low- or zero-carbon energy sources such as nuclear and renewables, conventional power generation integrated with carbon capture (CC), demand-side measures (DSM) and efficiency improvements, reducing non-CO_2 GHG emissions, and carbon dioxide removal (CDR).

Carbon capture, utilisation and storage (CCUS) remains an important lever in the context of industrial emissions reduction. CCUS use, particularly in hard-to-abate sectors, features in the Paris Agreement's first Global Stocktake outcome document endorsed at COP 28 in 2023 (also known as "the UAE Consensus"), as part of a list of zero and low emissions technologies for Parties to act on and accelerate [1]. Further, three of the four pathways depicted in the IPCC's AR6 on 1.5 °C involve major use of carbon capture and storage (CCS) specifically, ranging from 350 to 1200 Gt CO_2 to be captured and stored within this century [2].

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According to IEA's Net-Zero Roadmap by 2050 [7], 7.6 Gt CO_2 will need to be captured per year by 2050, meaning the use of CCS must increase relative to today's levels by at least 100-fold by 2050 to meet the roadmap targets. This need for CCS in the IEA's Sustainable Development Scenario (IEA-SDS) translates to an estimated 70–100 CCS facilities built per year, which is estimated to require a total capital investment of between 655 billion USD and 1280 billion USD. In its Global Status of CCS 2024 report (GSR), the Global CCS Institute indicated current CCS deployment levels of 51 Mt. CO_2, with 365 Mt. CO_2 currently under different stages of development, highlighting the urgent need to accelerate the pace and scale of deployment globally [8]. We note that although these specific documents discussed the use of CCS, here we adopt CCUS as the broader term in our paper discussion, except where the more specific CCS term is appropriate.

Given that CCUS is a critical cross-cutting tool for CO_2 emissions mitigation, complimenting other key net-zero technology levers, including renewables, nuclear, energy efficiency and clean hydrogen [9], it is important to enable and accelerate global adoption rates of CCUS technologies across sectors, with particular focus on where it is considered most crucial. To accelerate global CCUS adoption, it is essential to address existing barriers and harness local drivers, as current deployment still lags far behind the required pace. Further, the extent to which CCUS adoption occurs in hard-to-abate sectors can meaningfully impact the degree to which current industrial infrastructure, primarily reliant on fossil-based energy sources, can continue to operate. Many Paris Agreement-aligned scenarios suggest that demand for fossil fuels will persist beyond 2050 [2]. As a result, several industrial sites will effectively require the use of CCUS to meet climate targets, should they continue operating with existing technologies. Thus, the issue of avoiding stranded assets [10–12] as a main barrier to decarbonisation efforts is an essential consideration. Indeed, a common criticism of CCUS is that it is a decarbonisation lever that provides a lifeline for the fossil fuel-based industry and business-as-usual polluting practices.

This narrative, however, is one that detracts from the critical need for CCUS as a realistic path to reduce industrial emissions. It must account for local context factors, including heterogeneous industrial emissions profiles, heterogeneous spatial distribution of CO_2 sources and potential sinks, and uncertainty surrounding sustainable injection rates in different geological formations that may result in uneven CO_2 storage prospects in different locations [13]. Beyond these purely technical considerations, and as we explore in this perspective, several key socio-technical challenges to CCUS adoption are present (Fig. 1) and must be addressed if adoption is to occur at scale. These include barriers along economic, technological, infrastructural, institutional and socio-cultural dimensions.

As such, countries with significant carbon emissions and the capacity to develop critical mitigation technologies, such as CCUS, have a dual responsibility: to take accountability for their emissions and to lead global efforts in deploying solutions [15,16]. The United Arab Emirates (UAE), as a leading exporter of fossil energy, specifically oil and to a

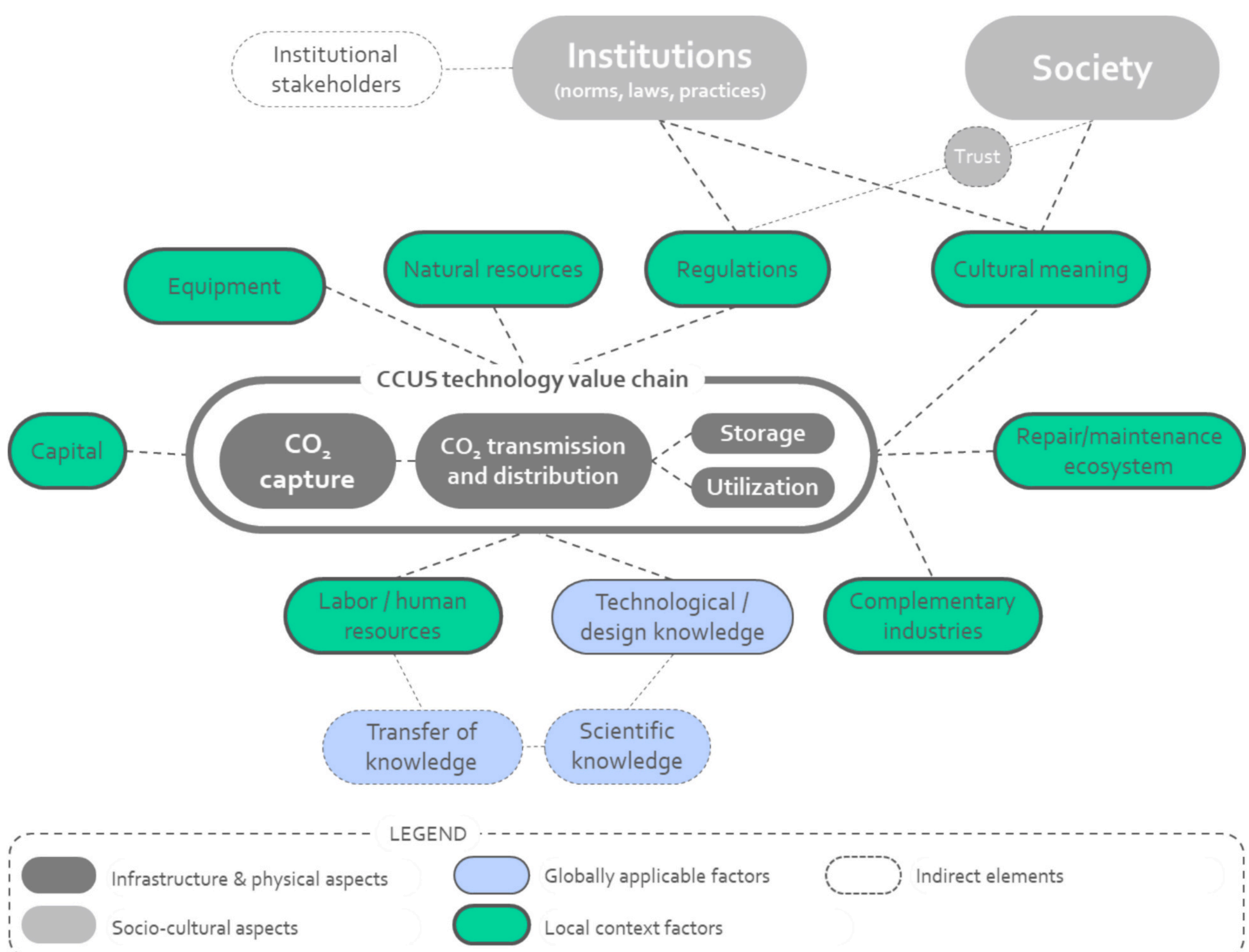

Fig. 1. Sociotechnical system elements of CCUS. Main technology value chain elements (dark grey) and socio-cultural elements (light grey) are shown alongside key elements used by Geels [14] to elaborate the multi-level perspective (MLP) framework; these elements are differentiated between local context factors (green) and globally applicable factors (blue). Source: Authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lesser extent gas, exemplifies this dual role. It has both the responsibility and the unique opportunity to catalyse the global energy transition by advancing decarbonisation technologies like CCUS. By integrating its industrial, economic, and social strengths into a strategy, the UAE can establish a global benchmark for how fossil fuel-based economies can address climate change while maintaining economic competitiveness.

This paper adopts a sociotechnical systems lens to explore the interplay of economic, regulatory, institutional, and cultural factors in CCUS adoption. We highlight the UAE as a case study to demonstrate how these barriers can be addressed holistically. The UAE's strong industrial base, supportive policies, and societal embrace of sustainability create an enabling environment to overcome barriers to CCUS deployment, such as investment risks, public scepticism, and regulatory uncertainties.

In the following sections, we examine the key sociotechnical barriers hindering global CCUS adoption and detail how the UAE's context-specific strategies address these challenges. By analysing the UAE's leadership in CCUS, this paper provides a framework for how fossil fuel-dependent economies can accelerate climate action. We conclude with a discussion on the lessons that can be extracted for other countries aiming to scale CCUS adoption for climate change mitigation.

2. Existing barriers to CCUS adoption that need to be addressed

2.1. CCUS readiness

CCUS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided that suitable geological storage is available [2]. Lessons from past projects show the importance of thorough site characterisation to address potential performance issues. For instance, at the Tomakomai CCS demonstration-scale project in Japan, injection capacity varied significantly depending on the geological layer being tested. At the Moebetsu Formation, a shallower sandstone layer, 300 kt CO_2 were injected between April 2016 to December 2019, while in the deeper volcaniclastic layers of the Takinoue Formation, only 98 t CO_2 were stored in the same period [17]. Further, site-specific geophysical characteristics can affect injection capacity as well. At the Gorgon CCS commercial project in Australia, issues with reservoir pressure in the Dupuy Formation showed the importance of implementing management strategies to reach CO_2 capture goals in the face of operational challenges [18].

CO_2 capture itself is a mature technology, although with limited adoption. Indeed, across hard-to-abate sectors, CC adoption readiness varies significantly. For some industries, such as oil and gas (O&G), prior adoption of related processes, unit operations and activities create a pool of expertise and a skilled workforce capable of being repurposed for CCUS. Such O&G processes and operations including "sweetening" (or sulphur removal) of natural gas [19] and enhanced oil recovery (EOR) via subsurface injection of fluids (e.g., in particular CO_2-containing gases) [20,21] support a fast deployment of CCS technologies in this industry [22]. Further, harnessing the subsurface and offshore expertise [23] of the O&G workforce can help navigate around similar-in-scope issues with geologic CO_2 storage on land. Comparatively, industrial point-sources of CO_2 in the other hard-to-abate sectors have a less certain prioritisation for CCUS. This is the current status not only in heavy industries, such as iron & steel [24], cement & concrete [25], chemicals [26], but also in the power sector [27,28].

The extent to which CCUS can be considered a primary lever to reduce carbon emissions varies depending on the industry, resulting from sector-specific aspects, such as: process technology value chains; physical configurations of industrial sites; and policy and regulatory ecosystems. For technology value chains where the bulk of CO_2 emissions can be associated with energy use, such as the glass industry [29], fuel switching and electrification are more relevant [30–32]. Regarding the physical configuration of industrial sites, these oftentimes comprise multiple individual emissions stacks, rather than a centralized one. This variation in the number of point sources, coupled with a heterogeneity in the composition of flue gases (both in terms of CO_2 concentration and of nature and quantity of other contaminants), can hinder cost-effective CCUS deployment at scale. In the case of process emissions, such as in the cement & concrete industry, decarbonizing current clinker production will require CO_2 capture. Alternative decarbonising options will depend on material substitution and commercialisation of novel cement chemistries. This, in turn, necessitates that the appropriate regulatory frameworks (e.g., building codes specifying minimum clinker content requirement in cement products, due to safety and performance criteria) be amended [33].

2.2. CCUS acceptance

The public and scholarly discourse on the role and importance of CCUS in climate action has evolved in recent years in parallel with the discourse among policymakers and other stakeholders. Critical perspectives of CCS, for instance, stem from wider debates on the role of fossil energy use in a net-zero context [34]. The framing of CCS among fossil industry stakeholders is one that supports a continued role of fossil energy in the global economy [35]. For CCU, critical perspectives have evolved from one characterising it as a potentially "costly distraction" [36] to one where the barriers and substantial challenges [37] may be overcome via actionable policy and technology efforts [38]. Trust and public perception also play a crucial role [39,40], as community opposition can undermine project success [41]. One example is the Barendrecht CCS project in the Netherlands, which was cancelled despite political support, largely due to public resistance [42]. Such views can be reinforced in the case of CCS project underperformance. As with the Gorgon CCS project discussed above, failing to reach CO_2 capture targets can negatively impact investor confidence in the financial viability of CCS projects [43], adding to such negative perceptions. For bioenergy with carbon capture and storage (BECCS), an important and potentially carbon-negative technology, uncertainty on the extent to which this technology may be a feasible option remains a point of contention among scholars. For instance, reconciling ambitious model-oriented assessments of BECCS feasibility [44] with physical constraints, such as the very large land requirements for implementation paths, highlights its more limited potential due to land-use challenges and associated socio-political factors [45].

2.3. CCUS investment

According to the GSR [8], leading nations are advancing CCUS through policies and funding. In North America, federal incentives are driving projects, while China's Green and Low-Carbon Technology Plan supports CCUS as part of decarbonisation efforts. In the 2018–2024 period, global project development has surged, with operating capture capacity set to double as new facilities come online. This increase in the CCS project pipeline (i.e., upcoming projects) can be seen in the CO_2RE database [46], which tracks facility count and CO_2 capture capacity. Despite this progress, investment in CCUS remains insufficient to meet climate objectives due to a number of regulatory, technical and commercial barriers. These include (i) fragmented net-zero strategies [47] (ii) limited policy and regulatory support [48], (iii) high initial capital investment [49], (iv) first mover penalty [50], (v) cross-value chain risk (i.e., risks a CCUS project faces due to failures in other elements of its value chain) [51], (vi) and increased perception of risk due to information failures [41]. When it comes to CCS projects, Rassool et al. frame such "hard-to-reduce" risks as five different types of market failure mechanisms at different points in the CCS value chain (Fig. 2). As we elaborate further in this perspective, appropriate de-risking mechanisms, from subsidies to government-backed guarantees, are suitable ways to address barriers to CCUS investment.

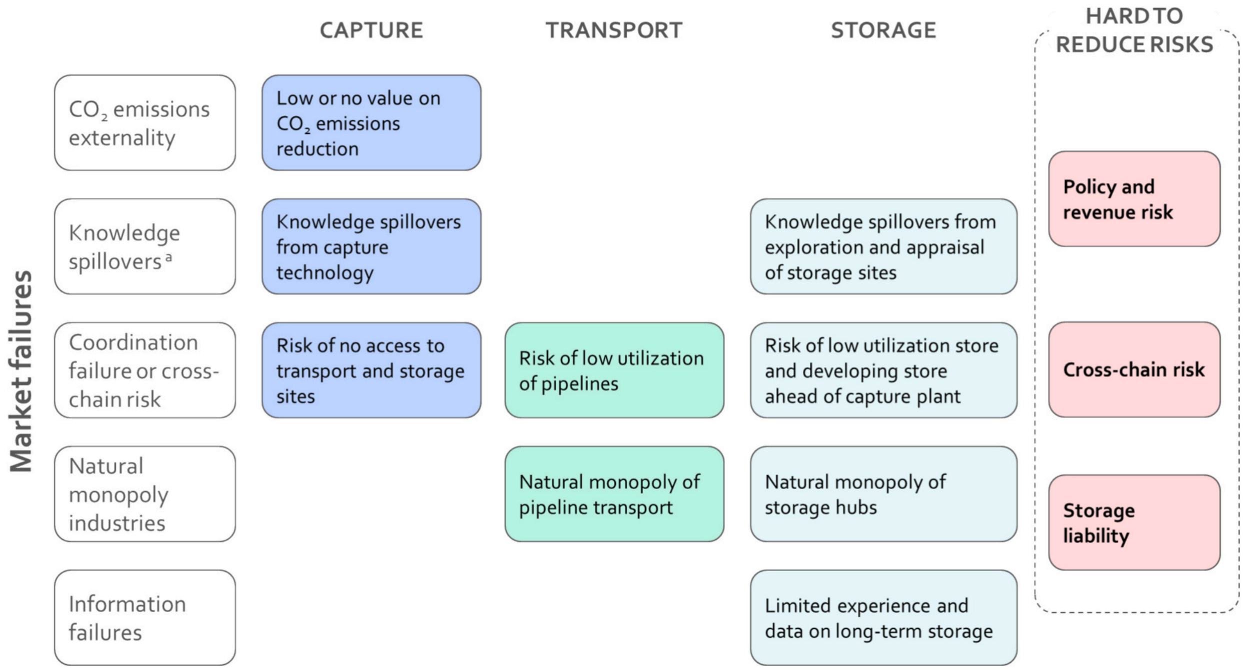

Fig. 2. Key CCS market failures lead to hard-to-reduce risks. Market failures in the capture (blue), transport (green) and storage (light blue) are categorised according to five types; market failures result in hard-to-reduce risks (red) for CCS adoption. Note: [a]: "knowledge spillover" is used in the intellectual property (IP) context of non-compensated access to proprietary information. Source: adapted from [52] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Lessons and opportunities from the UAE, a fossil fuel-exporting economy

The case for CCUS adoption must address and provide solutions for technical, economic and sociocultural barriers. For hard-to-abate sectors, CCUS remains a technically feasible and needed solution [53], which co-exists among other policy and technology tools to enable global industrial decarbonisation [54]. Increasingly, commercial barriers to CCUS adoption at scale are being tackled, as economically feasible paths for commercial CCUS adoption are proposed [55]. For societal acceptance, it is important to stress that CCUS is a climate change mitigation technology portfolio, and not merely a fossil energy-supporting one.

Countries, such as the UAE, are uniquely positioned to support, and perhaps have the responsibilty for supporting, CCUS adoption and to expedite its commercial scale implementation. By leveraging its strong industrial base and strategic vision, the UAE can address barriers by (i) relying on anchor industries to centralize efforts, (ii) promoting circular carbon economy (CCE) initiatives, (iii) establishing robust knowledge-sharing platforms and capacity building initiatives, (iv) improving the understanding of physical (i.e., geologic) capacity in the country to store CO_2, (v) leveraging societal support for CCUS, (vi) developing novel business models to avoid cross-value chain risks, and (vii) addressing regulatory and policy gaps [56]. Further, streamlined development of a CCUS ecosystem in the country would lead to additional benefits beyond achieving economies of scale to unlock significant cost reductions [57]. These include potentially localising carbon capture technology manufacturing and building regional interconnections with neighbouring CCUS hubs to tap into cross-border CO_2 storage. As summarised in Fig. 3, the barriers described in the preceding sections are associated with the sociotechnical elements depicted in Fig. 1 and can be mapped against eight CCUS sociotechnical elements for which the UAE has the capacity to address.

In the following sections, we elaborate on how the UAE is positioned to address the barriers to CCUS adoption indicated in Fig. 3.

3.1. Industrial anchors facilitate CCUS

As the UAE pursues an ambitious industrial growth strategy, addressing the industrial decarbonisation challenge is central to achieving its carbon neutrality goal by 2050. From Abu Dhabi's Mussafah, to Jebel Ali in Dubai, as well as key industrial clusters in Sharjah and Ras Al Khaimah, the UAE serves as a hub for large-scale, integrated industrial complexes, where an array of energy- and carbon-intensive industries converge, including power generation, oil refining, natural gas processing, liquefied natural gas (LNG) production, steel manufacturing, cement, petrochemicals, and aluminium production. These industries are fuelled primarily by natural gas, Liquefied Petroleum Gas (LPG), and other conventional fuels, alongside power from both the electricity grid and off-of-the-grid generation. As a result, they are responsible for nearly half of the country's GHG emissions, at around 103 Mt. CO_2 in 2019 (Fig. 4), necessitating deployment of CCUS to mitigate emissions from both processes requiring high-temperature heat, where electrification coupled with renewables may not be viable, and residual emissions.

The concentration of major industrial players in the UAE, each contributing significantly to both industrial output and emissions, streamlines the coordination of decarbonisation efforts compared to regions with more fragmented industrial landscapes.

In 2021, the UAE's industrial sector accounted for the largest share of the country's total energy demand, with natural gas making up 98 % of its consumption. As part of "Operation 300 Billion", the UAE aims to double the sector's GDP contribution to 300 billion AED by 2031, increasing energy demand and posing challenges to carbon neutrality targets. To address this, the UAE's Industrial Decarbonisation Roadmap targets a 93 % reduction in industrial emissions by 2050 relative to 2019 levels.

The roadmap identifies that CCUS, energy efficiency measures, and clean electricity could collectively contribute 70 % of the reductions. A rigorous examination of 50 low-carbon technologies and innovative solutions was undertaken, including clean hydrogen, fuel switching, clinker substitutes, recycling, and manufacturing efficiency

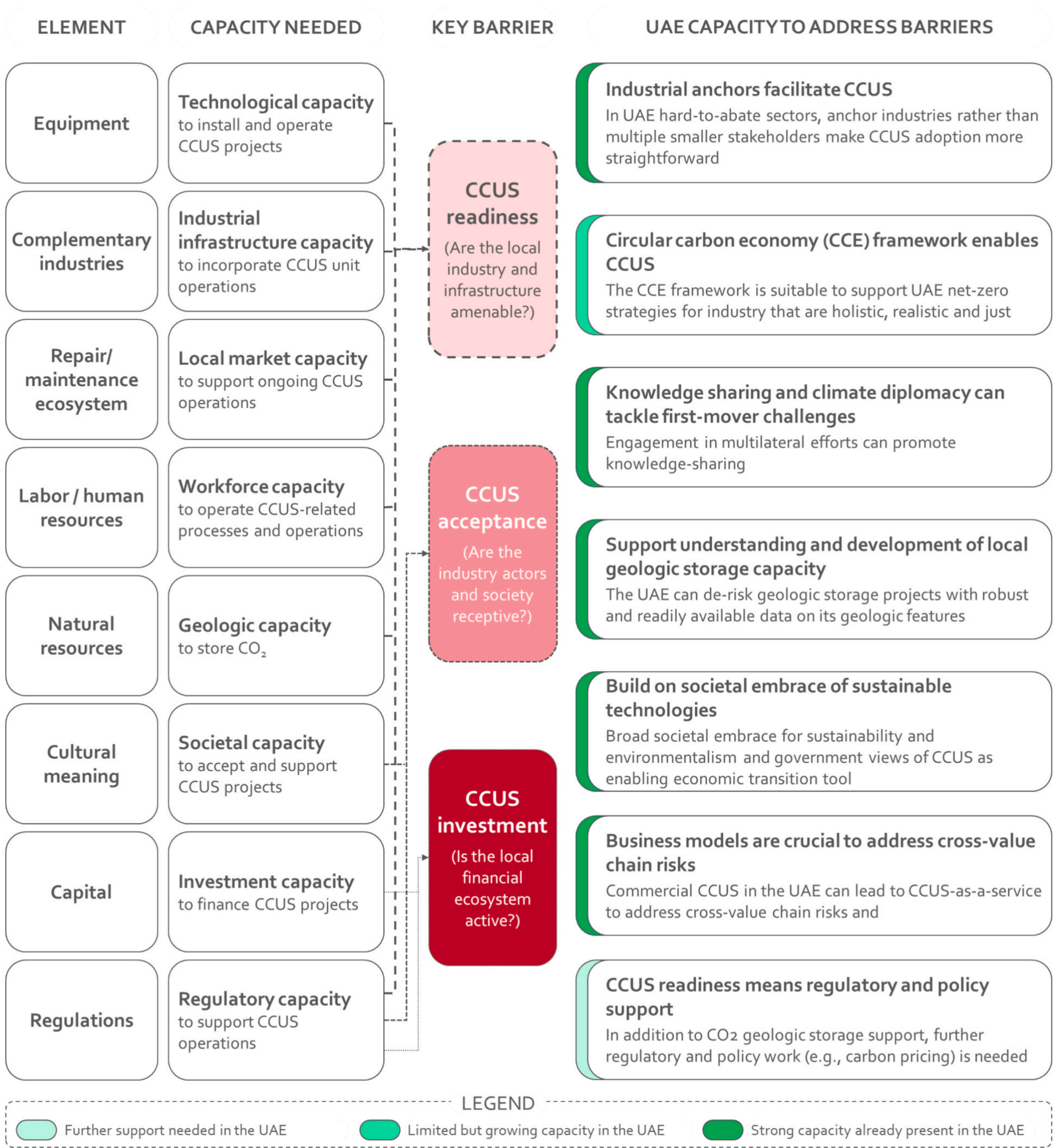

Fig. 3. Summary of main barriers to CCUS adoption and local UAE capacity to address them. UAE capacity to address barriers associated with main CCUS socio-technical elements are categorised (see legend). Source: Authors.

improvements [59].

Notably, industrial anchors in the UAE operate with relative ease compared to other regions where industrial clusters may concentrate many independent stakeholders. This diversity of stakeholders adds a layer of complexity in cross-sectoral coordination and cooperative efforts [60].

The UAE's hard-to-abate sectors benefit from geographical proximity of CO_2 source and sinks, facilitating streamlined infrastructure development for CCUS. The close proximity of upstream oil extraction activities further enhances this potential, leveraging existing infrastructure and a skilled workforce to support CCUS initiatives. While CCUS clusters offer the opportunity to capture CO_2 from multiple emitters and to reduce costs by utilising shared transport and storage infrastructure, the presence of anchor industries also create economies-of-scale.

3.2. Circular carbon economy (CCE) framework enables CCUS

The UAE's industrial decarbonisation roadmap embodies the circular carbon economy (CCE) concept, which was endorsed by G20 ministers in 2020, focusses on the 4Rs of reducing, reusing, recycling and removing CO_2 emissions [61,62]. The UAE's carbon management strategy can set an example for a holistic and practical approach toward leveraging CCE principles for achieving net-zero targets. This is important given that net-zero scenarios that focus solely on reducing or eliminating the use of fossil fuels often pose significant socio-economic

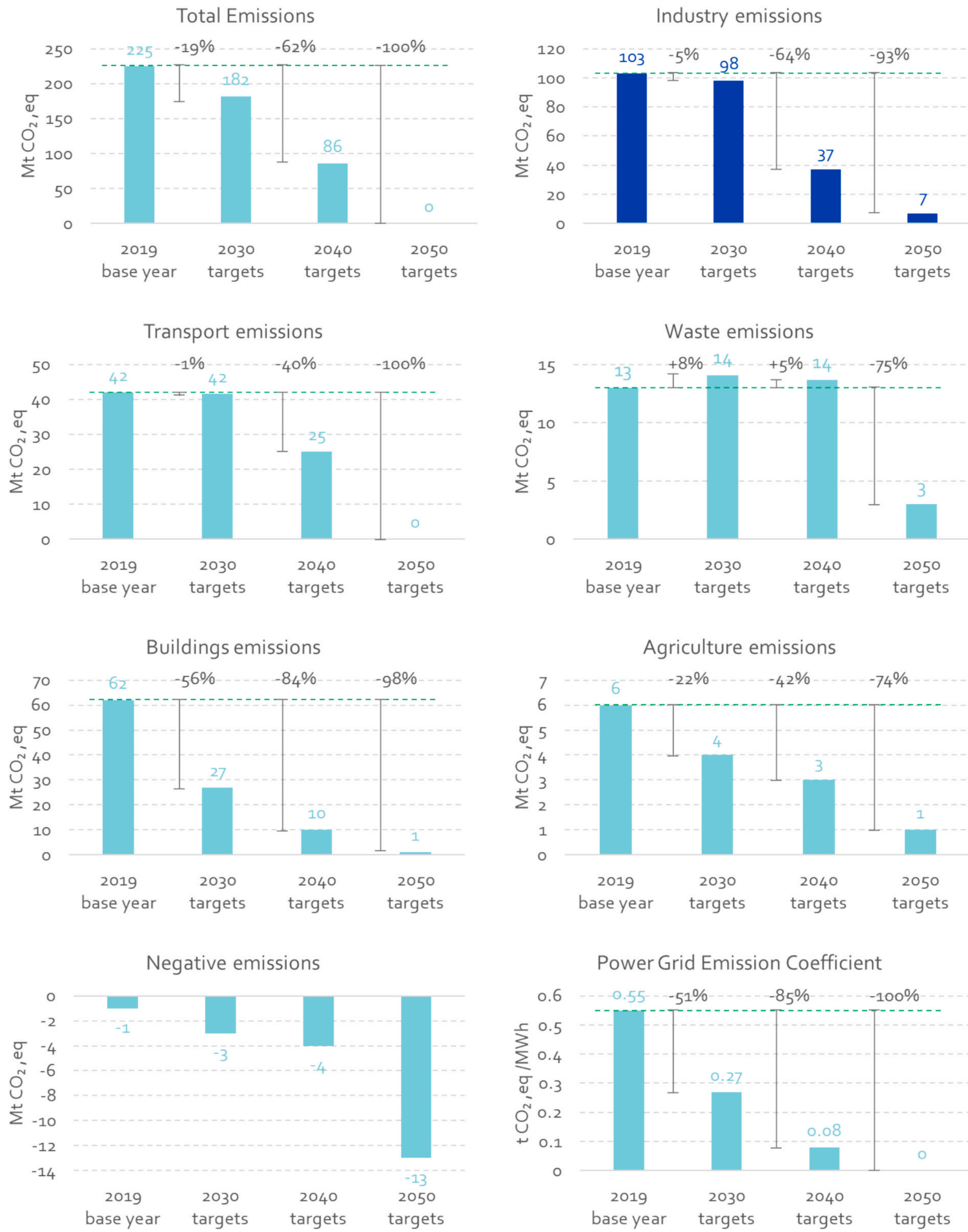

Fig. 4. Sectoral emissions in the UAE, historical (2019) and scenario forecast (up to 20,250). Emissions (in Mt. CO_2,eq) and percentage reduction over 2019 baseline are rounded to the nearest unit. Power grid emission coefficient (in t CO_2,eq/MWh) are estimated from electricity generation mix. Note: sectoral emissions include indirect emissions from power and water use. Source: Adapted from [58]

challenges for countries in the Global South. A purely fossil fuel-independent energy transition implies the potential squandering of existing infrastructure investments while a potentially lengthy and costly transition to new energy sources is pursued. Further, such scenarios could undermine energy security, neglecting the pressing needs of developing countries in the Global South seeking affordable and dependable energy access. A blanket avoidance of CCUS options would further overlook practical negative emissions solutions, such as CCU (emphasis on utilisation), BECCS, and Direct Air Capture (DAC), that may be essential for achieving net-zero in the long term. In short, net-zero scenarios that exclude CCUS technologies are likely to be socially unacceptable and more challenging to finance and implement in a multitude of contexts [63].

The UAE's pursuit of the CCE paradigm reflects what is perhaps the most realistic approach for the country to achieve net-zero by 2050. While renewable energy has made significant progress, relying solely on renewables is impractical, if not impossible. Therefore, a more realistic strategy is required, one that acknowledges an ongoing role of fossil fuels in the economy and therefore necessitates effective carbon management. The CCE concept, which is a logical extension of the circular economy paradigm, integrates all carbon mitigation strategies into a cohesive system aligned with the Paris Agreement's climate objectives and hence can serve as this basis for the needed strategy [62]. CCUS core to the CCE framework: it focuses on removing CO_2 from the atmosphere, reusing CO_2 to produce value-added products (e.g., chemicals and fertilisers), and recycling CO_2 to produce low-carbon fuels (e.g., Sustainable Aviation Fuels (SAF) and low-carbon shipping fuels), which in turn reduces the use of conventional fossil energy (Fig. 5). Thus, the development of a CCE is only feasible with the integration of CCUS technologies, which in turn promotes the establishment of a support ecosystem for such projects.

The UAE's CCE approach is driven by strong public acceptance and supportive policies and regulations developed through the UAE Circular Economy Policy [64]. Table 1 outlines the UAE's carbon management initiatives, underscoring CCE as a foundational component of the country's strategy for industrial decarbonisation.

3.3. Knowledge sharing and climate diplomacy can tackle first-mover challenges

A "first-mover penalty" in CCUS projects poses a challenge for early adopters globally. While pioneers incur higher costs and regulatory uncertainties, they also bear the burden of setting precedents and testing uncharted waters. This challenge is exacerbated by perceptions of high risks due to information failures. For example, while geological storage of CO_2 is well understood and has been proven through decades of experience, there is still only a very small pool of commercial operational data for it compared to other industries, increasing perceived risk [52]. As one of the first large-scale CO_2 storage projects, the Sleipner Project off the Norwegian coast has faced regulatory and technical challenges, despite its success in demonstrating CO_2 storage in a saline aquifer. The project's early adoption led to higher initial costs, and its success did not immediately trigger widespread CCUS uptake, partly due to perceptions of high risk and limited commercial data on CO_2 storage.

Working with owners and operators of international projects can help disseminate best practices and close information gaps. For instance, developers of the Boundary Dam and Petra Nova CCS facilities have both indicated that by applying what was learned the first time, they can replicate their plants with at least a 20 % reduction in capital costs [52]. Through knowledge sharing platforms, the UAE can enhance transparency in CCUS, and address misinformation campaigns aimed at discrediting it, with emphasis to be placed on the understanding of CCUS efficiency, costs, CO_2 storage viability, and the supportive policies and regulations.

The UAE has an opportunity to positively promote CCUS through the leveraging of its active international presence in climate action. The country is a member of global initiatives, such as Mission Innovation [73] and the Carbon Sequestration Leadership Forum (CSLF) [74], and can build on its pioneering initiatives in industrial decarbonisation, such as the Al Reyadah CCUS project. The country can also leverage its position as a key participant in the Carbon Management Challenge ‒ a joint effort and call to action by countries globally to accelerate the deployment of CCUS technologies, with over 20 participants including the UAE, Brazil, Indonesia, the US, Canada, the UK ‒ to advocate for CCUS adoption.

Workforce capacity building is equally critical to addressing first-mover challenges. Developing highly skilled personnel is essential for wider CCUS adoption. Sharing lessons learned across the value chain will empower early adopters to lower costs and gain insights from past projects.

3.4. Support understanding and development of local geologic storage capacity

To realise its CCUS ambitions, the UAE should continue to invest heavily in geological data collection and make it accessible. The CO_2 Storage Resources Committee (CSRC) identified significant storage potential in the UAE, including 5.9 Gt in depleted gas reservoirs and 16.7 Gt in 'undiscovered capacity' [75]. However, this potential needs to be verified and operationalised, as technical challenges may arise in the process of developing such CO_2 storage sites. Without a comprehensive geological understanding of such formations, the UAE risks facing the same issues experienced in other CCS projects around the world, as discussed in section 2.1.

The UAE ranks 36th globally on the Global CCS Institute's CCS Readiness Index, alongside South Korea and just behind Saudi Arabia

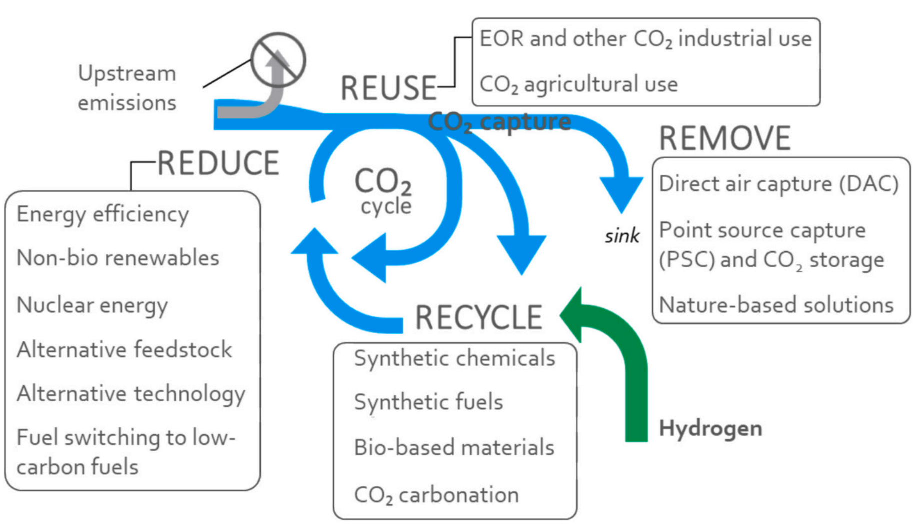

Fig. 5. Circular carbon economy (CCE) in context. The CO_2 cycle under the CCE framework is shown via blue arrows, which represent the 4R conceptualisation: reduce, reuse, recycle and remove. Both hydrogen (green) and methane emissions reduction (grey) are also shown as technology levers. Examples of technology applications for each of the 4R components is listed in the white boxes. Source: Authors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Circular Carbon Economy (CCE) Practices in the UAE.

Reduce	i. The UAE revised its 2050 National Energy Strategy, replacing the previous 12 % "clean coal" target with a goal of achieving a GHG-free power and water sector by 2050. In addition, energy consumption efficiency by 2050 should increase 42–45 % over 2019 baseline [58]. ii. In less than 15 years, the UAE became a global leader in solar energy, ranking second globally in terms of per capita solar energy consumption. It built three of the world's largest solar power plants, namely DEWA's Mohammed bin Rashid Al Maktoum Solar Park of 2.6 GW, EWEC's 2 GW Al Dhafra PV project and the 1.2 GW Noor PV project. iii. To complement the deployment of renewables with zero-carbon baseload power generation, the UAE built the Barakah nuclear power plant, currently delivering 2.8 GW and will reach 5.6 GW by 2025 [65]. iv. The UAE National Water and Energy Demand Side Management Programme 2050 targets a 40 % reduction in energy consumption. v. The UAE's National Hydrogen Strategy targets 15 Mtpa of clean hydrogen production, including 7 Mtpa of CCUS-integrated hydrogen production by 2050 [66]. vi. ADNOC plans to achieve net-zero by 2045 and eliminate methane emissions by 2030 [67]. The company implemented a zero routine flaring policy, resulting in an 89 % reduction in gas flaring since the company's inception. Since January 2022, 100 % of ADNOC's grid power has been supplied by nuclear and solar energy [58].
Reuse	i. ADNOC installed the world's first commercial-scale CCUS facility integrated with a steel manufacturing facility, Al-Reyadah CCUS, which captures 800 kt CO_2/yr [68]. This facility enables the reuse of captured CO_2 for enhanced oil recovery (EOR) at Bab and Rumaitha oilfields, a process that results in 37 % reduction in CO_2 emissions per barrel compared to conventional oil production [69].
Recycle	i. The UAE's National Sustainable Aviation Fuel (SAF) Roadmap aims to produce 1 % of total fuel to national airlines by 2031, using locally produced SAF. According to the UAE's Power-to-Liquids Roadmap, the country has the potential to produce up to 11.2 Mt. of SAF by 2050 through the use of DAC [70].
Remove	i. The UAE plans to use DAC to complement mangroves, providing negative emissions of a projected 9.5 Mtpa by 2050 [58]. ii. The UAE's Long Term Strategy highlights a 32 % CCS-specific contribution in the industrial sector's decarbonisation by 2050, equivalent to 43.5 Mt. of CO_2 captured and stored from oil and gas processing, aluminium, iron & steel, petrochemicals, cement and refining. iii. ADNOC announced 3 Mtpa worth of CCUS projects to decarbonise gas processing at the Habshan and the Hail and Ghasha plants [71]. iv. ADNOC already commenced a pioneering CO_2 capture and mineralisation pilot project in Fujairah Emirate, which uses DAC and mixes the captured CO_2 with seawater then injects it into peridotite formations underground [72].

[46] (Fig. 6). Although the UAE's storage readiness score of 81 is strong, competing with Australia (86) and China (87), its policy and regulatory measures need improvement. Adoption of newly developed policies and regulatory measures will certainly improve the UAE's CCS readiness score while providing guidance for countries interested in CCS adoption and with similar sociopolitical contexts.

To address oversized CCS infrastructure investments, the UAE could co-invest with the private sector in CO_2 transport infrastructure, drawing lessons from Norway's Northern Lights Project. In this project, the government covered initial costs, reducing financial risks for private companies and incentivizing participation. This model fosters economies of scale as more CO_2 is captured, with the government able to recoup its investment through equity sales once the infrastructure matures.

3.5. Build on societal embrace of sustainable technologies

Public discourse and perception of CCUS is positive in the UAE. The UAE society strongly embraces environmental measures and the promotion of sustainable technologies, as views on sustainability in the country are actively endorsed by the national government. The UAE's 2023 hosting of COP28, for instance, was viewed as not only an opportunity to catalyse action toward international climate objectives, but also to promote information dissemination across the society [76].

At the governmental level, such visible emphasis on environmental stewardship is seen not only as a diplomatic tool, but also as a lever to ensure continued economic growth for the country. That is, the energy transition paradigm is strongly aligned with economic planning to move away from fossil fuel-based industries and to promote the development of a knowledge-oriented economy. Unlike other geographies, where institutions standing against CCUS may be present and vocal, pushback against CCUS in the UAE is generally not widely seen. However, leveraging existing support from civil society must not be taken for granted and ensuring that communication efforts are made for societal support of CCUS must be continued.

3.6. Business models are crucial to address cross-value chain risks

The CCUS value chain demands a diverse range of expertise. Apart from natural gas separation, skills needed for handling dense phase gases, operating geological storage facilities, and CO_2 separation and capture typically exceed the capabilities of a single plant operator. For instance, a cement manufacturer lacks the know-how in CO_2 capture, transport, or geological storage. Therefore, the most effective CCUS projects often involve specialized entities handling specific stages of the process.

To mitigate CCUS cross value-chain risks, UAE industries can outsource CO_2 capture, transport, and storage to specialized service providers. Capture-as-a-Service (CaaS) providers, such as might be setup under ADNOC, can design and operate CO_2 capture systems, allowing emitters to focus on their core business. This approach streamlines operations and lowers costs through economies of scale, especially when CO_2 sources are geographically concentrated. The potential for cross-border CO_2 transport could further boost large-scale CCUS feasibility.

Subsequently, Transport-as-a-Service (TaaS) providers facilitate efficient transport of captured CO_2 to storage or utilisation sites via pipelines, shipping, rail, or barges. One example is the Alberta Carbon Trunk Line project, in which industrial CO_2 captured in Alberta is transported by Wolf Carbon Solutions via pipeline to offshore storage sites [77]. TaaS providers ensure seamless transport operations and implement monitoring systems for CO_2 movement integrity. Again, an ADNOC subsidiary may play such a role in the UAE.

Finally, Storage-as-a-Service (StaaS) providers manage CO_2 storage solutions, encompassing site selection, well design, reservoir management, compliance, liability, and insurance. In Abu Dhabi, ADNOC oversees CO_2 storage, employing injection wells and monitoring systems for secure long-term storage and EOR. In the Netherlands, the Porthos project demonstrates a combined TaaS and StaaS approach, with the Port of Rotterdam, Gasunie and EBN leveraging expertise across the value chain to address nearby industrial emissions (i.e., via a dedicated 30 km pipeline in the Rotterdam port area and offshore storage in depleted oil fields).

Business cases based on outsourcing CCUS capacity are already envisioned in the country. Sharjah National Oil Company (SNOC), though less known internationally than ADNOC, is leading one such effort in the UAE, in line with its 2032 net-zero target. SNOC plans to capture CO_2 from emitters in Sharjah and nearby Emirates, transporting it to a mature onshore gas field it owns and operates for storage. It aims to provide CCS-as-a-Service (CCSaaS) to emitters and/or generate carbon credits, envisioning the ultimate creation of a large-scale CCUS hub. With storage capacity exceeding several hundred million tons and proximity to major CO_2 sources like power and industrial plants, SNOC's gas field offers a competitive, strategically located carbon sink for sequestration [78].

3.7. CCUS readiness means regulatory and policy support

The development of necessary laws and regulations has been critical

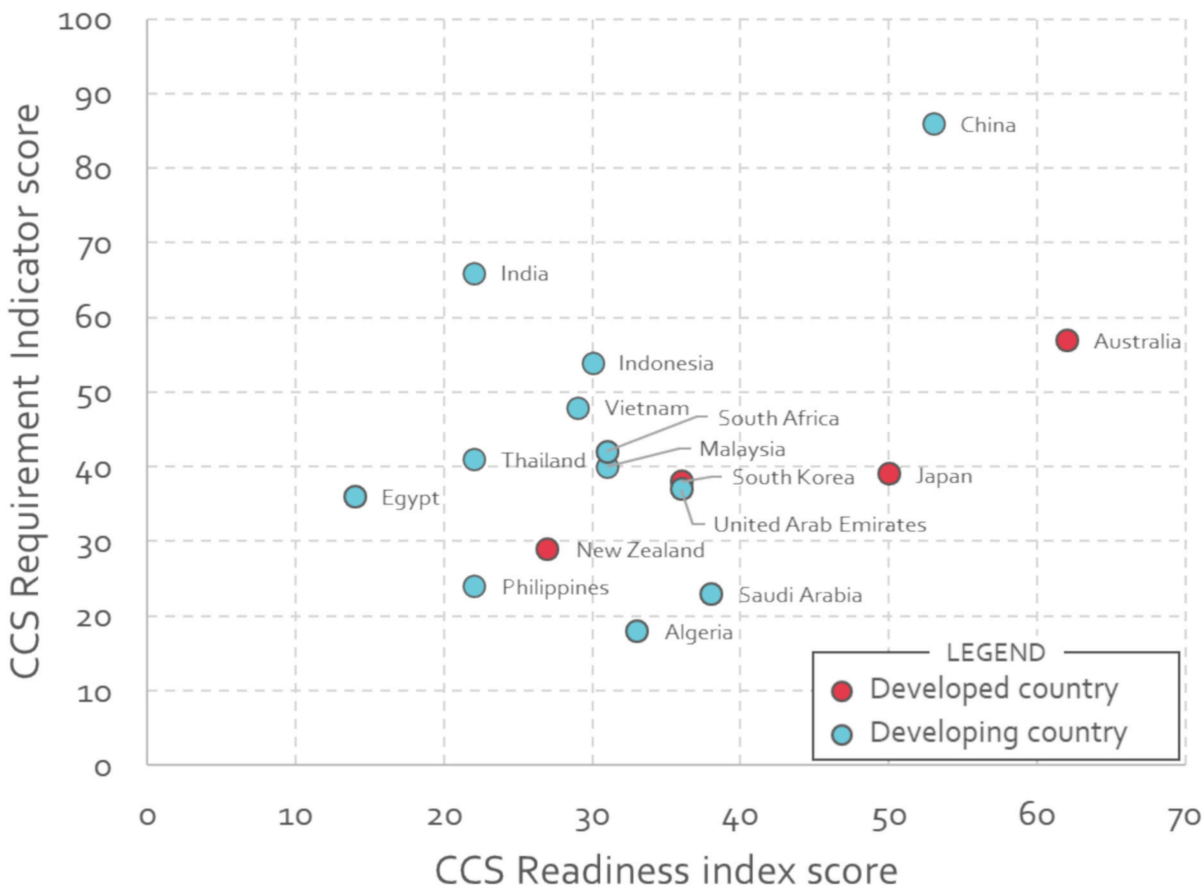

Fig. 6. Overall CCS Readiness Index for the UAE. Select developed (red) and developing (blue) countries are shown for context. Source: Adapted from [46]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in shaping CCUS deployment. Early studies [79–83] highlighted the lack of legal frameworks as a barrier to investment, especially around property rights, pore space rights and access, operational requirements such as monitoring, reporting, and verification, and long-term liability. These regulatory uncertainties have hindered CCUS investment substantially, necessitating robust legal frameworks to instil investor confidence.

Historically, the UAE has navigated CCUS initiatives under existing oil and gas legislation, primarily focussing on CO_2 utilisation in EOR. This approach, reflective of broader practices in the GCC region, underscores a collaborative approach between project developers and regulatory authorities operating within established regulatory frameworks. Further, it is reflective of the national policy style in the country [84], following the theoretical conceptualisation of Howlett and Tosun [85]. Such characteristics are important to note, as they may influence the form and extent to which policymaking efforts in the UAE may be generalisable to other geographies.

However, the UAE's proactive steps to establish a dedicated CCUS regulatory framework for CO_2 storage by Abu Dhabi authorities signals a pivotal shift in regional climate policy. The country is also developing a CCUS policy package, which includes plans for Carbon-Contracts-for-Difference (CCfDs), regulated Transport and Storage (T&S) schemes, and mechanisms for liability transfer from storage operators to the government [86]. In addition, the country plans to implement a mandatory Cap-and-Trade system [58], which could potentially be linked to a future Gulf Emissions Trading System (GETS). This carbon pricing policy will incentivise CCUS deployment and at the same time address carbon leakage, maintain local industrial competitiveness and pre-emptively address exposure to international carbon border taxes like the EU's carbon border adjustment mechanism (CBAM) [87].

Work is still ongoing at the national level in the UAE to establish a carbon pricing mechanism and carbon market in the country. The UAE Carbon Pricing Policy Committee, comprising federal and regional level governmental representatives, presented a carbon pricing study in the first quarter of 2024 [88], but an official carbon pricing policy is yet to be established as of 2024.

4. The duty of fossil fuel-exporting economies

This perspective has argued that accelerating global adoption of CCUS requires addressing the full range of sociotechnical barriers within the value chain. Effective CCUS deployment goes beyond purely techno-economic considerations, demanding integration with economic, regulatory, institutional, and sociocultural systems. By applying a sociotechnical systems lens, we demonstrate that the success of CCUS depends on aligning these interconnected elements to create an ecosystem conducive to large-scale adoption.

Using the UAE as a case study, we have shown how fossil fuel-exporting countries are uniquely positioned to lead CCUS deployment. The UAE's approach highlights the importance of leveraging local advantages, such as industrial anchors, societal acceptance of sustainability measures, and proximity between CO_2 sources and sinks, to overcome barriers that include investment risks, public scepticism, and regulatory gaps. The UAE's own implementation of the CCE framework exemplifies how integrated carbon management strategies can align industrial decarbonisation goals with broader climate objectives while maintaining economic competitiveness.

The UAE's example additionally demonstrates the critical role of systemic enablers, such as targeted regulatory frameworks, public-private partnerships, and innovative business models like CaaS, in de-risking and scaling CCUS. Moreover, the UAE's active role in global climate diplomacy, coupled with its investments in workforce development and knowledge-sharing, provides a framework the similar countries might follow for overcoming the CCUS "first-mover penalty" and fostering global collaboration.

The UAE case underscores that stimulating CCUS adoption at scale is not a one-size-fits-all solution. While the UAE's context-specific strategies offer valuable insights, global CCUS adoption will require tailored approaches that account for regional differences in resources, infrastructure, and policy environments. By showcasing a leadership model rooted in external showcases of accountability and systemic advantages, the UAE demonstrates how fossil fuel-exporting countries can reconcile energy and economic security with decarbonisation, creating an equitable path forward for industrial transition.

CCUS represents both a duty and an opportunity for wealthy fossil fuel-exporting economies to lead in industrial decarbonisation. By addressing sociotechnical barriers and setting a precedent for scalable solutions, countries like the UAE can help establish CCUS as a cornerstone of global climate action, offering a practical pathway toward a just and sustainable energy transition. This will undoubtedly benefit countries in the Global South, which may need to rely on the use of fossil fuels for many years to come and there will need economically viable technologies and policies for CCUS implementation.

CRediT authorship contribution statement

Maryem El Farsaoui: Writing – original draft, Investigation, Formal analysis. **Joao M. Uratani:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Mohammad Abu Zahra:** Writing – review & editing, Project administration, Conceptualization. **Steve Griffiths:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this perspective.

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