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Discussion Paper

The Role and Deployment Timing of Direct Air Capture in the Kingdom of Saudi Arabia's Net-Zero Transition

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July 2024 | Doi: 10.30573/KS--2024-DP23

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Abstract

The Kingdom of Saudi Arabia (KSA) has pledged to achieve net-zero greenhouse gas (GHG) emissions by 2060. Direct air carbon capture and storage (DACCS) is critical for the country to meet its net-zero target given its reliance on fossil fuels and limited options for carbon dioxide (CO_2) removal (CDR). However, the role of DACCS in national climate change mitigation in the KSA has not been studied in the literature. In this study, we aim to understand the potential role of DACCS and the effect of its deployment timing on the KSA's transition toward its net-zero target using the Global Change Analysis Model (GCAM)-KSA, which is a version of the GCAM with the KSA split out as an individual region. We find that the annual DACCS CO_2 sequestration rate in the KSA will reach 0.28 to 0.33 Gt/yr by 2060 depending on the deployment timing. Early DACCS deployment, driven by its early and rapid cost reduction worldwide, can bring about significant savings (~420 billion USD during 2020–2060) in the costs of climate change mitigation in the KSA – an approximately 17% reduction relative to delayed DACCS deployment – driven by its delayed cost reduction worldwide. Our study suggests the strong role of the KSA in proactively investing in the research and development (R&D) of DACCS, initiating early DACCS deployment, and exploring a broad suite of CDR options.

Keywords: Direct air capture; national decarbonization pathway; Saudi Arabia; deployment timing

1. Introduction

Achieving the ambitious climate targets under the Paris Agreement requires immediate actions to reduce carbon dioxide (CO_2) emissions to net zero by as early as the middle of the century. Such actions entail not only the rapid decarbonization of energy, industrial, and land systems but also large-scale deployments of CO_2 removal (CDR) measures at several to tens of gigatons of CO_2 per year by the end of the century (IPCC 2022; Rogelj et al. 2018).

Direct air carbon capture and storage (DACCS) is a CDR technology that removes CO_2 from the atmosphere based on engineered processes and permanently stores it in deep geological formations. DACCS has gained increasing attention given its advantages (e.g., flexibility of deployment location, scalability potential, and lower carbon footprint in land use) compared with bioenergy with carbon capture and storage (BECCS) (Smith et al. 2016; Fuss et al. 2018; Creutzig et al. 2019). However, this technology has not yet reached full commercial deployment, with only pilot-scale plants operating worldwide, due mainly to high costs, substantial energy inputs, a lack of experience in large-scale operations, and public concerns about safety (Fuss et al. 2018; Cox, Spence, and Pidgeon 2020; Ozkan et al. 2022). Currently, 27 small-scale direct air capture (DAC) plants have been commissioned globally, which together capture a total of 10 kt of CO_2/yr. Six DAC projects are currently under construction, with the largest two expected to come online in 2024 in Iceland (37 kt CO_2/yr) and in 2025 in the United States (U.S.) (500 kt CO_2/yr) (IEA 2022).

The timing of mitigation actions can have a significant impact on the effectiveness, costs, and overall outcomes of addressing climate change (Jakob et al. 2011; Luderer et al. 2013; Obersteiner et al. 2018; Victoria et al. 2020). As an emerging mitigation option, the role of CDR technologies, including DACCS, in contributing to global and national climate change mitigation has not yet been widely studied in the literature. Available studies have focused mostly on the global level and several major regions (e.g., China, Europe, and the U.S.). These studies generally show that CDR plays an important role in offsetting emissions from difficult-to-abate sectors and therefore can significantly reduce mitigation costs for both national and sectoral decarbonization pathways (Realmonte et al. 2019; Bistline and Blanford 2021; Fuhrman et al. 2021b). However, postponing CDR deployment can otherwise increase mitigation costs and limit overall CO_2 removal potential, putting global and national mitigation targets at risk (Galán-Martín et al. 2021). As countries are beginning to implement their climate commitments and undertake domestic actions that will set the foundations for longer-term emissions reductions, it is important to understand the role of key CDR technologies, such as DACCS, in facilitating mitigation in various regional and national contexts.

The Kingdom of Saudi Arabia (KSA) is the largest economy in the Middle East and has pledged to achieve net-zero greenhouse gas (GHG) emissions by 2060 (Saudi Green Initiative 2021). However, this ambitious climate target faces challenges given that the KSA's economy relies heavily on its oil industry; the KSA's oil industry contributes to 41% of the country's gross domestic product (GDP) (in 2019), and its energy supply comes predominantly from oil and natural gas (Hasanov, Javid and Joutz 2022; Energy Institute 2023). To achieve the net-zero climate target while maintaining a vibrant economy, the KSA has adopted key initiatives to diversify its economy and encourage sustainable development. For example, energy price reform aims to increase domestic energy prices (which have long been incentivized to make energy affordable domestically) and link them with the international market. Studies have shown that this initiative effectively curbed the KSA's gasoline and electricity consumption in 2018 (Aldubyan and Gasim 2021) and can contribute to the significant expansion of renewable energy technologies in the KSA's power sector (Wogan, Carey and Cooke 2019; Groissböck and Pickl 2018). Improving energy efficiency is another important effort undertaken by the KSA under the Saudi Energy Efficiency Program (SEEP), which aims to rationalize energy consumption and improve energy efficiency across key sectors (including industry, construction, and transportation) (Ministry of Energy 2022; Saudi Energy Efficiency Center 2023). This initiative can reduce the carbon intensity of energy consumption, contributing substantially to overall carbon mitigation in the KSA (Belaïd and Massié 2023). Additionally, numerous studies have further incorporated the KSA's national decarbonization targets and current sectoral policy initiatives to evaluate the contributions of key economic sectors (industry, electricity, transportation, and construction) to the KSA's carbon mitigation targets (Kamboj et al. 2023a, 2023b).

These previous studies cover a wide range of policy initiatives and mitigation strategies in the KSA and provide important insights to assist in relevant decision making. However, studies evaluating the role of CDR in climate change mitigation in the KSA are limited in the literature. Alatiq et al. (2021) qualitatively suggest that Arabian Gulf countries, including the KSA, have abundant solar resources and CO_2 sequestration capacity, which make this region a good candidate for DACCS implementation (Alatiq et al. 2021), and Kamboj et al. (2023) further quantify the DACCS capacity needed for the KSA to achieve net-zero GHG emission targets (Kamboj et al. 2023b). However, these studies do not evaluate the implications of DACCS deployment and its timing on the cost of climate change mitigation and future transitions of different socioeconomic sectors in the KSA. Understanding these implications is important for informing KSA policy decisions on national decarbonization pathways and providing relevant policy support for the innovation and deployment of DACCS in the KSA. Therefore, this study aims to investigate the effects of DACCS deployment and timing on the policy costs of climate change mitigation and the energy consumption of different socioeconomic sectors in the KSA.

2. Methods

In this study, we use a modified version of the Global Change Analysis Model, version 6 (GCAM 6.0), to investigate the role of DACCS and its deployment timing in the KSA's transition toward net-zero GHG emissions by 2060. The GCAM 6.0 is an open-source, multisector integrated assessment model that is available in a public repository (Bond-Lamberty et al. 2022). This model represents the behavior and interactions among the following five systems: economy, energy, agriculture and land use, water, and climate. These systems have different geographical resolutions, including 32 geopolitical regions, 384 land subregions, and 235 water basins globally. The GCAM 6.0 operates in 5-year time steps from 2015 (model calibration year) to 2100 and is driven by exogenous assumptions about population growth, labor participation rates, and labor productivity in the 32 geopolitical regions, together with other assumptions of resources, technologies, and policy. The GCAM 6.0 solves for the equilibrium prices to ensure that supply and demand levels are equal for various energy, agricultural, water, land-use, and GHG markets in each time step and region. Each system in the GCAM 6.0 has technological detail. Individual technologies compete for market share based on their levelized costs. The GCAM 6.0 also includes a representation of three CDR strategies that are deployed in scenarios with emission policies, namely, DACCS, BECCS, and afforestation (Fuhrman et al. 2021a).

A modified version of the GCAM 6.0 (GCAM-KSA) is developed by explicitly separating the KSA from the Middle East (which is one of the 32 existing regions in the GCAM 6.0) as one individual region (Kamboj et al. 2023b). In the GCAM-KSA, we use regionalized data inputs for the KSA that capture key socioeconomic and technological developments in the country. In particular, due to the arid and hot climate, the availability of dedicated biomass resources for energy generation is limited in the KSA (Demirbas et al. 2017), and, thus, BECCS is not considered a CDR option in our current modeling efforts for the KSA. Additional details about the modeling framework of the GCAM and how the KSA is separated as its own individual region are provided in **Supplementary Note 1**, and a list of modifications and regionalized data inputs used in this study is included in **Supplementary Table 1**.

Three central scenarios are considered in this study, namely, *Reference, Net-Zero KSA w/ early DACCS,* and *Net-Zero KSA w/ delayed DACCS* (**Table 1**). *Reference* is a counterfactual scenario that assumes no explicit climate policies and no CDR deployment. The two *Net-Zero KSA* scenarios include emission constraints, which assume that the KSA will meet its nationally determined contribution (NDC) target (reducing GHG emissions by 278 Mt CO_2 eq. by 2030) and achieves net-zero GHG emissions by 2060 and that the rest of the world will achieve their NDCs in addition to long-term strategies and net-zero pledges following the assumptions from a previous study (Iyer et al. 2022). Under the two *Net-Zero KSA* scenarios, it is anticipated that the global surface temperature change will be limited to < 2°C warming in this century. Both of the *Net-Zero KSA* scenarios include DACCS deployment worldwide. Two types of DACCS technologies are considered in this study, namely, high-temperature solvent-based DACCS and low-temperature solid-based DACCS. Depending on the heat source, the high-temperature solvent-based DACCS can use heat from either natural gas combustion (HT-DACCS-NG) or heat supplied by an electric furnace (HT-DACCS-ELEC). For the low-temperature solid-based DACCS, heat is supplied by a heat pump (LT-DACCS-HP). Detailed information about the technology description and parameter inputs (cost, energy use, etc.) used in the GCAM-KSA can be found in (Fuhrman et al. 2021a).

The two *Net-Zero KSA* scenarios differ in their projections of the levelized costs of nonenergy capture (LCOCs) of DACCS (i.e., excluding the costs of electricity and/or fuels), which ultimately leads to different timings of DACCS deployment. The *Net-Zero KSA w/ early DACCS* assumes that with earlier investment in research and development (R&D), the LCOCs of DACCS worldwide (including KSA) will start to decline linearly in 2020 and reach floor costs in 2030, after which they will remain constant. In contrast, the *Net-Zero KSA w/ delayed DACCS* scenario assumes a delay in R&D investment, which results in the LCOCs of DACCS remaining at their starting level until 2050 and then declining linearly to the same floor costs in 2080 (**Table 1**). Fuhrman et al. (2021) develop different cost trajectories for DACCS, which capture the changes in DACCS cost, performance, and deployment across a range of socioeconomic futures with different near-term incentivizing policies. In these central scenarios, the minimum LCOCs of DACCS are adopted from the moderate-cost DACCS scenario (Fuhrman et al. 2021a). Note that cost projections under the two *Net-Zero KSA* central scenarios are intended as bounding assumptions to test the effects of DACCS deployment timing (induced by its drastically different cost projection) on the KSA's policy cost of climate change mitigation. In addition to these central scenarios, we consider a suite of additional sensitivity scenarios to examine the sensitivity of our core findings and results to key assumptions (see **Supplementary Note 2**).

For all of our scenarios, we evaluate the implications of DACCS deployment timing and level on the cost of climate change mitigation in the KSA using the estimated carbon prices and policy costs of climate change. The carbon price is the price of CO_2 emissions that the GCAM calculates endogenously based on emissions constraints. The carbon price is passed down to all the systems in the GCAM and affects the costs and relative competitiveness of those goods and services whose production processes use emit CO_2. The added carbon price also affects the supply and demand of these goods and services to ensure that the system CO_2 emissions meet the emission constraints in each model period. The policy costs of climate change mitigation are also estimated by the GCAM as the area under the marginal abatement curve (MAC) (representing the carbon price with respect to the CO_2 abatement level) (Calvin et al. 2019). This method of calculation, while not unique, is well established in the literature, particularly because it is based on partial equilibrium economic models and represents the deadweight loss to the economy associated with emission reduction measures (IPCC 2022; Iyer et al. 2015). Each policy cost metric has its own advantages and disadvantages. A detailed comparison with other methods of calculating policy costs (e.g., GDP loss) is beyond the scope of this study. In this study, we calculate the cumulative policy costs of climate change mitigation in the KSA from 2020 to 2060 (present value based on the 5% discount rate in the main results) under the two *Net-Zero KSA* scenarios, which represent the total cost of climate change mitigation in the KSA over the 40-year period.

Table 1. Design of central scenarios in this study.

Scenario[a]	Climate Policy	DACCS Availability	Assumption on DACCS Cost Projection				
			Year when DACCS costs start to decline	Year when DACCS costs reach the assumed minimum costs	Assumed minimum costs of DACCS[c] (2020 USD/t CO_2)		
					HT-DACCS-NG	HT-DACCS-ELEC	LT-DACCS-HP
Reference	No policy	No DACCS deployment worldwide	Not applicable				
Net-zero KSA w/ early DACCS	The KSA meets the NDC target of reducing GHG emissions by 278 Mt CO_2 eq. by 2030 compared to the Reference case and reaches net-zero GHG emission by 2060. The rest of the world achieves their NDC targets in addition to long-term strategies and net-zero pledges.[b]	With DACCS deployment worldwide	2020	2030	241	249	275
Net-zero KSA w/ delayed DACCS			2050	2080			

Source: Authors' analysis.

[a] *See Supplementary Note 2 for additional sensitivity scenarios.*

[b] *The KSA GHG emissions results under these climate policies of different central scenarios can be found in Supplementary Figure 5.*

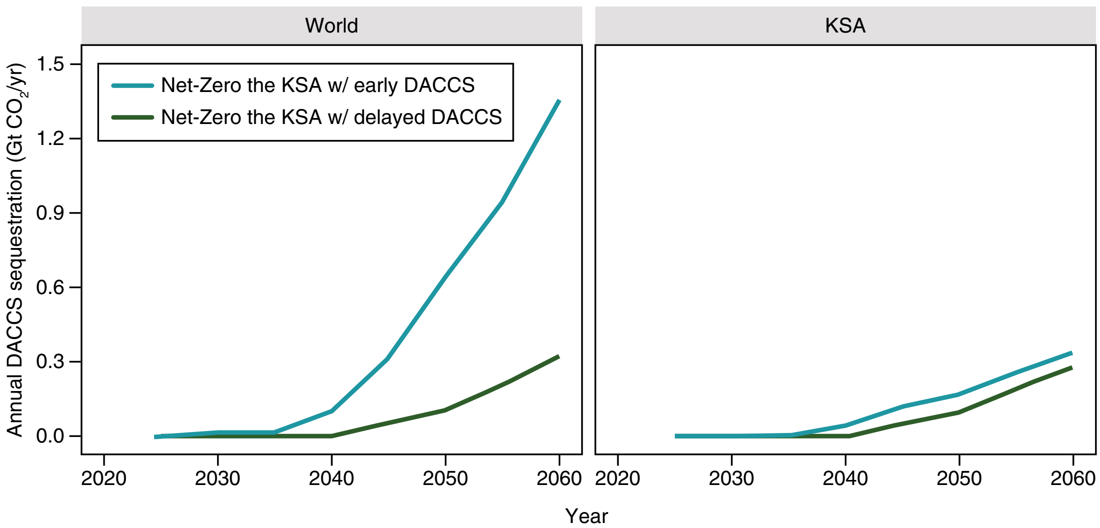
[c] *Fuhrman et al. (2021) develop different cost trajectories for DACCS, which capture the changes in DACCS cost, performance, and deployment across a range of socioeconomic futures with different near-term incentivizing policies. In the central scenarios, the minimum LCOCs of DACCS are adopted from the moderate-cost DACCS scenario (Fuhrman et al. 2021a). The LCOC trajectories of DACCS of the two Net-Zero KSA central scenarios used in this study are displayed in Supplementary Figure 2.*

3. Results

DAC Deployment Level and Timing at Global and KSA Levels

DACCS deployment has different timings and levels both globally and in the KSA, with different underlying cost assumptions under the two *Net-Zero KSA* scenarios (**Figure 1**). The global DACCS deployments under the two scenarios both start around 2025, but the speed at which DACCS deployment scales up differs. The annual DACCS CO_2 sequestration is projected to reach 0.10 Gt/yr in 2040 under the *Net-Zero KSA w/ early DACCS* scenario. However, in the *Net-Zero KSA w/ delayed DACCS* scenario, achieving the same level of CO_2 sequestration will be delayed by 10 years (in 2050). In 2060, the annual CO_2 sequestration of DACCS globally will reach 1.36 Gt/yr under the *Net-Zero KSA w/ early DACCS* scenario, which is approximately 4.3 times greater than the CO_2 sequestration level under the *Net-Zero KSA w/ delayed DACCS* scenario (0.32/yr Gt CO_2).

Figure 1. Annual CO_2 sequestration of DACCS in the world (left panel) and the KSA (right panel).



Source: Authors' analysis.

There is a smaller difference in DACCS deployment in the KSA between the two *Net-Zero KSA* scenarios. In the *Net-Zero KSA w/ early DACCS* scenario, the annual CO_2 sequestration of DACCS in the KSA will reach 0.1 Gt/yr in 2044, and the same level of CO_2 sequestration will be delayed only by 6 years (2050) under the *Net-Zero KSA w/ delayed DACCS* scenario. The projected 2060 CO_2 sequestration rates of the two *Net-Zero KSA* scenarios are also relatively close, with values of 0.34 and 0.28 Gt CO_2/yr for the *early* and *delayed DACCS* scenarios, respectively. The relatively small difference in DACCS deployment in the KSA indicates that the country needs to rely more on DACCS to achieve its net-zero GHG emissions target when other CDR options are limited (e.g., BECCS is not an economically feasible option), despite the high cost of DACCS under the *Net-Zero KSA w/ delayed DACCS* scenario.

The scaling up of DACCS deployment in the KSA also requires a significant amount of energy for DACCS operation. The total energy consumption of DACCS in the KSA is projected to reach 1.88 and 1.85 EJ/yr in 2060 under the *Net-Zero KSA w/ early* and *delayed DACCS* scenarios, respectively. These figures account for approximately 13% of the total primary energy consumption in the KSA under the two scenarios (**Supplementary Figure 6**). The total energy consumption of DACCS consists of electricity and heat consumption (from natural gas combustion). In the *Net-Zero KSA w/ early DACCS* scenario, the electricity and heat consumption of operating DACCS in 2060 are estimated to be 0.62 EJ/yr (equivalent to 172 TWh/yr, approximately 12% of the KSA's estimated electricity generation in 2060) and 1.26 EJ/yr, respectively. With delayed DACCS, the electricity and heat consumption will be 0.39 EJ/yr (equivalent to 108 TWh/yr) and 1.46 EJ/yr, respectively, in 2060. These findings emphasize the necessity for the KSA to develop additional energy capacity to cater to the growing demand of DACCS technologies. Ideally, this energy supply should come predominantly from clean energy sources to ensure the high-level CO_2 sequestration efficiency of DACCS.

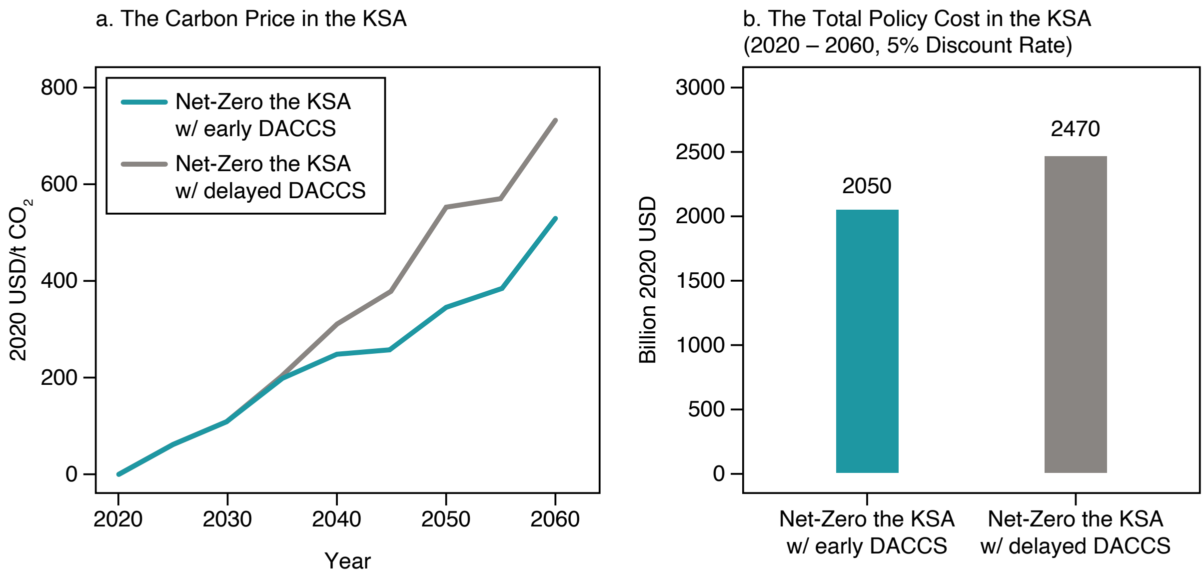
Implications of DACCS Deployment Timing on the Cost of Climate Change Mitigation

The different levels and timing of DACCS deployment in the KSA under the two *Net-Zero KSA* scenarios result in widely divergent cost implications. The carbon prices in the KSA under both scenarios increase from 2020 to 2060 due to the progressively stringent mitigation targets, which necessitate the adoption of mitigation options with higher costs. In 2060, the KSA carbon price under the *Net-Zero KSA w /delayed DACCS* scenario reaches $732/t CO_2, while with the early cost reduction and deployment of DACCS, the 2060 KSA carbon price can be reduced by 28% to $530/t CO_2 (**Figure 2a**). Similarly, a stark difference is also observed in the cumulative policy cost of achieving net-zero GHG emissions in the KSA. Early DACCS cost reduction and deployment can reduce the policy cost by approximately 17% to $2,050 billion compared to that of the *Net-Zero KSA w/ delayed DACCS* scenario ($2,470 billion) (**Figure 2b**).

An additional sensitivity analysis is conducted to further explore the responses of the policy cost to two key factors — the decline rate and minimum level of DACCS LCOCs. The results from the sensitivity analysis are consistent with our core findings that the early cost reduction and deployment of DACCS can substantially reduce the policy cost of climate change mitigation in the KSA (**Supplementary Note 2**).

The higher carbon price and policy cost in the KSA under the *Net-Zero KSA w/ delayed DACCS* scenario compared to the early scenario are driven by two separate yet related factors. First, due to the limited number of CDR options considered in this study (modeling a full portfolio of CDR options is beyond the scope of this study but can be explored in future endeavors), the KSA relies on DACCS to achieve its net-zero GHG emissions target.

Figure 2. Carbon price trajectories (a.) and cumulative policy costs (from 2020 to 2060, 5% discount rate) of achieving the KSA's net-zero target (b.) under *Net-Zero KSA w/ early* and *w/ delayed DACCS* scenarios. The policy cost result under 3% discount rate is provided in **Supplementary Figure 7.**



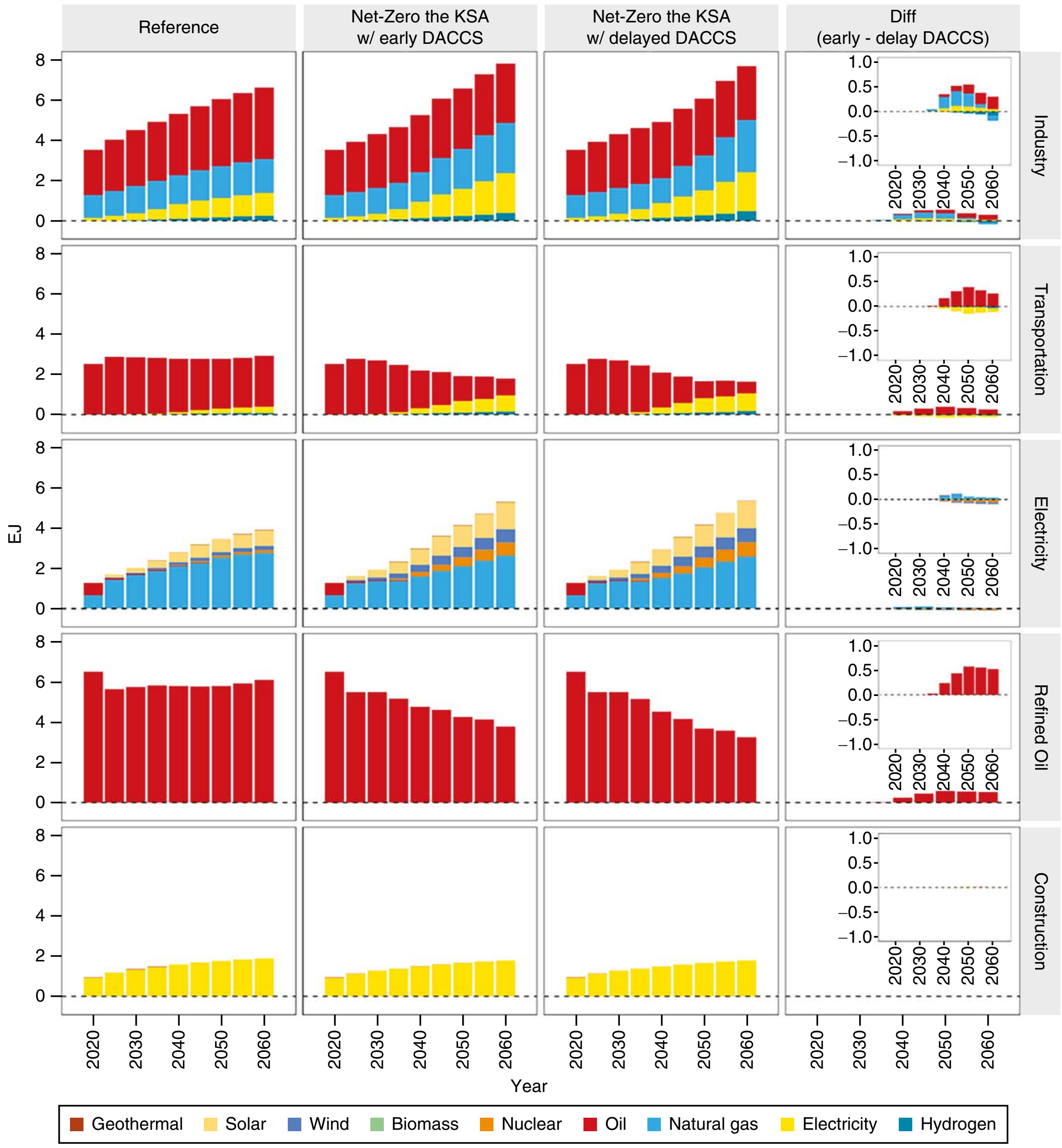
Source: Authors' analysis.

This inelastic demand for DACCS, together with the delayed cost reduction of DACCS, contributes to a higher carbon price in carbon emitting sources and therefore a higher cumulative policy cost for the country. Second, delaying DACCS deployment results in reduced oil and gas consumption levels in the industry and transportation (only oil) sectors, increased deployment of nuclear and renewable solar and wind in the power sector, and increased electrification (**Figure 3**). Due to the KSA's high level of reliance on oil and gas and associated path dependence, displacing even small amounts of these fossil fuels and replacing them with alternative fuels results in significant increases in the cost of achieving net-zero emissions.

Effects of DACCS Deployment Timing on Sectoral Energy Consumption in the KSA

Early DACCS deployment (compared to delayed deployment) reduces the need for other mitigation options, such as less electrification (mainly in transportation), less hydrogen use (mainly in the industry sector), and less demand for nuclear and renewable electricity (mainly in the power sector). Overall, these changes are relatively small, accounting for at most 8% of the annual energy consumption and generation in these sectors of the *Net-Zero KSA w/ delayed DACCS* scenario. Conversely, the earlier and faster cost reduction of DACCS slows the displacement of oil consumption in the KSA (due to the lower carbon price imposed on the fossil fuel energy sources) and allows for more oil and gas consumption in the industry, transportation (oil only), and power (mostly gas) sectors.

Figure 3. Fuel composition of the KSA's energy system by sector under the *Reference*, *Net-Zero KSA w/ early DACCS,* and *Net-Zero KSA w/ delayed DACCS* central scenarios and the difference between the two *Net-Zero KSA* central scenarios (last column).



Source: Authors' analysis.

However, the additional amounts of these two fuel types together also remain relatively small, accounting for no more than 8% of the annual energy consumption of the three sectors combined under the *Net-Zero KSA w/ delayed DACCS* scenario. As a major oil-producing and exporting country, the KSA has higher oil production levels with early DACCS deployment. In 2060, the annual oil production under the *Net-Zero KSA w/ early DACCS* scenario is 0.52 EJ (16%) higher than that under the *Net-Zero KSA w/ delayed DACCS* scenario (3.25 EJ). This difference is approximately 18% of the oil production loss (-2.84 EJ) in 2060 due to the need to achieve the net-zero target (the difference in oil production between the *Reference* and *Net-Zero KSA w/ delayed DACCS* scenarios). Overall, due to the KSA's high degree of reliance on fossil-based energy sources and associated path dependence, early DACCS deployment in the KSA, facilitated by rapid and early cost reductions, can help it avoid a smaller amount of fossil fuel (mainly oil) being displaced with alternative clean energy sources, but it can contribute to significant savings in the costs of achieving net-zero CO_2 emissions in the country.

4. Discussion

This study provides several key implications for the KSA in terms of deploying DACCS for climate change mitigation. First, DACCS is an important CO_2 mitigation option in the KSA. The cost reduction projection of DACCS, which affects the timing and level of technology deployment, can lead to substantial changes in the policy costs of climate change mitigation in the KSA. Therefore, actively investing in the R&D of DACCS and deploying the technology in a timely manner are important measures for climate change mitigation in the KSA. Historically, learning by doing (experience gained through increased production or technology deployment) and learning by researching (technology improvement due to R&D activities) have contributed to the cost reduction of energy technologies (Sagar and van der Zwaan 2006; Rubin et al. 2015). Similar cost reductions in DACCS can also be achieved through significant R&D investments and the scaling up of deployment. According to the R&D agenda laid out by the National Academies of Sciences, an average of $150 million/yr of federal funding is recommended in the U.S. over the next decade to deliver commercial-scale DACCS at a substantially lower cost – $100/t$CO_2$ (National Academies of Sciences 2018; Mulligan et al. 2020). Regions and countries worldwide are also making notable progress in adopting policy support for the R&D and scaling up of DACCS deployment (Smith et al. 2023), including direct funding support and tax credits for investment in the US (United States Department of Energy 2021; United States Internal Revenue Service 2021), Europe (European Commission 2021, 2022), Canada (Government of Canada 2021), and the U.K. (His Majesty's Treasury 2023). Hence, the KSA can also proactively adopt favorable policies and financial support for DACCS and initiate its early deployment within the country.

Additionally, it is also important for the KSA to support the development of upstream and downstream infrastructures related to DACCS, including energy supply, CO_2 transport, and storage (or utilization) infrastructures. Under the *Net-Zero KSA* central scenarios, the projected amount of CO_2 captured by DACCS in the KSA will reach approximately 0.3 Gt by 2060, thus requiring an equivalent scale of CO_2 transport and storage (or utilization) facilities to be built in the KSA as well. Given the importance of the oil industry in the KSA, the CO_2 captured by DAC can also be utilized to extract oil through enhanced oil recovery (EOR). The potential feasibility and implications of combining DAC with EOR can be evaluated in future studies. The total energy (electricity and natural gas) consumption of DACCS can also be substantially increased by 2060 (13% of the total primary energy consumption in the

KSA). Ideally, the electricity consumed by DACCS should be generated by renewable or low-carbon sources to achieve high-level CO_2 sequestration efficiency. This result suggests that the future planning of energy system expansion in the KSA also needs to account for the potential energy demands of DACCS. Future planning for DACCS and energy systems in the KSA may also consider climate impacts. Climate change can have substantial impacts on both the supply and demand of the energy system as well as potentially induced adaptation mechanisms (Khan et al. 2021; Santos da Silva et al. 2021; Yalew et al. 2020). A recent study reveals that ambient temperature and humidity can affect the electricity consumption and productivity levels of solid-based DAC plants (Sendi et al. 2022). Therefore, these impacts can be incorporated into future studies to better guide the KSA's decision making on energy system planning and DACCS deployment.

In addition to DACCS, it is essential for the KSA to explore other CDR options that are suitable for the country's geographical and environmental conditions and study the feasibility and implications of deploying such CDR options. The KSA announced the Saudi Green Initiatives in 2021 to steer the country toward a green and sustainable future. As an important part of these initiatives, the country plans to plant 10 billion trees to improve air quality, reduce the number of sandstorms, and rehabilitate degraded land (Saudi Green Initiative 2021). Future studies can evaluate the contribution of this afforestation effort to overall CO_2 sequestration in the KSA and the potential sensitivity to various key aspects, including the required water demand, plant species, and implications for regional ecosystems and the environment. Another potential CDR option that the KSA can consider is direct ocean carbon capture and storage (DOCCS), which exploits the higher CO_2 concentration of sea water compared to the atmosphere (by an approximate factor of 120) (DeVries, Holzer and Primeau 2017). One DOCCS approach involves electrochemical processes to change the pH of ocean water and off-gas CO_2, which is then captured and sequestered. An advantage of this technology is its potential for integration with desalination plants, which use the seawater discharged from CO_2 capture plants to produce freshwater, thereby creating cost-saving opportunities and the co-benefits of carbon mitigation and freshwater production (Digdaya et al. 2020). This co-benefit holds significant meaning for the KSA, which aims to achieve net-zero GHG emissions by 2060 (Saudi Green Initiative 2021) and currently possesses the world's largest amount of desalination plants (Mahmoudi et al. 2023). A recent study also indicates that DOCCS paired with desalination plants has substantial potential in the Middle East region (Fuhrman et al. 2023). Future research needs to further investigate the feasibility of deploying DOCCS in the KSA and quantify the potential capacity associated with the demand for desalination water to materialize the benefits of this technology. Furthermore, several other emerging CDR options, such as enhanced weathering and biochar, can also be explored in future studies to better understand their feasibility and potential implications for deployment in the KSA.

5. Conclusions

This study highlights that DACCS can play a critical role in enabling the KSA to reach its net-zero GHG emissions by 2060. Due to the KSA's high degree of reliance on fossil-based energy sources and associated path dependence, the early deployment of DACCS in the KSA can help the country avoid displacing a small amount of oil consumption with other clean energy sources and significantly reduce the costs of achieving the net-zero goal. Our study suggests a strong role for the KSA in proactively investing in the research, development, demonstration, and deployment (RDD&D) of DACCS, providing favorable policy support to reduce the cost of DACCS to as low and as early as possible, which can contribute to the early scale-up of DACCS and lead to a substantially lower cost of climate change mitigation in the KSA. Our study also suggests that the KSA build relevant upstream and downstream energy and CO_2 transport and storage infrastructures that are needed for the increasing deployment of DACCS. Furthermore, the KSA can diversify its CDR portfolio by exploring other options that are suitable for the geographical and environmental conditions in the country, such as afforestation (which is already part of the Saudi Green Initiatives) and DOCCS.

A critical component of policy actions to facilitate the RDD&D of CDR in the KSA is the thorough evaluation of the feasibility of deploying various CDR options, their implications for the energy-land-water-climate system, and the optimal integration of these CDR options in contributing to the KSA's national climate change mitigation target. In this sense, our study and the GCAM-KSA model set the stage for future analytical research on potential CDR options within an integrated assessment framework. Such research can help decisionmakers identify the optimal portfolio of CDR technologies and understand their broader implications for human and earth systems. These insights can then facilitate informed decisions on CDR deployment and the design of climate change mitigation strategies.

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About the Project

This study is part of the Climate Adaptation and Mitigation Partnership (CAMP) project. The CAMP project is timely and crucial for the KSA given the mounting risks associated with climate change impacts, the urgency of pushing toward a low-carbon future while maintaining economic growth nationally, and the potential economic ramifications of global mitigation efforts on the Saudi energy sector and economy. Against this backdrop, the CAMP project investigates (1.) the climate conditions in the KSA, (2.) the sectoral impacts and the role of adaptation measures, and (3.) the pathways through which the Saudi economy can achieve a low-carbon future or climate neutrality by mid-century. (4.) This study also adopts the circular carbon economy concept in characterizing the Saudi government's efforts to decarbonize its own economy while meeting its growth aspirations.

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