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King Abdullah Petroleum Studies and Research Center

Discussion Paper

Reaching Net-Zero GHG Emissions in Saudi Arabia by 2060

Transformation of the Industrial Sector

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Abstract

The industrial sector plays a crucial role in the economy of the Kingdom of Saudi Arabia (KSA). Its energy consumption primarily relies on natural gas and oil due to the abundance of these resources and their relatively low administered prices. To reduce oil dependence and create a more sustainable and resilient economy, the KSA has adopted several important policies to improve energy efficiency, manage domestic energy consumption, and pursue ambitious climate targets. In this study, we incorporate key policies and mitigation targets into an integrated assessment model to analyze their effects on the future evolution of the KSA's industrial sector and reveal potential opportunities to mitigate industry-generated carbon emissions. We find that the KSA's current Nationally Determined Contribution and the pledge of achieving net-zero GHG emissions by 2060 are crucial for effectively mitigating CO_2 emissions in its industrial sector. The reduction in CO_2 emissions is mostly driven by the deployment of carbon capture and storage (CCS) technologies in several key industrial sectors, such as the chemical, steel, and cement sectors. To achieve KSA's 2060 net-zero GHG emissions target, KSA needs to scale up direct air carbon capture and storage (DACCS) deployment to offset residual emissions, which necessitates additional energy infrastructures in the industrial sector that are capable of meeting the energy demand for DACCS operation. The CO_2 captured from both DACCS and point-source carbon capture utilization (CCU) could provide long-term opportunities for the KSA to unlock the value chain of CCU.

Keywords: Saudi Arabia; Climate change mitigation; Industrial sector; Carbon capture, utilization and storage

1. Introduction

The industrial sector of the Kingdom of Saudi Arabia (KSA) plays a crucial role in its economy and has experienced rapid growth over the past several decades. The value added from industry in the KSA has been increasing since the 1970s, with an average annual growth of 5%; it reached 53.3% of the country's GDP in 2022 (The World Bank 2023). While the industrial sector is the largest contributor to the KSA economy, the total energy consumption of this sector also increased at an annual rate of 8.3% from 1990–2019 (Muhammad 2023), accounting for nearly half (47%) of the total primary energy consumption in the Kingdom in 2022 (Ministry of Energy 2022).

Energy for the KSA's industrial sector has primarily come from the consumption of natural gas and oil due to the abundance of these resources and their relatively low administered prices. The KSA has long set domestic energy prices below international market levels. These incentives help keep prices stable and energy affordable, while encouraging high demand growth in the oil and gas industries. Due to its reliance on fossil fuel resources, the industrial sector is responsible for energy-related CO_2 emissions reaching approximately 230 Mt CO_2 in 2019, making it the largest contributor (accounting for 46%) to total CO_2 emissions in the country (Climate Transparency 2020).

In recent years, the KSA has adopted several important initiatives aimed at enhancing the sustainability and resiliency of the country's economy; some of these initiatives could also impact the future development of the KSA's industrial sector. The Saudi Energy Efficiency Program (SEEP), launched by the Saudi Energy Efficiency Center (SEEC) in 2012, aims to rationalize and enhance energy consumption and improve energy efficiency across three key sectors — the industrial, building, and transportation sectors. For the industrial sector, the program involves two phases. In the first phase, initiatives were designed and implemented to improve energy efficiency in major manufacturing industries, including iron and steel, cement, and petrochemicals, by 2019 (Ministry of Energy 2022). The second phase, which began in 2020 and will last until 2025, expands the industrial energy efficiency framework to include aluminum and other subsectors. Additionally, initiatives have been adopted to improve feedstock utilization efficiency for primary raw materials (Saudi Energy Efficiency Center 2023).

The Fiscal Balance Program (FBP), which was launched in 2016, is another important program that aims to achieve a balanced government budget. The FBP encompasses several initiatives, such as a value-added tax, expatriate levies, and energy price reform. Energy price reform is one of its most critical and visible initiatives and involves two waves of energy price reforms (in 2016 and 2018) that increase the price of fuels (e.g., gas, crude oil, and other petroleum products), electricity, gasoline, and water to reflect the actual costs (Aldubyan and Gasim 2021). These policy initiatives under the FBP also aim to manage domestic energy consumption, encourage greater investment in energy efficiency, and influence consumer behavior, which could affect energy use in the industrial sector of the KSA.

Additionally, the KSA plans to implement major economic and social changes following the announcement of Saudi Vision 2030, which was established in 2016 with the goal of improving the sustainability of resources for future generations, encouraging economic diversification, and maximizing citizens' well-being (Saudi Vision 2030). In the updated Nationally Determined Contribution (NDC) submission, the KSA committed to reducing its GHG emissions by 278 Mt CO_{2eq} by 2030 (Kingdom of Saudi Arabia 2021). Furthermore, the Kingdom also pledged to achieve net-zero GHG emissions by 2060 under its recent Saudi Green Initiative (Saudi Green Initiative 2021).

The literature lacks studies that comprehensively examine the effects of various policies on Saudi Arabia's national decarbonization strategies and sectoral dynamics within the country. To close this gap, we adopted an integrated assessment model (IAM) to analyze the future evolution of the KSA's industrial sector under the impacts of different policies. The IAM can represent various human and natural systems, and it captures the interactions among these systems. We incorporate key policies and mitigation targets adopted by the KSA into the model to understand how these measures collectively shape the future of the Kingdom's industrial sector. Specifically, this study aimed to reveal the potential opportunities and specific sectors that could contribute to carbon mitigation in the KSA's industrial sector. The following two sections of the paper discuss the overall modeling framework for the GCAM-KSA, the structure of key industrial sectors in the GCAM-KSA, the scenario design of this study, the results, and the conclusions.

2. Methods

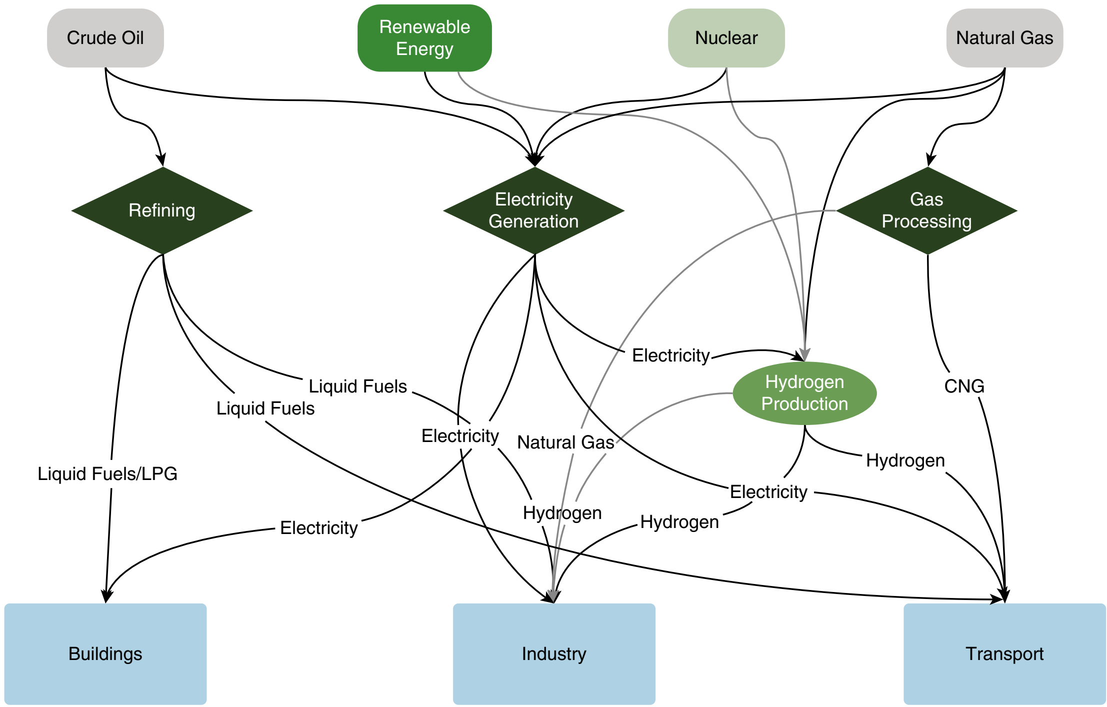
2.1 Modeling Framework

In this study, we use a modified version of the Global Change Analysis Model (GCAM 6.0) to analyze the implications of various policy measures for the future evolution of the KSA's industrial sector. GCAM 6.0 is an open-source, multisector IAM that represents the behavior and interactions of the energy system, water, agriculture, and land use, the economy, and the climate (Calvin et al. 2019). The GCAM has been utilized to support policymakers for more than 30 years and has been documented through hundreds of peer-reviewed publications (Edmonds and Reilly 1986; Kim et al. 2006; Calvin et al. 2019). For example, the GCAM was used to develop scenarios for the "United States Mid-Century Strategy for Deep Carbonization" and support the State Department during the Paris Negotiations (White House 2016). The GCAM was also one of the core models utilized in China's recent carbon neutrality report ("Energy Foundation China" from 2020).

Here, we developed the GCAM-KSA by separating the KSA from the Middle East as an individual energy economy region; the model includes 33 energy economy regions (32 original regions plus the KSA). The GCAM-KSA operates in 5-year time steps from 2015 (base year) to 2100 by solving for the equilibrium prices and quantities of various markets in each modeling period. The GCAM-KSA is a dynamic recursive model. Hence, the solutions for each modeling period depend only on the conditions of the previous modeling period. GCAM-KSA tracks the emissions of 24 gases, including GHGs (i.e., CO_2, N_2O, CH_4, F-gases), short-lived species, and ozone precursors, endogenously based on the resulting energy, agriculture, and land-use systems. A list of modifications to the KSA-related data inputs, which were conducted for the GCAM-KSA-based region-specific data and assumptions, are described in detail in the Supplementary Notes (Table 2).

Although the GCAM has detailed representations of water, agriculture, and land use systems, in GCAM-KSA v1.0, we primarily focus our analysis on the energy system and associated emissions only. The model's energy system for Saudi Arabia (**Figure 1**) contains representations of fossil resources (oil and gas), uranium, and renewable sources (wind, solar, and geothermal), along with processes that transform these resources into final energy carriers (electricity generation, refining, hydrogen production, and gas processing), which are ultimately used to deliver goods and services demanded by end-use sectors (residential building, commercial building, transportation, and industrial sectors).

Figure 1. Diagram of the KSA energy system in the GCAM-KSA.



Source: KAPSARC.

2.2 Structure of the Industrial Sector in the GCAM-KSA

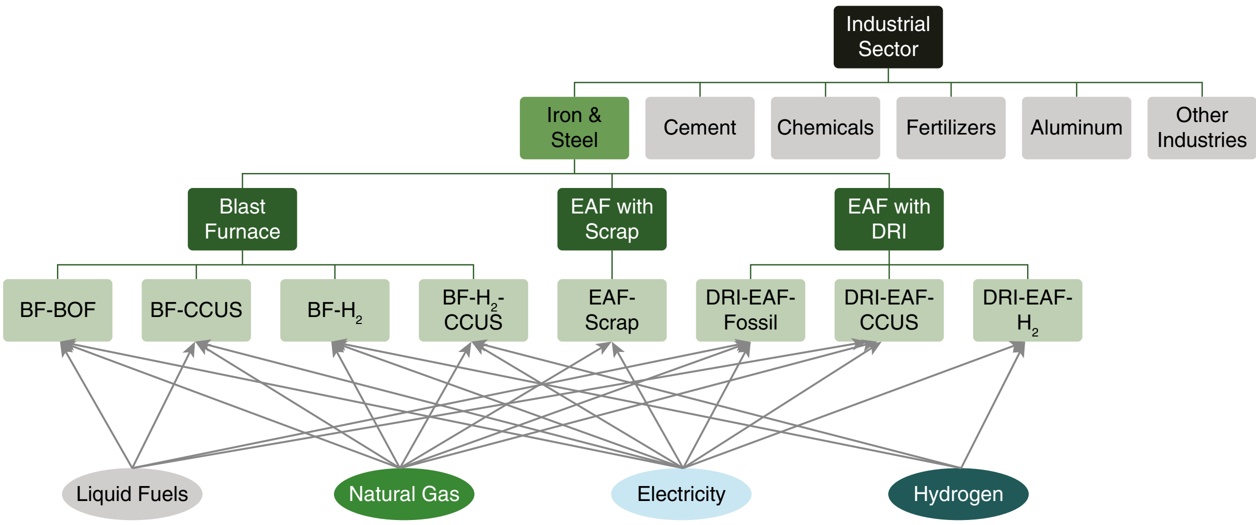
A total of six specific industrial sectors are modeled in GCAM-KSA. These include five manufacturing sectors (iron & steel, chemicals, aluminum, cement, and fertilizer) and other industries that are used to calibrate the total industrial energy according to the IEA energy balance. IEA energy balances are used to calibrate the sectoral energy consumption. Sectoral outputs such as physical commodity flows are calibrated based on historical data from different industrial associations. All these calibrations are conducted until the base year (2015). For each sector, future industrial output growth is driven by GDP, income elasticities, and price elasticities. We also include the refining sector (which is considered part of the energy transformation processes in GCAM-KSA) as part of the KSA's industrial sector given its important role in the KSA.

Different technologies and energy sources in each industrial sector compete on the basis of their costs (including endogenously calculated fuel costs, exogenously specified nonfuel costs, and any emissions costs if included) and choice parameters in a modified logit discrete choice model (Clarke and Edmonds 1993). In this model, the share of a given technology or energy source is determined by its levelized cost mediated by the influence of non-cost factors, which are captured by share weights and a logit exponent. A detailed description of the modified logit discrete choice model is included in the Supplementary Notes at the end of this paper.

In the following sections, we provide detailed descriptions of several key industrial sectors:

The iron and steel sector consists of three distinct technologies: basic oxygen furnace (BOF), electric arc furnace (EAF) with scrap, and EAF with direct reduced iron (DRI). (Note: In the KSA, BOF has rarely been used in steel production, so this option is excluded for the KSA). Each technology includes several competing fuels, such as fossil fuels with and without CCS, electricity, hydrogen, and biomass (**Figure 2**). For the iron and steel sector, the future per capita consumption across all regions is estimated using the nonlinear inverse with the time-efficiency-factor (NLIT) function (Van Ruijven et al. 2016), which is described in detail in the Supplementary Notes. The future total iron and steel demand (in Mt) for each region is then estimated by multiplying the per capita iron and steel consumption by the total population projection in each region.

Figure 2. Structure of the iron and steel production sector in the GCAM-KSA.

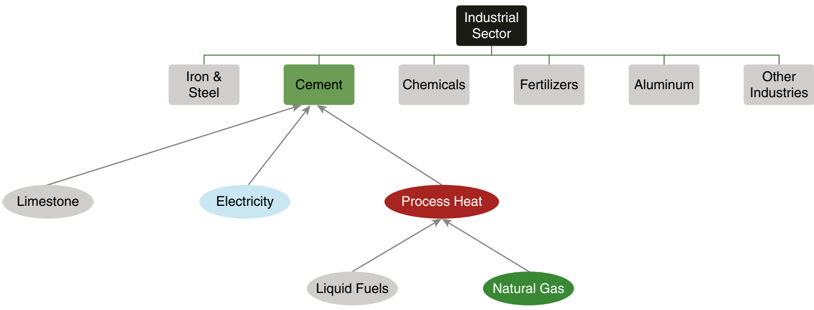


Source: KAPSARC.

The cement sector captures the physical output of cement production (in Mt), energy consumption (in EJ), and CO_2 emissions derived from both the chemical process of cement production (calcination of limestone) and energy consumption. The cement sector includes production technologies both with and without CCS technology. CCS in cement production captures the CO_2 emissions from limestone calcination. **Figure 3** shows the mass and energy flows in the cement sector in the model structure (with only cement (without CCS) displayed). The process heat for cement is treated as a specific energy commodity under which different types of fuel compete for the market share of this input, but process heat for cement does not compete with electricity for market share because they are both needed for cement production with predefined input-output coefficients. The future demand for cement in each area is estimated based on the future GDP, population, income, and price elasticities, which are explained in detail in the Supplementary Notes.

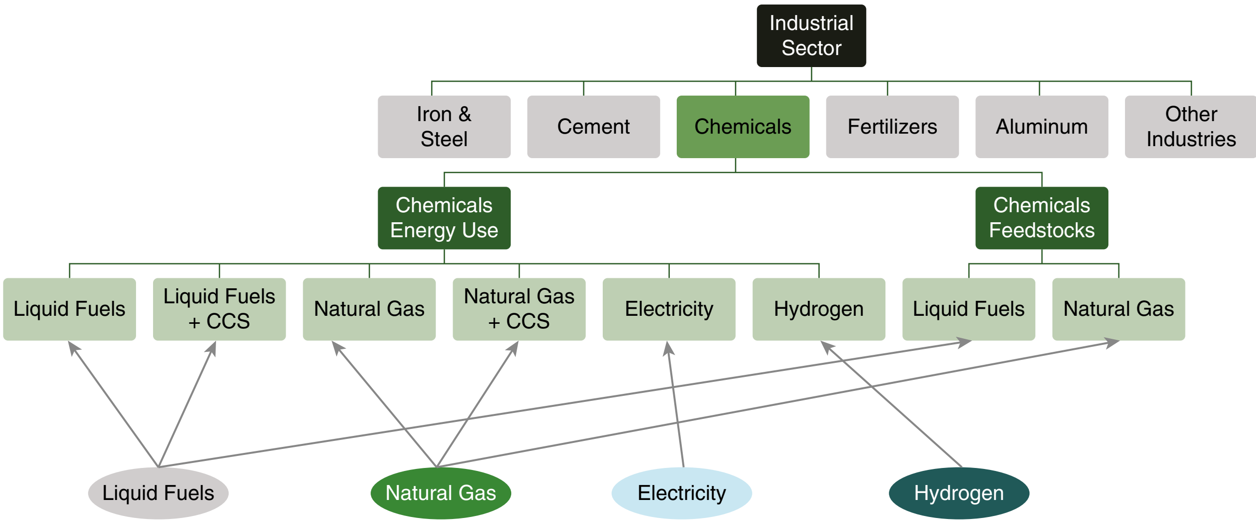
The chemical sector represents the chemical and petrochemical industry, which is split into two areas: chemical energy use and feedstocks (**Figure 4**). No specific physical output is modeled for the chemical sector; instead, the service output of this sector is represented in generic terms (EJ of energy services). Historical chemical energy use and feedstocks are calibrated based on data collected from IEA energy balances (IEA 2021). Similar to cement, the future service output of the chemical sector is driven by GDP, income elasticities, and price elasticities.

Figure 3. Structure of the cement production sector in the GCAM-KSA.



Source: KAPSARC.

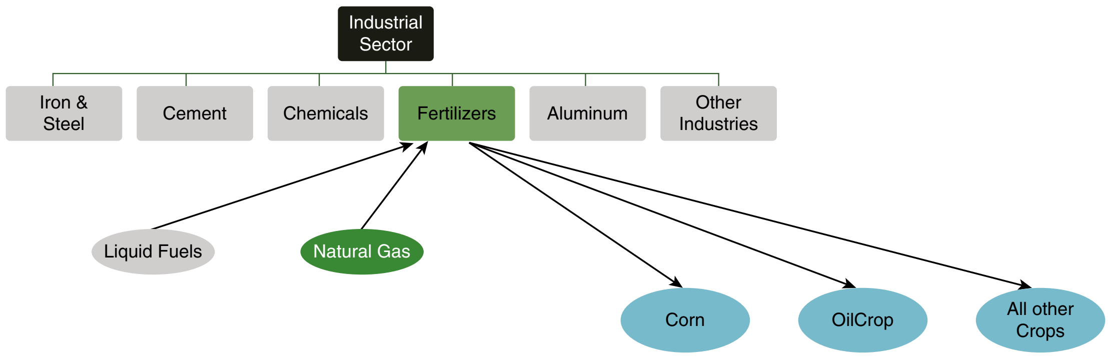
Figure 4. Structure of the chemicals sector in the GCAM-KSA.



Source: KAPSARC.

The N fertilizer (nitrogenous fertilizers) sector includes both the specific production technologies for transforming various feedstocks into N fertilizer and the demands for the commodity in the agricultural sectors (**Figure 5**). Nitrogenous fertilizers manufactured for nonagricultural purposes are excluded from the commodities modeled in GCAM-KSA. The physical output from the N fertilizer sector is indicated in Mt of fixed N in synthetic fertilizers. The fuel and feedstock sources and input-output coefficients of the N fertilizer sector are calibrated based on data collected from IEA energy balances (IEA 2021). The schematic below shows how the N fertilizer sector is situated between the energy and agricultural systems. The future demand for fertilizer is determined by the fertilizer input-output coefficient and the level of crop production, which are described in the Supplementary Notes.

Figure 5. Structure of the fertilizer production sector in the GCAM-KSA (the fuel/feedstock sources are competing technologies, not fixed inputs to a production function).



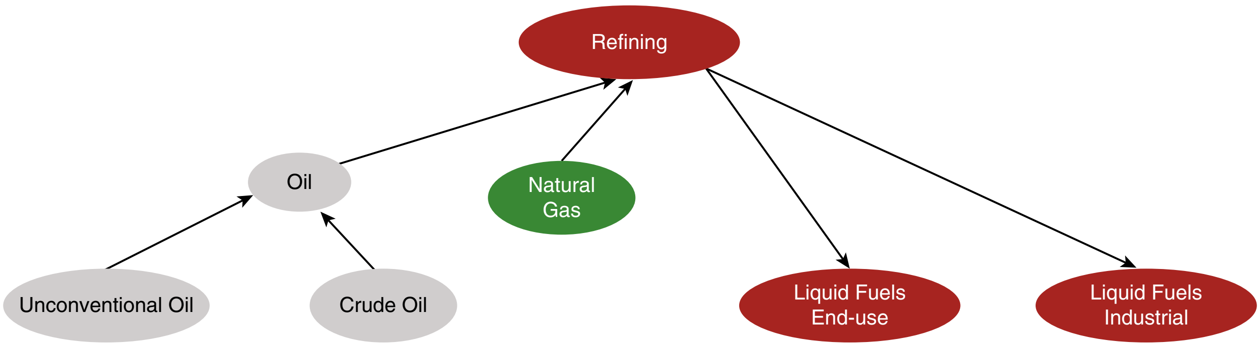
Source: KAPSARC.

The other industrial sectors collectively include various sectors, such as food processing, paper pulp and printing, machinery, textiles and leather, other nonmetallic minerals, and other nonferrous metals. This sector is represented as a consumer of generic energy services and feedstocks. Within "other industry", there is cost-based competition between fuels but with a low elasticity of substitution, as the specific uses of the energy are not specified. The outputs of aggregate industrial sectors are represented in generic terms (EJ of energy services). The future service output of the other industrial sectors is again driven by GDP, income elasticities, and price elasticities (similar to those of the cement and chemical sectors).

The refining sector, unlike the industrial sectors described above (which are considered part of the end-use sectors in the GCAM), is part of the energy transformation processes in the GCAM, but we include the results of the refining sector given its important role in the KSA industrial sector. The refining sector explicitly tracks all energy inputs, emissions, and costs involved in converting primary energy forms into various liquid fuels (including gasoline, diesel, kerosene, ethanol, and many other liquid hydrocarbon fuels), but GCAM models only a single "refined liquids" product that is consumed by all end-use sectors. The refining sector includes the subsectors of oil refining, biomass to liquids, gas to liquids, and coal to liquids (**Figure 6**), but we removed the options of biomass to liquids and coal to liquids for the KSA in the GCAM-KSA, given that these options are either economically infeasible or are not being utilized in the Kingdom. In the current structure of the model for both oil refining and gas-to-liquid conversion, there is no technology option with CCS. The future demand for refined liquids in GCAM is endogenously estimated based on the demands in various end-use sectors (e.g., electricity, transport, industry, etc.).

The GCAM-KSA also models direct air carbon capture and storage (DACCS) technologies as an industry service. These technologies remove CO_2 from the atmosphere and sequester it at a geological storage site, along with any captured combustion emissions from process heat. DACCS operations consumes thermal and/or electrical energy, which is considered energy consumption in the industrial sector. Detailed information about the characteristics of different DACCS options, technology competition, and future demand estimation can be found in Fuhrman et al. (2020) and Fuhrman et al. (2021).

Figure 6. Structure of the refining sector and associated products within the energy system.



Source: KAPSARC.

2.3 Scenario Design

In this study, four scenarios up to the 2060 area are considered using the GCAM-KSA. These scenarios were chosen to evaluate the long-term impact of various policies and mitigation efforts on Saudi Arabia's energy system. For all the scenarios, we assume a growing economy and an increasing population, with per capita income reaching USD 37,000 (2020 prices) in 2060 and a total population of 60 million. We include the impact of COVID-19 on the GDP growth rate in 2020 and the recovery thereafter in 2025 as per the International Monetary Fund (IMF) projections (International Monetary Fund 2023a). The population and GDP growth rate thereafter aligns with the Shared Socioeconomic Pathways – Middle of the Road (SSP2) assumptions for the growth rate from the shared socioeconomic pathways database (Fricko et al. 2017). The specific critical policies and mitigation targets of Saudi Arabia that are used to characterize the scenarios in this study are described in **Table 1**.

Under the *NDC continuance* and *NZ2060* scenarios, we assume that other model regions (except for Saudi Arabia) fulfill their own NDCs and net-zero targets, as reflected in the NDC scenario from Iyer et al. (2022). This assumption includes various countries' commitments during COP 26 and the continued ambition scenario presented by Ou et al. (2021).

Table 1. The scenario design of this study and the key assumptions of the scenarios.

Scenario Name	Policies and Mitigation Targets
No policy	No energy efficiency gains in the building and transport sectors. No energy price reforms, i.e., incentivized fuel prices continue. No climate mitigation policy, i.e., no NDC target. No market/support for low-carbon technologies.
Current policy[1]	Reflects energy efficiency gains based on various initiatives by SEEC in the end-use sectors. Reflects energy price reforms by calibrating the 2020 fuel prices in the model to the actual fuel prices in Saudi Arabia post two rounds of price reforms in 2016 and 2018. Attains equal electricity generation capacity of renewable (50%) and gas-based plants (50%) by 2030.
NDCs continued[2]	Includes the policies from the current policy scenario and meets the NDC target of emissions reductions of 278 $MtCO_{2eq}$ by 2030 compared to no policy scenario. Beyond 2030, continuation of the same declining rate of GHG intensity of the economy as achieved from 2020 to 2030 to meet the NDC target.
NZ 2060	In addition to the NDCs continued scenario, the net GHG emissions beyond 2030 linearly decline to zero by 2060.

[1] The current policy scenario does not include the impact of two key initiatives in the KSA due to insufficient information to assess their long-term impacts on emissions. First is the plantation of 650 million trees in the KSA by 2030. Second is the impact of the King Abdulaziz Project on Riyadh's public transport, which aims to equip Riyadh with an extensive public transport network, including metro lines and bus routes.

[2] Saudi Arabia has not officially defined the baseline emissions in their updated NDCs; thus, we have assumed the no policy scenario as the baseline emissions in this study.

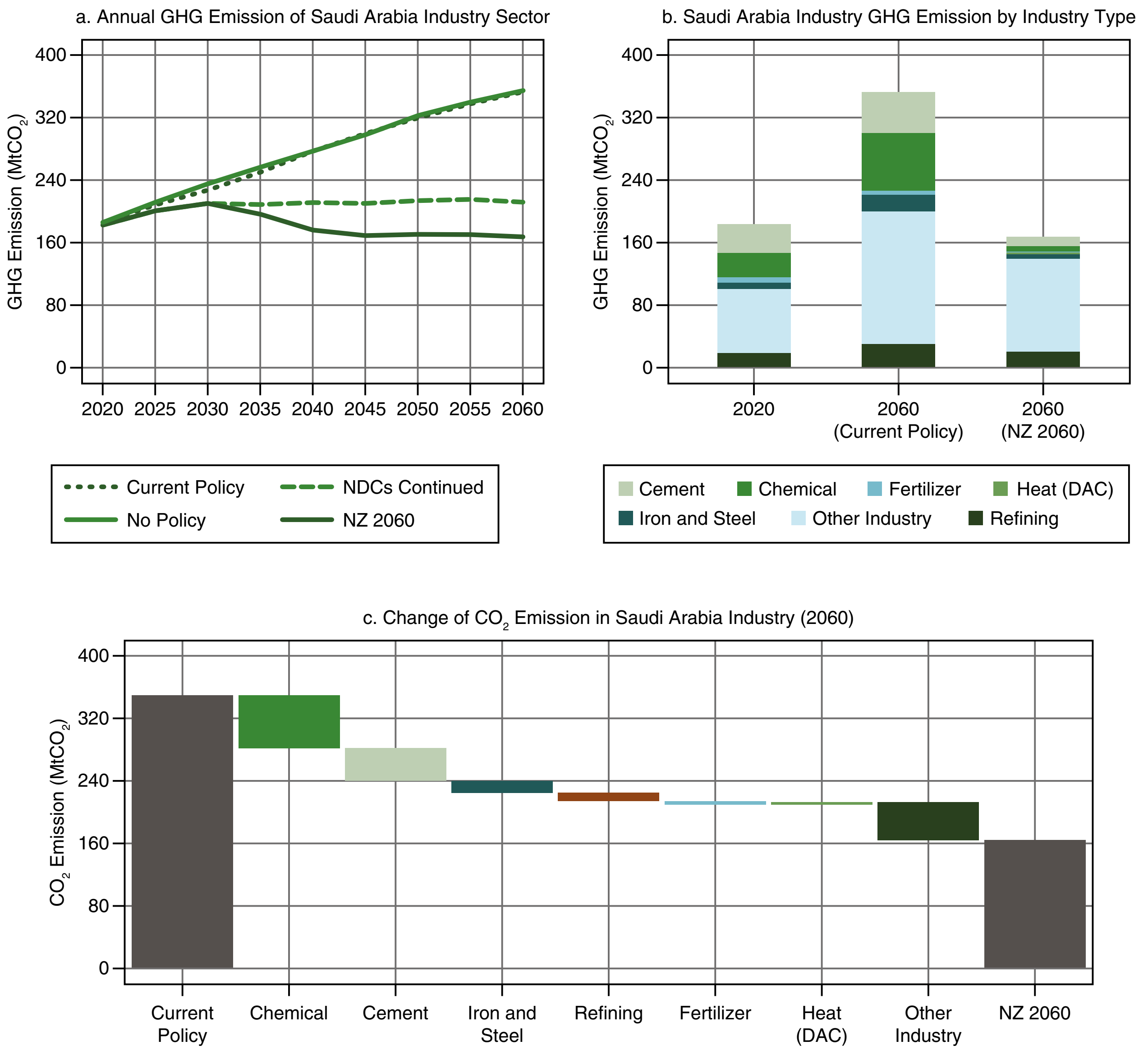
3. Results

3.1 The Reductions in CO_2 Emissions in KSA Industry Under the NZ 2060 Scenario are Mainly Attributed to Emissions Reductions from the Chemical, Cement, and Iron and Steel Sectors

The annual CO_2 emissions of the KSA's industry under the different scenarios are shown in **Figure 7a**. Given that the representation of policies and energy efficiency gains for the industrial sector are similar under the *No Policy* and *Currently Policy* scenarios (Table 1), they show almost identical CO_2 emissions trajectories, which increase from 2020 and reach 349 and 347 Mt CO_2, respectively, by 2060. The industrial CO_2 emissions under the *NDC Continued* scenario follow a relatively steady trajectory after 2030, and they reach 221 Mt CO_2 by 2060. Under the *NZ 2060* scenario, the CO_2 emissions of the KSA industrial sector will decline after 2030 and reach 164 Mt CO_2 by 2060.

Petrochemical, cement, steel, and refining are the four largest contributors (together accounting for 52%) to the 2020 CO_2 emissions in the KSA industrial sector (**Figure 7b**). By 2060, the CO_2 emissions from these four sectors will continue to increase and will remain the largest contributor to the total CO_2 emissions in the KSA industrial sector under the *current policy* scenario. In comparison, the industrial CO_2 emissions of the KSA under the *NZ 2060* scenario significantly decreased over time, reaching less than half (47%) of those under the *current policy* scenario in 2060. This reduction is mostly driven by overall lower CO_2 emissions from the chemical, cement, steel, and refining sectors. Under the *NZ 2060* scenario, the 2060 CO_2 emissions of these four industrial sectors decrease by 134 Mt compared to those under the *current policy* scenario, which account for 73% of the total 2060 CO_2 emissions reduction (183 Mt CO_2) in the KSA industrial sector (**Figure 7c**).

Figure 7. Annual emissions from the KSA industrial sector. .



Notes: Panel (a) shows the annual GHG emissions of the KSA industrial sector from 2020 to 2060 under the four scenarios. Panel (b) shows the annual GHG emissions of the KSA industrial sector in 2020 and 2060 (breakdown by sectors), with 2060 results showing for the Current Policy and NZ 2060 scenarios. Panel (c) shows the sectoral contributions to the reduction of 2060 CO2 emissions in the KSA industrial sector (reductions in comparison to the Current Policy and NZ 2060 scenarios).

Source: KAPSARC.

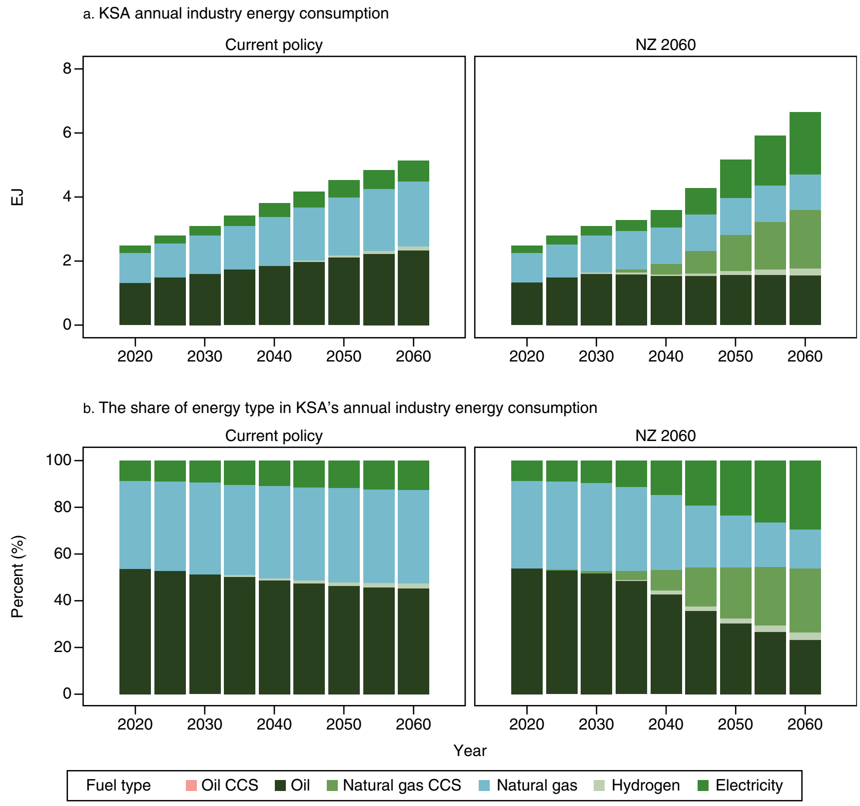
3.2 The Implementation of Carbon Capture and Storage Plays a Crucial Role in Reducing CO_2 Emissions from KSA's Industrial Sector

The reduction in CO_2 emissions in the KSA industrial sector is driven by the implementation of carbon capture and storage (CCS) for both energy generation and the production of industrial goods. Energy consumption in the KSA industrial sector is dominated by unabated natural gas and oil under the *current policy* scenario, accounting for 85% of the total energy consumption in the KSA industrial sector in 2060. However, under the NZ 2060 scenario, natural gas with CCS plays a more important role across various sectors, including chemicals, N fertilizer, and alumina, by replacing natural gas and oil (without CCS). In 2060, natural gas with CCS will provide 1.8 EJ of energy, accounting for 27% of the total energy consumption in KSA's industrial sector. Despite its overall small share (< 5%) of energy consumption in 2060, hydrogen consumption in the KSA industrial sector will also double in 2060 (0.2 EJ) under the NZ 2060 scenario (compared to the *current policy* scenario, 0.1 EJ), mainly due to increased consumption in the steel subsector (Figure 8).

The implementation of CCS in cement and steel production is the key mitigation strategy that contributes to CO_2 emissions reduction in these two industrial sectors under the *NZ 2060* scenario. In the cement and steel sectors, CCS is mainly used to capture and store CO_2 originating from process emissions (e.g., the calcination of calcium carbonate in cement production and the reduction in iron ore in steel production). Under the *Current Policy* scenario, cement production in the KSA completely relies on conventional processes (i.e., cement without CCS) from 2020 to 2060. However, under the *NZ 2060* scenario, cement plants will be equipped with CCS after 2035 (with a market share of 10%), and its share will rapidly increase to 96% by 2060 (**Figure 9**).

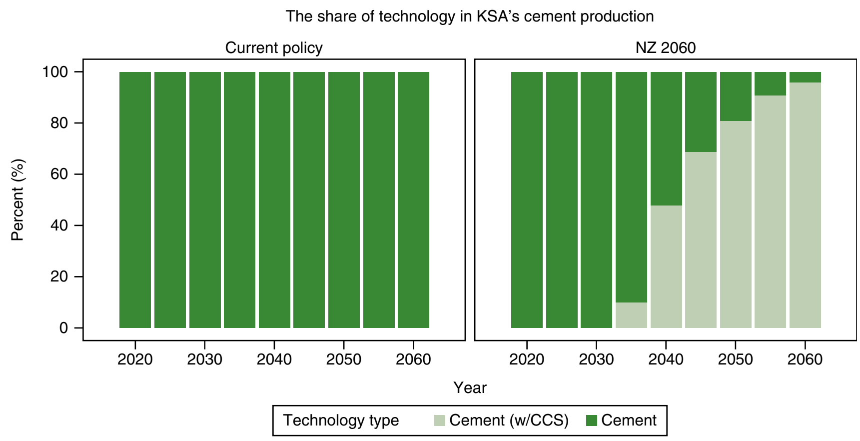
Similarly, iron and steel production in the KSA is dominated by both the EAF with the DRI and the EAF with scrap under the *Current Policy* scenario until 2060. An EAF with a DRI (hydrogen-based) gradually penetrates the overall technology portfolio, but this technology will account for only 9% of the total KSA steel production in 2060. However, under the *NZ 2060* scenario, a growing share of EAFs with DRIs will be retrofitted with CCS technologies to reduce CO_2 emissions from iron and steel production. The market share of iron and steel produced based on EAF with DRI (with CCS) will increase from 10% in 2030 to 47% of KSA's iron and steel production in 2060 (**Figure 10**).

Figure 8. The annual energy consumption by fuel type (a.) and their shares (b.) in the KSA industrial sector.



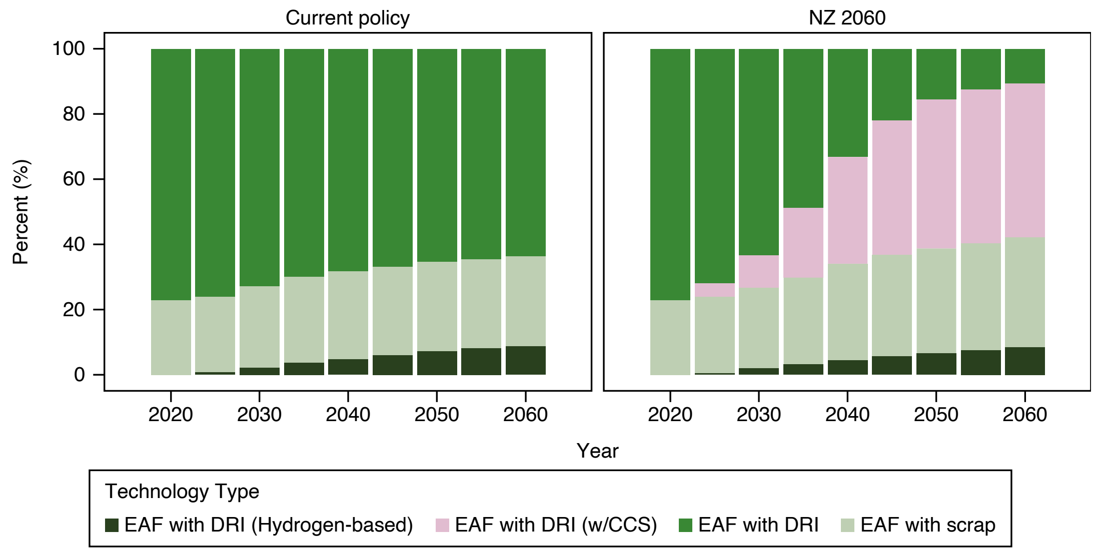
Source: KAPSARC.

Figure 9. The share of different cement production technologies in the KSA under the *current policy* and *NZ 2060* scenarios.



Source: KAPSARC.

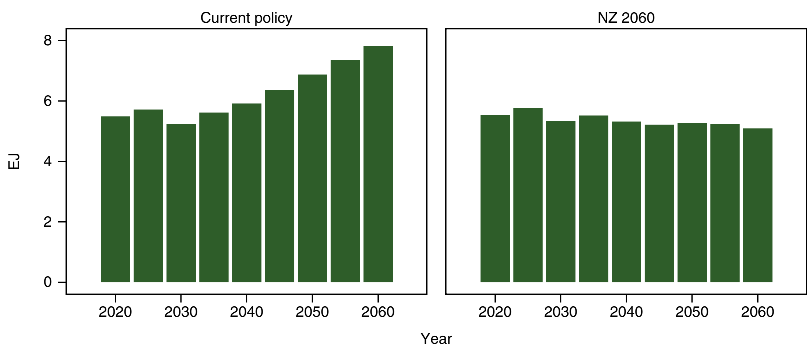
Figure 10. The share of different iron and steel production technologies in the KSA under the *current policy* and *NZ 2060* scenarios.



Source: KAPSARC.

For the refining sector, 2060 CO_2 emissions under the *NZ 2060* scenario (20 Mt CO_2) are reduced by approximately 35% compared to emissions under the *Current Policy* scenario (31 Mt CO_2). This is mainly driven by overall less refined liquid production and less energy consumption in the refining sector in the KSA under the *NZ 2060* scenario (in which the overall global demand for refined liquids is reduced) (**Figure 11**).

Figure 11. The production of refined liquids (represented by the red color) in the KSA (from the refining sector) under the *current policy* and *NZ 2060* scenarios.



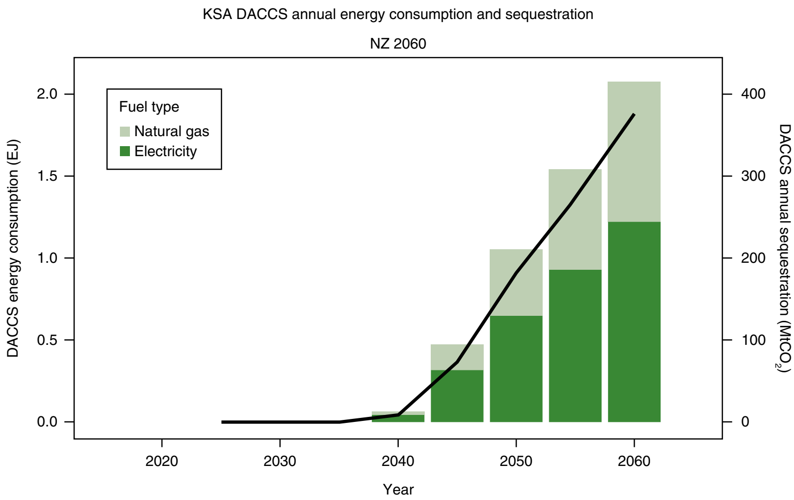
Source: KAPSARC.

3.3 DACCS Deployment and Operation Under the NZ 2060 Scenario Leads to Additional Energy Consumption in KSA's Industrial Sector

The deployment of DACCS plays a crucial role in offsetting residual emissions from hard-to-abate sectors and will contribute to the achievement of KSA's net-zero GHG emissions target in 2060. Under the NZ 2060 scenario, the introduction of DACCS in the KSA is projected to increase in momentum by approximately 2040, and the annual CO_2 sequestration by DACCS will need to reach 374 Mt CO_2/yr in 2060. Operating the DACCS at this scale also requires 0.9 EJ/yr (250 TWh/yr) of electricity and 1.2 EJ/yr of heat (assumed to be provided through natural gas) (Figure 12), which also leads to additional energy consumption in the KSA industrial sector (Figure 8). These results highlight the need to build necessary CO2 transport and storage facilities as well as compatible energy infrastructure capable of meeting the energy demand from DACCS should its deployment scale up in the future.

It is critical to understand that while 374 million tons of CO_2 removal capacity through DACCS annually presents a significant milestone, this number should not be viewed in isolation. The reliance on DACCS, a technology that remains costly and energy-intensive, underscores an urgent need for a broader spectrum of research and development efforts. Future efforts by Saudi Arabia must aim to diversify the approach to carbon removal, exploring more sustainable and cost-effective ways that can complement and potentially reduce our dependency on DACCS. This pivot toward innovation is not merely advantageous but essential for scaling up the response to climate change in a manner that is both economically viable and environmentally sustainable. Therefore, while DACCS will undoubtedly play a role in the Kingdom's mitigation strategies, it is imperative for the Kingdom continue to seek out and invest in alternative solutions that could offer more scalable and financially accessible options for carbon removal.

Figure 12. Annual energy consumption and CO_2 sequestration of DACCS in the KSA under the *NZ 2060* scenarios.



Annual energy consumption (bar) correspond to y-axis on the left. Annual CO2 sequestration (black line) correspond to y-axis on the right. Natural gas is used to provide heat in the DACCS operation to regenerate the solvent of DACCS. The CO2 emissions from natural gas combustion can be collected and sequestered.

Source: KAPSARC.

4. Discussion

In this study, we have assessed the future evolution of the KSA's industrial sector under different energy and climate policies. Our results show that, in addition to current policy measures on energy efficiency improvements and energy price reforms, it is necessary to increase ambitions to be in line with the KSA's 2060 goal of achieving net-zero GHG emissions and thus effectively mitigating CO_2 emissions in the industrial sector. These ambitious climate targets could halve industry CO_2 emissions by 2060.

The chemical, steel, cement, and refining sectors are the key contributors to the substantial CO_2 reduction observed in 2060. This reduction in CO_2 emissions is mostly driven by the deployment of CCS technologies to capture both energy-related and process emissions in the steel and cement sectors. As a broad range of countries and companies increase their climate ambition and targets, the development and deployment of CCS technologies in the KSA's industrial sector could also help build a competitive advantage for the KSA as an exporter of low-carbon industrial products. It could help maintain the existing market share of petrochemicals and open new markets for other products, such as iron and steel, nonferrous metals, hydrogen, and even carbon storage services, thus driving the future-oriented diversification of the KSA economy.

By 2060, the KSA's industrial sector will still have some hard-to-abate CO_2 emissions and ambitious climate targets. To achieve the 2060 net-zero GHG emissions target, the KSA will need to scale up the deployment of DACCS to offset residual CO_2 emissions. This will necessitate additional energy infrastructure capable of meeting the energy demand from the operation of DACCS facilities. On the other hand, the CO_2 captured from both the DACCS (and point-source CCS) could provide long-term opportunities for the KSA to unlock the value chain of carbon capture and utilization (CCU), especially within the KSA's circular carbon economy framework. CCU could provide a cost-effective way to use the captured CO_2 and produce new commodities. KSA already has expertise in the CCU value chain, including the use of captured CO_2 for enhanced oil recovery and the production of methanol and urea fertilizers (SABIC 2023; Gnana 2023). Future opportunities for CCU in the KSA could include the production of synthetic fuel and carbonate (e.g., converting saline brine from desalination plants into sodium bicarbonate and soda ash) (Oil and Gas Climate Initiative 2021).

In addition to the policy measures and climate targets analyzed in this study, several other policy initiatives that could shape the future of the KSA's industrial sector are also envisioned. For example, under the National Hydrogen Strategy, the KSA aims to produce 4 Mt/yr of clean hydrogen (with 1.2 Mt/yr from green hydrogen and the remainder from blue hydrogen) by 2030, making it a global leader in hydrogen production and export and reducing its reliance on oil (Hassan et al. 2023; World Economic Forum 2023). The KSA is also planning to establish a CCS hub in the Jubail region, which will have the capability to capture and store up to 9 Mt CO_2/yr from the petrochemical industry in 2027 and further expand its overall CCS capacity to 44 Mt CO_2/yr by 2035 (Reuters 2022). Future work could incorporate these policy initiatives and study their potential impacts on the future development of the KSA's industrial sector and their potential contributions to the overall national climate change mitigation targets of Saudi Arabia.

5. Supplementary Notes

5.1 GCAM-KSA Modifications for the Data Inputs Related to the KSA

In the GCAM-KSA, we modify some KSA-related inputs based on KSA region-specific data and assumptions. The relevant modifications are listed in Table 2.

Table 2. A list of modifications conducted for KSA-related data inputs based on KSA region-specific data and assumptions.

Sectors/items	Modifications
GDP	Update the KSA's GDP input data, including: • Historical Saudi Arabia GDP data until 2021 (accounting for COVID impacts) (General Authority for Statistics 2023). • Up-to-date near-term future GDP growth rate projections (up to 2024) (International Monetary Fund 2023b).
Power sector	No electricity generation from coal and biomass (excluding waste-to-energy) in the KSA, as there is no current capacity and no domestic resource available. No new oil capacity to be built in KSA after 2015 based on KSA's target of achieving equal generation capacity of renewables and natural gas power plants by 2030. Updated the lifetime of KSA's generation technologies based on the discussions with the experts on KSA electricity sector.
Resource use	No use of coal, biomass, or nuclear in H_2 production, gas processing, and refining in KSA after 2015 (based on consultations with experts on KSA's energy sector).
Transport sector	Updated load factor, energy intensity, speed and annual travel distance for KSA's four wheelers based on Alwosheel and Dua (2023).

Sectors/items	Modifications
Industrial sectors	Cement sector: • Updated KSA's cement production for 2015 (General Authority for Statistics 2019) and 2020 (The Journal Cement 2021) (also reflecting the COVID impact on cement production in 2020). • Updated KSA's cement energy and emissions intensity based on the KAPSARC Energy Model (KEM) for Saudi Arabia.
	Chemicals sector – Updated KSA's 2015 chemicals sector energy and feedstock consumption based on the KAPSARC Energy Model (KEM) for Saudi Arabia.
	Fertilizer sector – Updated the KSA's ammonia production from 2010 to 2015 based on data from Statista (Statista 2023) and cross-checked with data from the International Fertilizer Association.
	Iron and steel sector – Updated the KSA's gas energy intensity data for steel production based on the KAPSARC Energy Model (KEM) for Saudi Arabia.
	Reallocated the energy consumption related to oil and gas exploration and production – In the IEA's World Energy Balances (which provide data for energy and feedstock consumption for industrial sectors in GCAM), energy consumption related to oil and gas exploration and production was assigned to "unspecified" industries. We reallocated it to the category of "mining energy use". Given the importance of the oil and gas industry in the KSA, this action is to ensure that relevant energy consumption is well represented.

5.2 A Modified Logit Discrete Choice Model

In this model, the market share of a given technology or energy source is determined by its levelized cost mediated by the influence of noncost factors, which are captured by share weights and a logit exponent. Shared weights allow calibrations to historically observed technology shares and the implementation of a measured phase-in of new technologies. The logit exponent dictates how large a cost difference is needed to result in a particular difference in market share among technologies and energy sources.

$$S_i = \frac{\alpha_i \rho_i^{\gamma}}{\sum_{i=1}^{N} \alpha_i \rho_i^{\gamma}} \qquad \text{Equation 1}$$

where S_i is the share of technology/energy source; i, α_i is the share weight of technology/energy source; i, ρ_i is the cost of technology/energy source; i, γ is the logit exponent (for GCAM technologies whose competition is determined mainly by technology costs, the logit exponents are typically set to negative values because having a logit exponent <0 favors technology with lower values of ρ (i.e., lower cost)); and N is the number of technologies/energy sources.

5.3 Nonlinear Inverse of the Time-Efficiency-Factor (NLIT) Function to Model Iron and Steel Demand

For the iron and steel sector, future iron and steel production across all regions is estimated using non-linear inverse with time-efficiency-factor (NLIT) function (Van Ruijven et al. 2016). The NLIT model describes the relationship between per capita GDP and per capita steel production, as detailed in Equation 2 below:

$$C = a \times e^{\frac{b}{GDP_{Pct}}} \times (1-m)^{(T-T_0)} \qquad \text{Equation 2}$$

where C is the per capita steel consumption; GDP_{Pct} is the per capita GDP, T is the year; T_0 is the base year from which improvements in material efficiency are achieved; a is the model constant representing the saturation level of the per capita steel consumption at high per capita income levels; b is the model constant representing the per capita GDP at which saturation levels are approached; and m is the model constant representing the annual improvement in material efficiency in per capita consumption. The future energy consumption from the steel sector is then estimated by multiplying the steel production and the energy intensity value in each model period.

5.4 Estimation of Future Demand for Cement and Chemical Sector Service Output

The future demand D for cement in region r and period t is given by Equation 3:

$$D_{r,t} = D_{r,t-1}\left(\frac{Y_{r,t}}{Y_{r,t-1}}\right)^{\alpha}\left(\frac{P_{r,t}}{P_{r,t-1}}\right)^{\beta}\left(\frac{N_{r,t}}{N_{r,t-1}}\right) \qquad \text{Equation 3}$$

where Y is the per capita GDP, P is the total service price aggregated across all modes, N is the population, and α and β are income and price elasticities, respectively. The future energy consumption of cement production is estimated based on future cement production and energy input coefficients.

5.5 Estimation of Future Fertilizer Demands

The future demand for fertilizer is determined by the fertilizer input-output coefficient and the level of crop production, which is shown in Equation 4:

$$D_{r,t} = \sum_{j=1} n \times Prod_{j,t} \times Coef_{j,t} \qquad \text{Equation 4}$$

where $D_{r,t}$ is the demand for fertilizer in region r at period t, $Prod_{j,t}$ is the crop production for technology j at period t, $Coef_{j,t}$ is the fertilizer input-output coefficient for technology j at period t, and j is the set of all agricultural technologies within region r.

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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 Saudi Arabia 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 Saudi Arabia, (2.) the sectoral impacts and the role of adaptation measures, and (3.) the pathways of the Saudi economy to achieve a low-carbon future or climate neutrality by the mid-century. (4.) The study will also adopt 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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