

GCAM-KSA: An Integrated Assessment Model for Saudi Arabia

Puneet Kamboj, Yang Qiu, Neal Graham, Page Kyle,
Raphael Apeaning, Gokul Iyer, and Mohamad Hejazi



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Key Points

- Introduces the first country-specific integrated assessment model implementation for Saudi Arabia, decoupled from the aggregated Middle East region while preserving global linkages.
- Addresses a key gap in the IAM literature, where aggregated regions obscure country-level structural specificities.
- Documents calibration, formulations, and updates across the power, refining, buildings, transport, water, land, and climate sectors, as well as six industry subsectors.

Abstract

This paper presents the Global Change Analysis Model for Saudi Arabia (GCAM-KSA), the first country-specific implementation of the Global Change Analysis Model tailored to the Kingdom of Saudi Arabia. The model enhances GCAM's global integrated assessment framework by introducing detailed representations of Saudi Arabia's energy system, industrial structure, water resources, land use dynamics, and socioeconomic drivers. GCAM-KSA incorporates national data on technology costs, energy prices, refinery configurations, industrial process routes, crop water requirements, desalination technologies, and building energy services, enabling a high-resolution, long-term assessment of transition pathways. Methodological advances include the explicit treatment of hydrogen in refining, carbon capture and storage (CCS)-enabled industrial technologies, Saudi-specific renewable resource characterization, and revised land- and water-system parameters reflecting regional biophysical constraints. This paper documents the model structure, calibration procedures, and sectoral updates, and demonstrates GCAM-KSA's capability to produce internally consistent scenarios of energy demand, emissions, land use, water use, and climate outcomes through 2060. Results from alternative scenarios highlight the importance of integrated, multisectoral linkages in shaping transition trajectories and identifying sector-specific constraints. GCAM-KSA provides a robust analytical platform for examining long-term decarbonization strategies in Saudi Arabia and serves as a foundation for future enhancements of the model.

Keywords: GCAM-KSA, Integrated Assessment Model, Net-Zero Pathways, Saudi Arabia, Greenhouse Gas Emissions



Integrated assessment models (IAMs) serve as critical tools in climate policy formulation and evaluation, enabling policymakers to analyze the complex interdependencies among energy systems, economic activities, land use, and climate dynamics. By synthesizing knowledge across multiple domains, IAMs offer comprehensive insights into how various policy pathways may influence future outcomes.

Among the globally recognized IAM frameworks, the Global Change Analysis Model (GCAM) stands out for its extensive application and robust analytical capabilities. GCAM facilitates integrated analysis across energy, the economy, water, land use, and greenhouse gas (GHG) emissions, and has been widely documented in academic literature for its versatility and regional adaptability (Calvin et al. 2019). The model has informed climate strategies in diverse contexts, including the U.S. Mid-Century Strategy and China's carbon-neutrality planning, and has played a pivotal role in scenario development during the Paris climate negotiations (Calvin et al. 2014).

Saudi Arabia, a major actor in the global energy landscape, faces distinct challenges in its transition toward a low-carbon economy, primarily due to its economic reliance on hydrocarbon exports. In alignment with Vision 2030 and the Saudi Green Initiative, the Kingdom has pledged to achieve net-zero GHG emissions by 2060. However, a comprehensive assessment of how various national climate policies collectively contribute to this target remains limited (Kamboj et al. 2024; Durand-Lasserve 2025).

IAMs, with their capacity to model sectoral interactions and feedback mechanisms, are essential for identifying viable decarbonization pathways tailored to Saudi Arabia's unique context.

Many IAMs are structured for global-scale analysis and therefore represent national economies through aggregated regional or sub-regional groupings. Consequently, Saudi Arabia is frequently subsumed within a broader Middle East region, which can obscure country-specific dynamics that are critical for granular climate policy evaluation (IAMC Wiki 2026). Prior studies have emphasized the importance of disaggregated regional modeling to better capture national characteristics (Bauer et al. 2017). Saudi Arabia's distinctive energy profile, its significant role in global energy markets, substantial renewable energy potential, and ambitious economic diversification goals necessitate a country-specific modeling approach.

The Global Change Analysis Model for Saudi Arabia (GCAM-KSA) addresses this gap by representing Saudi Arabia as an independent region within the IAM framework. As the first model of its kind, GCAM-KSA enables high-resolution analysis of the Kingdom's energy-economy interactions and the implications of its climate policies, thereby offering a more granular and policy-relevant assessment of its transition to net-zero emissions.

The remainder of the paper is structured as follows. Section 2 describes the GCAM-KSA framework, including the model architecture, equilibrium formulation, and its relationship

to the core GCAM model. Section 3 details the Saudi-specific updates and sectoral representations across power, refining, buildings, transport, industry, water, and land use systems. Section 4 presents the socioeconomic assumptions and scenario framework used in the analysis. Section 5 discusses results

from the current-policy and net-zero scenarios, highlighting economy-wide and sectoral dynamics. Finally, Section 6 concludes with key insights, limitations, and priorities for future model development.



GCAM-KSA is a customized, country-specific implementation of the standard 32-region Global Change Analysis Model (hereafter referred to as GCAM-Core), developed to reflect the distinct socioeconomic, energy, and resource characteristics of Saudi Arabia. GCAM-Core is a well-established partial equilibrium integrated assessment model widely used to analyze interactions among long-term energy transitions, economic development, land systems, water constraints, and climate outcomes (Kim et al. 2006; Wise et al. 2009; Calvin et al. 2019). In its standard formulation, the Middle East is represented as a single aggregated region, and GCAM-KSA extends this framework by treating Saudi Arabia as an independent region (Figure 1).

This disaggregation enables a more granular representation of the Kingdom's economic structure, fossil resource endowment, energy demand patterns, and emerging low-carbon technology pathways, thereby improving the relevance and accuracy of long-term scenario analysis for national planning.

GCAM-KSA incorporates detailed representations of Saudi Arabia's energy system, including upstream oil and gas production, refining, electricity generation, desalination, building energy services, transport demand, and industrial activity. The model operates in five-year time steps from 2015-2100, enabling the exploration of long-term decarbonization trajectories under various socioeconomic and policy assumptions (Kamboj et al. 2024).

Population and GDP projections – key drivers of energy service demand – are derived from globally harmonized shared socioeconomic pathways (Samir and Lutz 2017; O'Neill et al. 2017) and modified using national statistics to align with the

Kingdom's demographic and economic outlook. Together with detailed assumptions on resource availability, technological cost evolution, and efficiency improvements, these inputs enable GCAM-KSA to simulate Saudi Arabia's potential pathways toward its 2060 net-zero emissions target.

The motivation for representing Saudi Arabia as a standalone region within an IAM framework is grounded in several structural and empirical considerations. Saudi Arabia is a major economy, both in terms of GDP and population, and plays a substantial role in global energy markets. The Kingdom's economy is highly dependent on hydrocarbon exports, and its energy system exhibits high per capita energy consumption and rapid growth in demand – patterns that are not captured in aggregated regional models (Bauer et al. 2017). Moreover, achieving net-zero emissions requires identifying feasible sector-level transformations in electricity, industry, transport, buildings, water, and land systems. Previous literature has emphasized that such transformations are highly sensitive to

regional heterogeneity and require finer spatial and sectoral resolution (Calvin et al. 2012; Riahi et al. 2017). GCAM-KSA addresses this need by embedding Saudi-specific resource curves, technology pathways, and sectoral parameters within GCAM-Core's global equilibrium structure.

Operationally, GCAM-KSA mirrors the core GCAM-Core architecture, based on simultaneous market equilibrium. Representative agents in each sector – such as power generation, refining, industrial production, agricultural supply, or building energy services – make decisions based on relative prices, technology costs, and input availability. Markets for energy, agricultural commodities, water, and emissions permits clear endogenously, with prices adjusting iteratively until supply and demand balance across all sectors (Calvin et al. 2019). This equilibrium-seeking mechanism allows GCAM-KSA to identify realistic structural shifts in energy and resource use as relative prices evolve under different socioeconomic and emissions scenarios.

For example, demand for refined liquids is determined by aggregating consumption across diverse end uses, such as passenger mobility, freight transport, refining, industrial heat, hydrogen production, and miscellaneous applications. Supply, in turn, depends on domestic resource extraction, trade, refining capacity, and technology availability. The model adjusts prices iteratively to reconcile the interplay of these drivers, ensuring that equilibrium conditions hold in each simulation period. Similar mechanisms govern electricity markets, water allocation at the basin level, and international trade in agricultural and industrial products.

GCAM-KSA is formulated as a recursive dynamic model rather than a forward-looking optimization model. Decisions at any time step are based on current market conditions, observed costs, and technology availability, rather than foresight of the entire future pathway. Long-lived capital investments incorporate cost expectations – such as projected learning by doing – but these expectations are anchored in current conditions rather than perfect foresight (Kim et al. 2006). After each model period is solved, GCAM-KSA updates energy

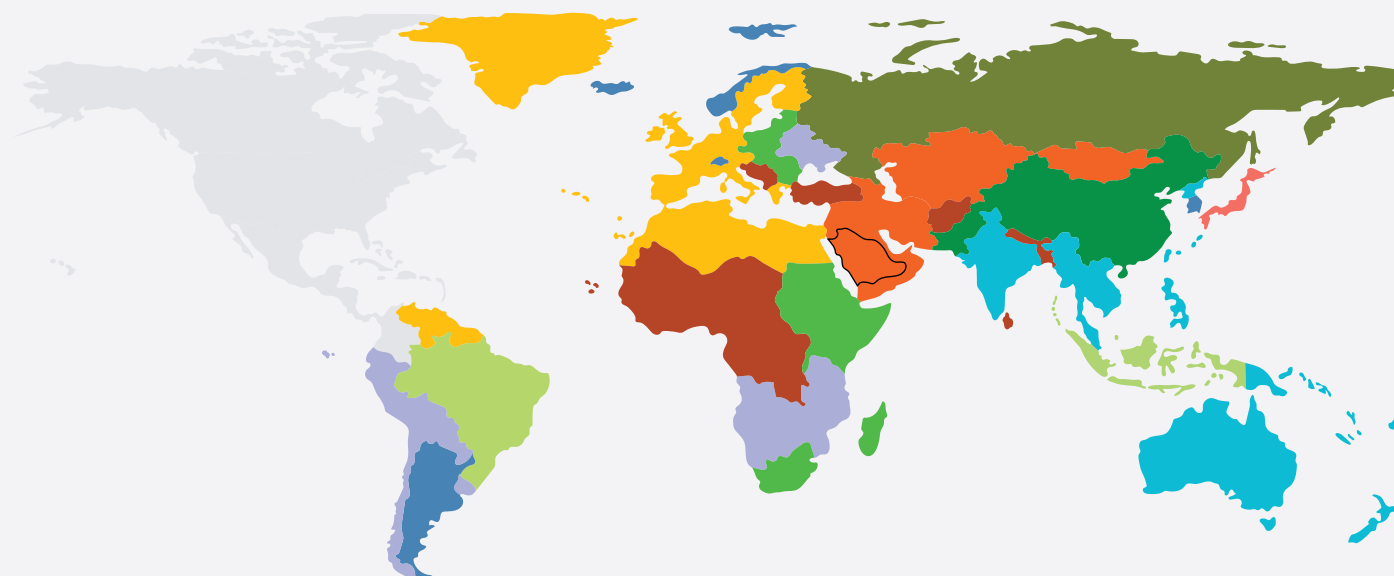
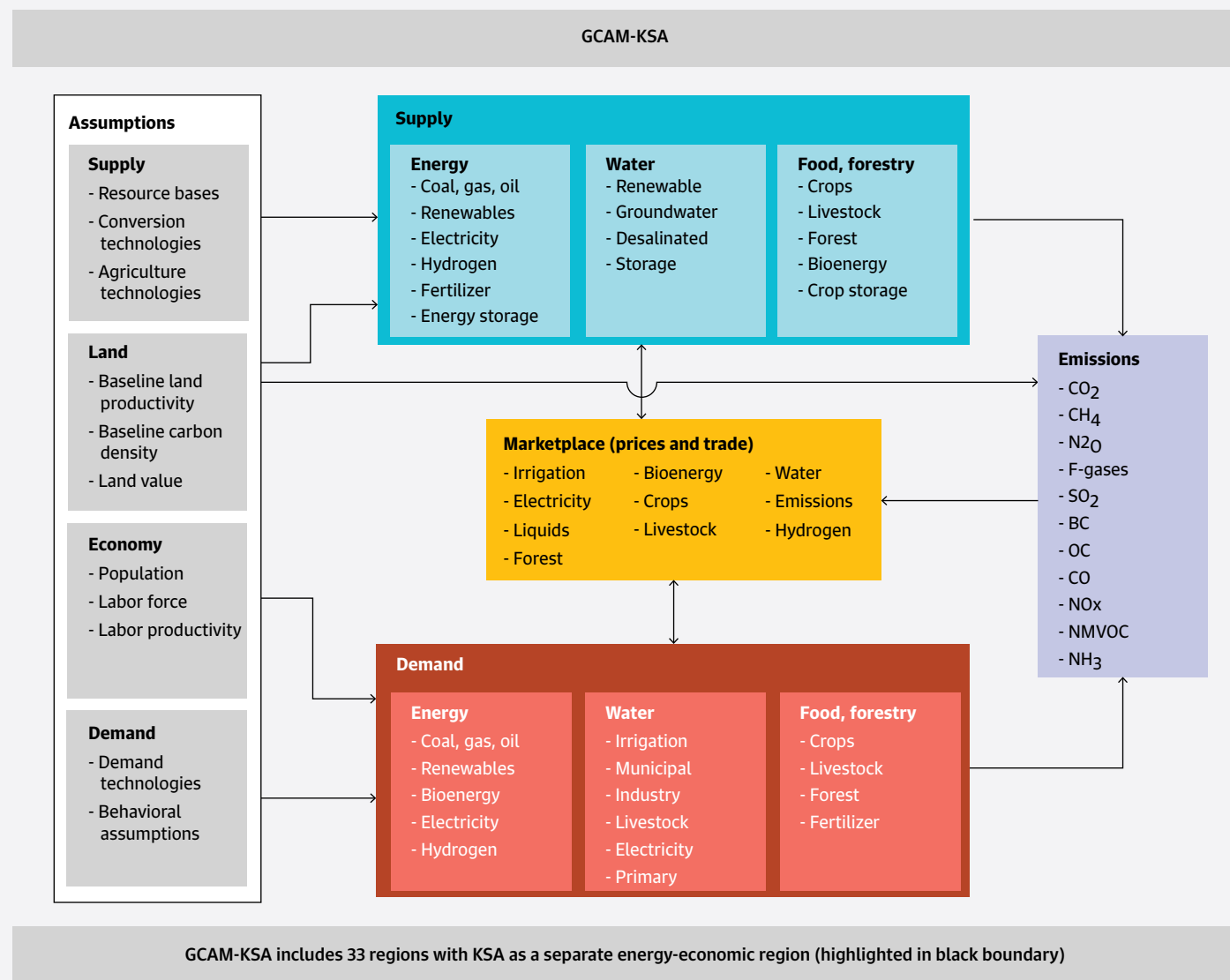
system stocks, resource depletion levels, capital turnover, land-use allocation, and atmospheric emissions, carrying these updated states forward as constraints for the next period. This recursive structure allows the model to capture the cumulative effects of historical decisions without implying optimization behavior across the century.

Technology allocation within GCAM-KSA is governed by a multinomial logit choice formulation, in which each technology's market share reflects both its levelized cost and non-cost factors such as technology preferences, historical penetration, and structural inertia. Formally:

$$S_i = \frac{\alpha_i \rho_i^\gamma}{\sum_{j=1}^N \alpha_j \rho_j^\gamma} \quad (1)$$

where S_i is the resulting market share of technology i , α_i is its share weight, ρ_i is its generalized cost, j indexes all competing technologies, γ is the logit exponent governing cost sensitivity, and N is the set of competing technologies. Negative logit exponents are typically applied in energy-demand sectors, emphasizing stronger cost-based competition. This mechanism allows GCAM-KSA to allocate technologies smoothly over time and to calibrate historical technology penetration using share weights, while retaining the flexibility to simulate future technological transitions.

Exogenous socioeconomic drivers shape initial demand trajectories in buildings, industry, and transport (JGCRI 2023). Energy service demands evolve endogenously in each scenario according to income and price elasticities, while technology costs reflect three components: (i) non-energy costs (capital, fixed, and variable operations and maintenance (O&M)); (ii) fuel costs, calibrated to Saudi-specific historical price reforms and endogenously determined thereafter; and (iii) emissions costs arising from carbon prices under mitigation scenarios. Taken together, these elements enable GCAM-KSA to simulate the interplay between energy, economy, land, water, and climate systems under a wide range of future conditions.

Figure 1. Schematic for GCAM-KSA and 33 energy-socioeconomic regions in GCAM-KSA.

GCAM-KSA: Updates from GCAM-Core

03



GCAM-KSA introduces structural and parameter modifications that reflect the Kingdom's unique resource endowments, demand patterns, climate conditions, and strategic energy transition pathways. By treating Saudi Arabia as a standalone region, GCAM-KSA captures heterogeneity that would otherwise be masked in GCAM-Core's aggregated Middle East representation.

The primary updates span socioeconomic projections, resource characterizations, electricity-sector technologies and costs, energy price calibrations, and detailed sectoral technology structures for transport, buildings, industry, water, and land use. Together, these enhancements enable GCAM-KSA to generate national-scale insights that would not emerge from the global default configuration.

In the following subsections, we document the Saudi-specific enhancements to GCAM-KSA relative to GCAM-Core v7.2 across eight key sectors: power, refining, buildings, transport, industry, water, agriculture and land use, and the climate system.

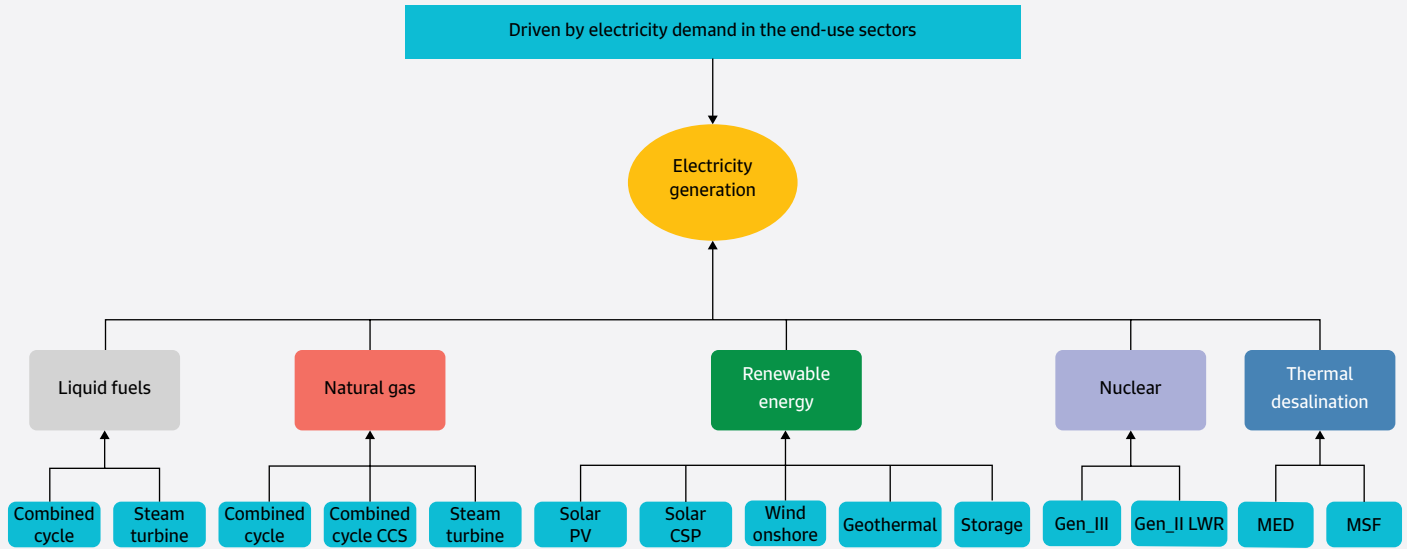
3.1 Power Sector

The power sector in GCAM-KSA incorporates substantial modifications to reflect the Kingdom's present-day infrastructure, resource potential, and policy direction. In contrast to GCAM-Core, the electricity system excludes coal-fired and biomass-fired generation technologies, consistent with the absence of domestic coal resources and the limited role of

bioenergy in the energy mix (SERA 2024). Furthermore, GCAM-KSA prohibits the addition of new oil-fired power plants after 2025, reflecting ongoing national efforts to phase out liquid-fueled electricity generation in favor of gas and renewable energy sources (Alaqrana and Ilyas 2025). These structural constraints ensure that the simulated future power mix aligns with the technical and policy context of the Kingdom.

Technology cost and performance parameters in the electricity sector were also updated extensively. Capital cost trajectories and fixed and variable O&M assumptions for solar PV, wind, gas turbines, and combined-cycle plants draw on the most recent National Renewable Energy Laboratory datasets (NREL 2024), while capacity factors reflect localized empirical estimates derived from Elshurafa et al. (2021) and other region-specific resource assessments. These updates ensure that modeled technology deployment pathways reflect realistic performance under Saudi climatic and geographic conditions. For detailed assumptions for different generation technologies, refer to Table A2.1-A2.4 in the Appendix.

Figure 2 shows the structure of the electricity generation sector for Saudi Arabia in GCAM-KSA. For the electricity generation

Figure 2. Structure of the electricity generation with technologies relevant to Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

from different energy carriers, the levelized cost of electricity (LCOE expressed in \$/MWh) is estimated as:

$$LCOE = \frac{C_f}{\eta} + \frac{1,000 * C_i}{8,760 * CF} * i + \frac{C_{O\&Mfix}}{8,760 * CF} + C_{O\&Mvar} \quad (2)$$

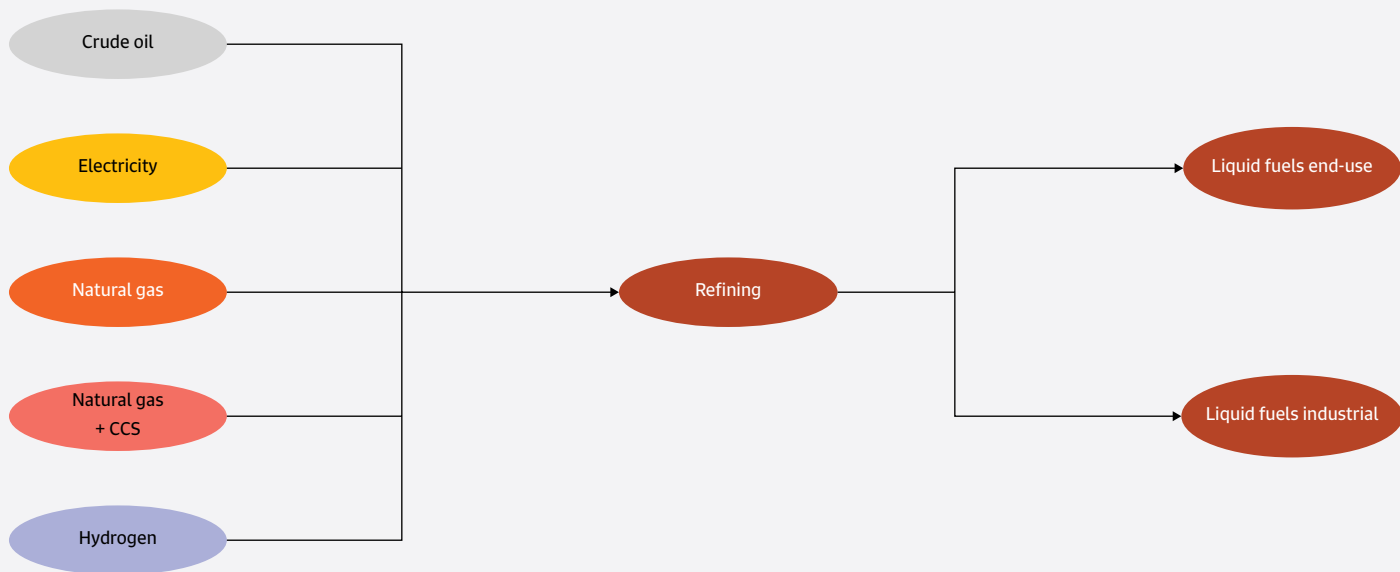
where C_f is the fuel cost, expressed in \$/MWh; η is the power plant efficiency; C_i is the capital investment cost, expressed in \$/kW; CF is the capacity factor, namely, the ratio of operating hours out of the total 8,760 hours in a year; i is the fixed charge rate, defined as the percentage of the total plant cost required over plant life per year to cover the minimal annual revenue requirements; $C_{O\&Mfix}$ is the annual fixed O&M cost, expressed in \$/MW per year; and $C_{O\&Mvar}$ is the variable O&M cost, expressed in \$/MWh.

Fuel costs for electricity generation are endogenously determined using fossil resource supply curves that have been adapted to Saudi Arabia's resource base, drawing on the global hydrocarbon resource assessments of Rogner (1997). Renewable technologies, by contrast, incur no fuel costs but are subject to resource cost curves that impose higher marginal costs as the most favorable solar or wind sites are utilized, consistent with GCAM-Core's global renewable resource methodology (Iyer et al. 2019). These curves represent the increasing difficulty of developing lower-quality sites and capture diminishing returns to scale – particularly relevant for large-scale solar deployment in arid regions.

GCAM-KSA also incorporates the implicit costs of intermittency associated with variable renewable energy (VRE). As the share of solar and wind rises, the intermittency penalty adjusts system costs to reflect additional backup, storage, or balancing requirements needed to maintain reliability (JGCRI 2023). This mechanism avoids overstating the competitiveness of VRE technologies and ensures that modeled electricity system transitions capture the operational realities of high-renewable grids.

3.2 Refining Sector

The refining sector occupies a central position in Saudi Arabia's energy system, both as a major consumer of primary energy and as a key source of greenhouse gas emissions. Within an integrated assessment modeling framework, the accurate representation of refining technologies, input fuels, and process emissions is essential for generating credible projections of energy demand, emissions profiles, and mitigation opportunities. GCAM-KSA, therefore, incorporates a series of targeted enhancements to GCAM-Core's default refining module to capture the technological complexity and operational characteristics of refining in the Kingdom. These modifications deepen the model's ability to represent emissions mitigation pathways in a sector of strategic importance to Saudi Arabia's domestic economy and its global energy role.

Figure 3. Structure of the refining sector with added hydrogen as a fuel input for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

In the GCAM-Core configuration, the refining sector is represented by a single generic technology that does not include CCS. To enable robust evaluation of decarbonization options in the Saudi refining industry, GCAM-KSA introduces an additional technology pathway: oil refining with CCS (Figure 3). The CO₂ capture rate for this technology is set at 65%, consistent with empirical performance ranges reported in the literature for industrial CCS applications (Leeson et al. 2017; Yao et al. 2018).

Given the absence of detailed empirical cost and performance data for commercial-scale CCS-enabled oil refining, GCAM-KSA applies scaling factors to the base refining technology's input and cost parameters. These scaling factors are derived by benchmarking against analogous technologies – such as coal-to-liquids and biomass-to-liquids pathways – that exist in GCAM-Core and have both CCS and non-CCS variants. Technology lifetimes, share weights, and other structural parameters are harmonized with CCS-enabled technologies elsewhere in the model to maintain internal consistency across the GCAM-Core technology architecture. These modeling choices ensure that the CCS-enabled refining pathway behaves realistically within GCAM-KSA's market equilibrium framework while preserving comparability across scenarios.

Another key enhancement in GCAM-KSA is the explicit representation of hydrogen as a refining input. In standard

GCAM-Core, hydrogen use in refining is embedded within natural gas consumption under the assumption that refineries produce hydrogen internally via steam methane reforming (SMR).

While this convention simplifies the model structure, it obscures important interactions between hydrogen demand, natural gas use, refining emissions, and the broader energy system – interactions that are particularly relevant for Saudi Arabia, which is a global hub of refining capacity and has growing interest in low-carbon hydrogen technologies. GCAM-KSA therefore introduces hydrogen as a distinct input commodity to the refining sector, enabling transparent accounting of hydrogen supply pathways and their corresponding emissions implications.

In real-world refinery operations, hydrogen is supplied through a combination of by-product hydrogen recovered from catalytic reforming and ethylene production units, and on-purpose hydrogen produced primarily from SMR. Industry estimates suggest that approximately 60%-70% of refinery hydrogen demand is met by by-product supply, with the remainder provided through dedicated SMR facilities. GCAM-KSA adopts a conservative assumption that 30% of total refinery hydrogen demand is met through on-purpose production, with the remaining 70% allocated to by-product recovery consistent with observed refinery operations. To quantify on-purpose hydrogen

demand, GCAM-KSA assumes a total hydrogen requirement of 4 m³ per barrel of crude oil processed – a representative value drawn from industry literature – and applies the following relationship:

$$\text{On-purpose } H_2 \text{ input coefficient} = 0.3 \times 4 \text{ m}^3/\text{barrel}$$

To avoid double-counting, the equivalent natural gas consumption required for SMR-based hydrogen production is subtracted from the refining sector's baseline natural gas input coefficient. This adjustment ensures that changes in hydrogen demand translate consistently into natural gas use, energy system emissions, and resource allocation within GCAM-KSA's equilibrium structure.

Together, these enhancements significantly improve GCAM-KSA's representation of the refining sector. They allow the model to simulate mitigation strategies such as refinery-level CCS deployment and shifts in hydrogen sourcing with greater fidelity. More broadly, they provide a foundation for exploring the evolving role of refining in Saudi Arabia's transition toward a more diversified and lower-carbon energy system within an integrated assessment modeling framework.

3.3 Building Sector

The buildings sector in GCAM-KSA is represented through a detailed characterization of residential and commercial (including governmental) building categories, each defined by cumulative floor space and its associated physical and economic attributes. As shown in Figure 4, floorspace serves as the fundamental driver of building energy service demand and is determined by sector-specific structural parameters, such as thermal conductance of the building envelope, the floor-to-surface-area ratio, and the distribution of floorspace across building types. For each category, the GCAM-KSA models three principal energy services: space heating, space cooling, and other services, which encompass appliances, lighting, water heating, and miscellaneous energy uses. These services are supplied through competition among end-use technologies that consume electricity, natural gas, liquid fuels, or combinations thereof, determined through the model's cost-based logit allocation mechanism (Eom et al. 2012; Clarke et al. 2018).

Because GCAM-KSA is embedded within a fully integrated assessment modeling framework, building-sector dynamics

respond not only to floorspace evolution but also to systemwide feedback arising from energy prices, socioeconomic change, and technological transformation. Two linkages are particularly important. First, demographic and income growth directly influence the demand for floor space and its associated services, reflecting well-documented relationships between economic development, household size, and built-area expansion (Isaac and van Vuuren 2009). Second, the cost of delivering building services depends on endogenous fuel prices, which evolve with resource availability, climate policy, and technology deployment elsewhere in the system (JGCRI 2023). Because GCAM-KSA determines fuel prices endogenously rather than relying on external projections, shifts in electricity system costs, natural gas supply curves, or carbon pricing propagate directly into end-use technology choices within the buildings sector.

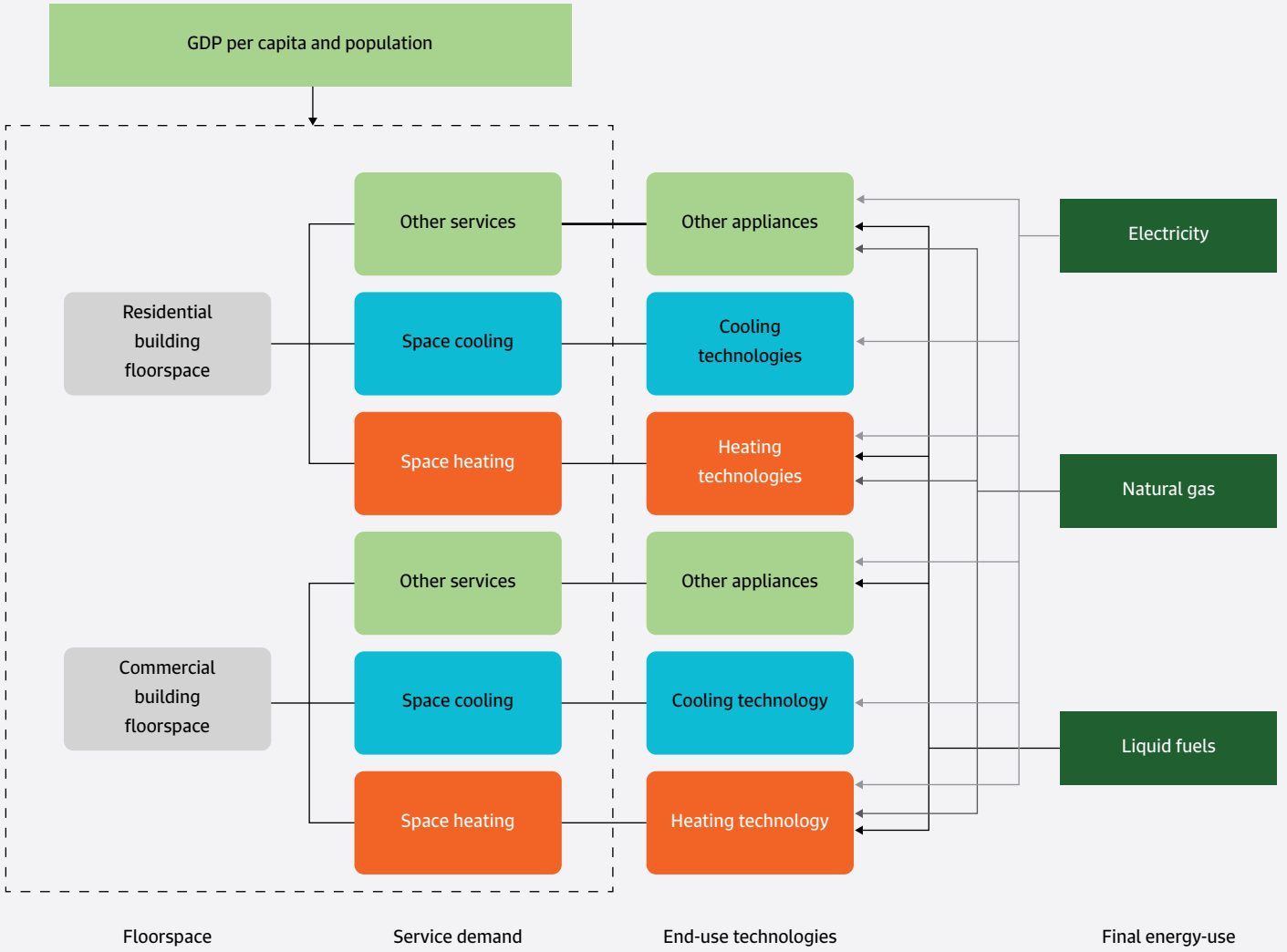
Floorspace expansion in GCAM-KSA is modeled via demand and supply functions that jointly determine market-clearing floorspace per capita. The demand for floorspace is a positive function of per capita income and a negative function of building service prices, while supply is governed by regional preferences and the cost structure of delivering new floorspace:

$$q_{D,t} = k_D P_{B,t}^a i_t^b \quad (3)$$

$$q_{S,t} = k_S P_{B,t}^j P_{B,t-1}^d \quad (4)$$

where $q_{D,t}$ and $q_{S,t}$ denote floorspace demand and supply, $P_{B,t}$ represents building service prices, i_t is per capita income, and a , b , j , and d are price and income elasticities (Eom et al. 2012). The calibration parameters k_D and k_S capture structural preferences, cultural norms, and unobserved drivers of floorspace expansion. This formulation ensures that floorspace growth remains consistent with both economic expansion and region-specific building characteristics, while also allowing for equilibrium adjustments in response to long-run changes in energy service costs.

Energy service demand for heating, cooling, and other services is modeled following the saturation-based behavioral framework developed by Eom et al. (2012) and extended by Chaturvedi et al. (2014) for emerging economies. This approach departs from traditional constant-elasticity demand formulations by recognizing that energy service consumption increases rapidly with rising income and affordability but eventually approaches a saturation point, beyond which additional increases in income yield diminishing marginal gains

Figure 4. Structure of the building sector for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation from Clarke et al. (2018).

in service demand. For a given service j , demand per unit of floorspace is given by:

$$d_j = k_j \bar{q}_j \phi_j(P_j, i) = k_j \bar{q}_j \left[1 - \exp \left(1 - \frac{\ln 2 \cdot i}{\mu_j P_j} \right) \right] \quad (5)$$

where k_j is a calibration parameter, $\bar{q}_j$ is the service-specific saturation level, P_j is the service cost, i is per capita income, and μ_j is the saturation impedance parameter governing responsiveness to affordability. Higher values of μ_j reflect services that reach saturation more gradually, such as comfort cooling in hot climates.

For heating and cooling, saturation levels depend explicitly on climatological variables and building physical characteristics:

$$\bar{q}_{\text{cooling}} = CDD \cdot \eta \cdot r + \lambda_c IG \quad (6)$$

$$\bar{q}_{\text{heating}} = HDD \cdot \eta \cdot r - \lambda_h IG \quad (7)$$

where cooling degree days (CDD) and heating degree days (HDD) describe local climatic severity, η is the building U-value, r is the floor-to-surface-area ratio, IG is internal heat gain that refers to the heat generated inside the building due to people, appliances, lighting, etc., and λ_c and λ_h scale internal heat gain for timing differences between occupancy and peak conditioning requirements. For example, internal heat gain would increase cooling demand and decrease heating demand. This formulation captures the physical determinants of building energy use, ensuring that cooling demand increases substantially as the built environment expands in a hot climate, such as that of Saudi Arabia.

By integrating socioeconomic drivers, climatic variables, building physics, and end-use technology competition, the GCAM-KSA buildings sector provides a detailed and dynamic representation of how floorspace and service demand evolve over time and how they interact with broader system-level changes in fuel prices, electricity generation, and mitigation constraints. This integrated approach ensures consistency between building-sector outcomes and the trajectories generated across the power, transport, industrial, land, and water systems in GCAM-KSA, providing a coherent framework for analyzing long-term building energy dynamics in Saudi Arabia.

3.4 Transport Sector

The transport sector in GCAM-KSA is represented through a detailed, multi-modal structure that captures both passenger and freight service demands and the competition among transport technologies supplying those services. The model explicitly simulates energy demand across road, rail, and domestic aviation for passenger transport; road and rail for freight; and international aviation and shipping, which operate at the global level before regional allocation. As in GCAM-Core, service demand in each transport category is driven by socioeconomic indicators – primarily population and GDP – while the allocation across modes and technologies is governed by GCAM's cost-based multinomial logit formulation (Kyle and Kim 2011; JGCRI 2023). In GCAM-KSA, this framework is calibrated to the 2015 base year to reflect the Kingdom's unique modal shares, vehicle characteristics, and fuel-use patterns.

Passenger service demand (Figure 5) is modeled on a per capita basis and aggregated across the population to derive total passenger kilometers (pkm). Demand evolves according to income and price indices, each expressed as a ratio relative to the previous model period, and is determined by:

$$D_p^{(r,t)} = \sigma_{t-1}^r \left(Y_i^{(r,t)} \right)^\alpha \left(P_i^{(r,t)} \right)^\beta N^{(r,t)} \quad (8)$$

where $D_p^{(r,t)}$ is total passenger demand, σ_{t-1}^r is the calibration parameter, $Y_i^{(r,t)}$ is the income index (per capita GDP – PPP), $P_i^{(r,t)}$ is the generalized cost of transport index, $N^{(r,t)}$ is population, and α and β are income and price elasticities. The nested structure of passenger transport, adapted from Kyle and Kim (2011), governs market competition at multiple levels:

two- and three-wheelers compete with four-wheelers to supply light-duty travel; light-duty vehicle services compete with bus services to supply road transport; road transport competes with rail, high-speed rail, and domestic aviation; and, finally, all domestic modes combine with international aviation to supply total passenger service. This hierarchical structure ensures that changes in relative technology costs propagate through a realistic modal competition framework.

A similar elasticity-based formulation governs freight service demand (Figure 6) but reflects the economic nature of freight activity rather than per capita mobility. Total tonne-kilometers (tkm) are determined by:

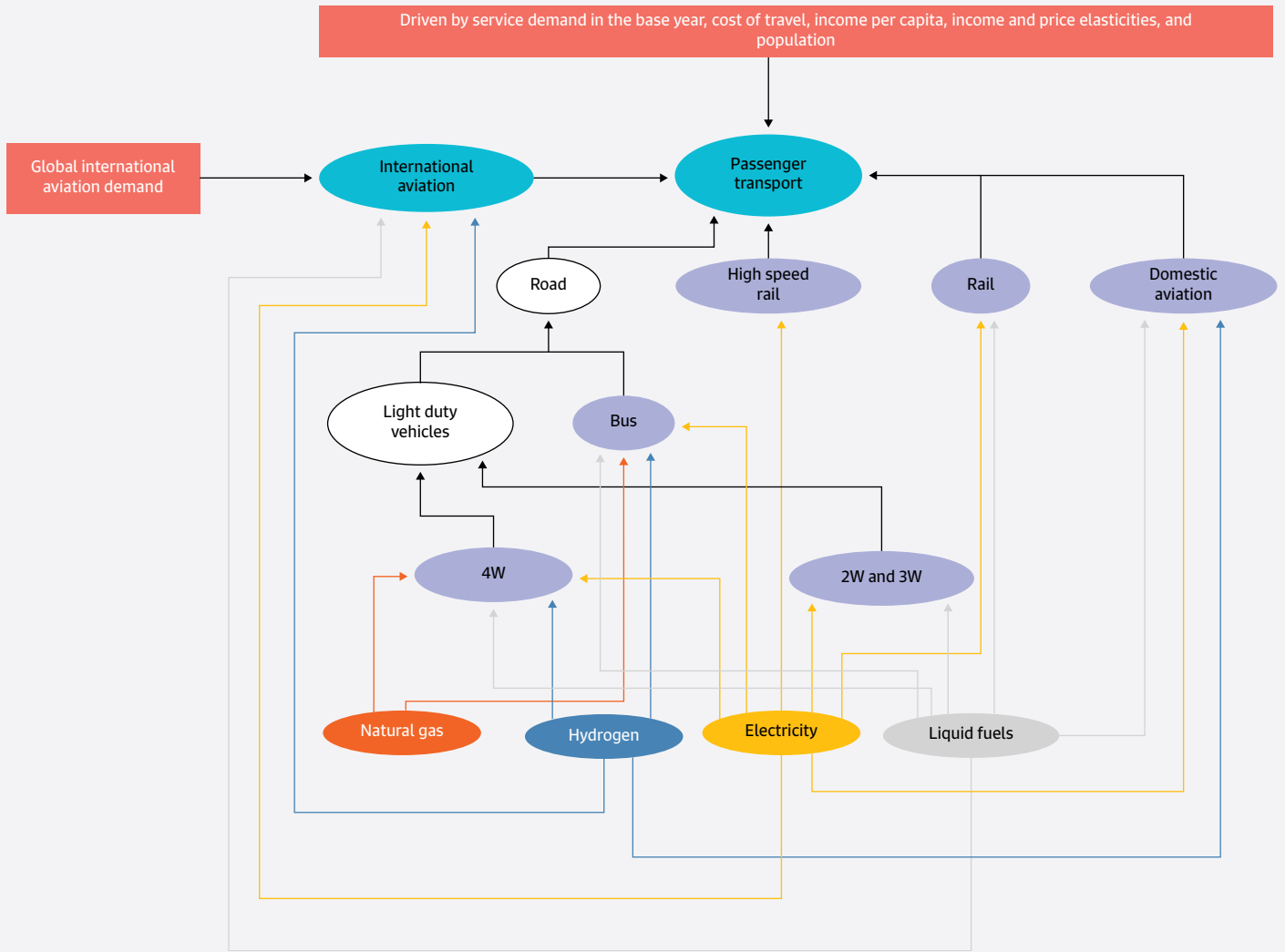
$$D_f^{(r,t)} = \sigma_{t-1}^r \left(GDP_i^{(r,t)} \right)^{\alpha'} \left(P_i^{(r,t)} \right)^{\beta'} \quad (9)$$

where $GDP_i^{(r,t)}$ is the GDP index, and α' and β' represent income and price elasticities for freight service demand. Freight demand in GCAM-KSA is structurally simpler than the passenger module, reflecting the predominance of trucking in Saudi Arabia's freight system and the limited competition among freight modes. Trucking, freight rail, and domestic shipping each compete for market share, whereas international shipping is modeled globally following Muratori et al. (2017), and regional allocation is based on historical base-year shares.

For both passenger and freight modes, the cost of travel is a critical determinant of technology shares. GCAM-KSA calculates the generalized cost of each passenger mode i in region r and time period t as:

$$P_{i,r,t} = \frac{FP_{i,r,t} \cdot I_{i,r,t} + NFP_{i,r,t}}{LF_{i,r,t}} + \frac{W_{r,t}}{S_{i,r,t}} \quad (10)$$

where $FP_{i,r,t}$ is the fuel price, $I_{i,r,t}$ is fuel intensity, $NFP_{i,r,t}$ is levelized non-fuel cost, $LF_{i,r,t}$ is the load factor, $W_{r,t}$ is the wage rate, and $S_{i,r,t}$ is the door-to-door travel speed. This formulation incorporates both economic and time costs, reflecting the increasing value of time as income rises – a critical behavioral feature of transportation demand. GCAM-KSA assumes no new high-speed modes beyond aviation, constant average travel speeds over time, and persistent local travel demand supplied by slower modes, consistent with empirical transport behavior literature (Goodwin, Dargay, and Hanly 2003; Kyle and Kim 2011).

Figure 5. Structure of the passenger transport for Saudi Arabia in GCAM-KSA.

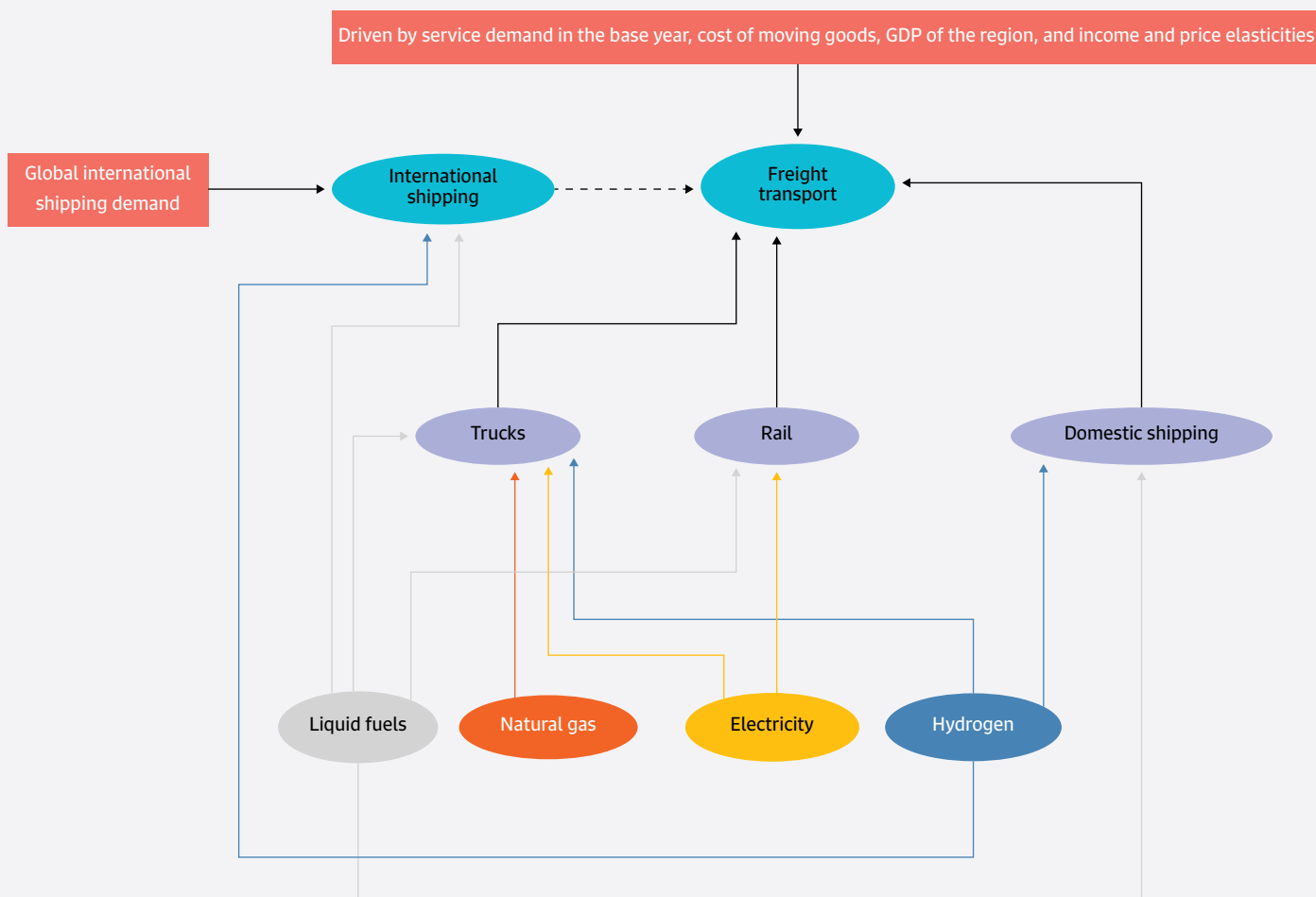
Source: Authors' adaptation.

For freight transport, the generalized cost excludes time valuation and is expressed as:

$$P_{i,r,t} = \frac{FP_{i,r,t} \cdot I_{i,r,t} + NFP_{i,r,t}}{LF_{i,r,t}} \quad (11)$$

reflecting the economic cost of hauling goods. Load factors, vehicle fuel intensities, and non-fuel costs are specified exogenously, consistent with the model's treatment of vehicle technologies as engineering systems whose characteristics do not adjust endogenously to service demand. Technological improvements are introduced exogenously through cost trajectories, capturing a composite of learning, R&D, and efficiency improvements (NREL 2024).

Across both passenger and freight transport, modal and technological shares are determined through the model's logit choice mechanism, which allocates market share based on relative costs while preserving historical inertia through share-weight calibration. This structure allows GCAM-KSA to reflect the unique characteristics of Saudi Arabia's transport sector – high automobile ownership rates, limited public transport penetration, and long-distance freight corridors – while enabling transitions to alternative fuels and vehicle technologies in response to changes in socioeconomic indicators, energy system evolution, or climate policy. Refer to Table A4-A4.4 in the Appendix for detailed assumptions for each mode in Saudi Arabia in GCAM-KSA.

Figure 6. Structure of the freight transport for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

3.5 Industry Sector

The industrial sector in GCAM-KSA is represented through six subsectors: five energy-intensive manufacturing industries – iron and steel, chemicals, aluminum, cement, and nitrogen fertilizers – and a residual “Other Industries” category. This structure follows the GCAM-Core framework but is refined using Saudi Arabia-specific data sources (Matar 2016), including IEA energy balances, national industrial statistics, and sectoral production data from industry. Calibration is performed for the model base year (2015), ensuring that sectoral energy consumption, fuel shares, and physical output levels align with observed historical conditions (IEA 2021). Future industrial output trajectories are driven by growth in GDP and by sector-specific income and price elasticities, allowing GCAM-KSA to

reflect the strong linkage between economic expansion and industrial activity.

Within each industrial subsector, GCAM-KSA models competition among multiple technologies and fuels through a modified logit discrete choice formulation. Technologies differ according to their non-fuel costs (capital, fixed and variable O&M), their fuel requirements, and their emissions intensities. Fuel costs are generated endogenously within the model, and carbon prices affect relative competitiveness where applicable. The logit structure ensures that technological transitions occur smoothly while preserving historical inertia through calibrated share weights (Calvin et al. 2019). This representation is critical for capturing heterogeneous decarbonization pathways across industries with fundamentally different process emissions, fuel dependencies, and technological substitution possibilities.

Below, we provide detailed descriptions of the six key industrial sectors represented in GCAM-KSA.

3.5.1 Iron and Steel

The iron and steel sector is one of the most energy-intensive and emissions-intensive industries represented in GCAM-KSA. The model encompasses three process routes commonly employed in global steel production (Figure 7): the Basic Oxygen Furnace (BOF), the Electric Arc Furnace (EAF) utilizing scrap, and the EAF using Direct Reduced Iron (DRI). However, because BOF production has historically been negligible in Saudi Arabia, GCAM-KSA restricts the sector to EAF-Scrap and EAF-DRI for future pathways, reflecting the Kingdom's established steel manufacturing practices. Each technology competes among multiple fuel and process options – including natural gas, electricity, hydrogen, and fossil or renewable fuels with or without CCS – capturing the technological diversity necessary for analyzing future decarbonization pathways (Hasanbeigi, Arens, and Price 2014; van Ruijven et al. 2016).

Future steel demand in GCAM-KSA is determined using the non-linear inverse with time-efficiency factor (NLIT) model developed by van Ruijven et al. (2016). This approach links per capita steel consumption to per capita GDP, capturing both

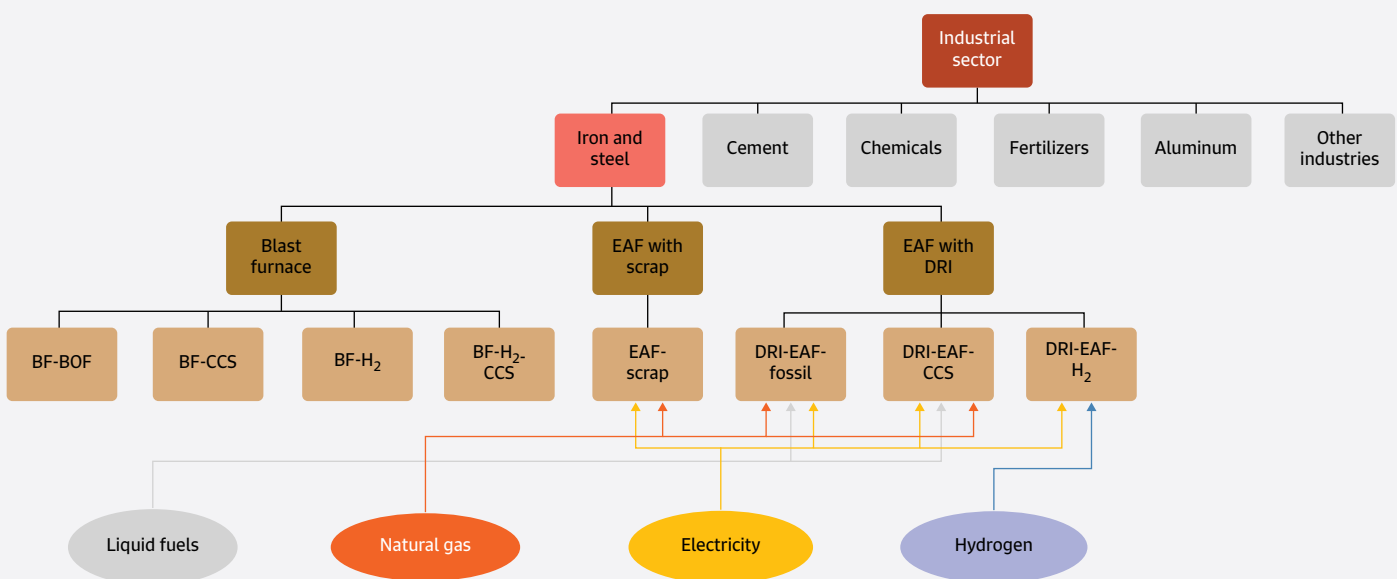
saturation effects at high income levels and improvements in material efficiency over time. The NLIT model is expressed as:

$$C = a \times e^{\frac{b}{GDP_{pct}}} \times (1 - m)^{(T - T_0)} \quad (12)$$

where C is per capita steel consumption, GDP_{pct} is per-capita GDP, T is the year, T_0 is the base year, a is the saturation level of steel consumption, b governs the approach to saturation, and m is the annual material-efficiency improvement rate. This formulation enables GCAM-KSA to project steel demand in a manner consistent with global patterns of industrialization while also capturing expected improvements in resource efficiency.

Once steel production is determined, GCAM-KSA multiplies sectoral output by fuel- and technology-specific energy intensities to estimate total industrial energy consumption. Energy intensities evolve over time based on exogenous assumptions about technological learning, reflecting global evidence of gradual efficiency improvements in both EAF and DRI pathways. The combination of the NLIT demand model and GCAM's technology competition structure enables GCAM-KSA to evaluate the interplay between process substitution, electrification, CCS deployment, and hydrogen-based pathways – central components of long-term decarbonization strategies for the steel industry.

Figure 7. Structure of the iron and steel industry for Saudi Arabia in GCAM-KSA.



Source: Authors' adaptation.

3.5.2 Cement

The cement sector in GCAM-KSA is represented through an explicitly physical, process-based formulation that tracks both cement output (Mt) and the associated energy use (EJ) and CO₂ emissions arising from two distinct sources: (i) process emissions from limestone calcination and (ii) energy-related emissions from providing high-temperature process heat. This dual-source emissions treatment is particularly important in the Kingdom, where cement production constitutes a major industrial activity and where both combustion and calcination emissions contribute significantly to total industrial CO₂ output. Unlike GCAM-Core, which represents CCS only for process emissions, GCAM-KSA extends the CCS capability to also capture fuel, combustion emissions, providing a more comprehensive representation of mitigation options within Saudi Arabia's cement industry (IEA 2018; Andrew 2019).

Figure 8 illustrates the mass and energy flow structure for the cement subsector in GCAM-KSA. Process heat is modeled as a distinct energy commodity required to meet the fixed thermodynamic needs of clinker production. Multiple fuels – such as natural gas with and without CCS, and liquid fuels with

and without CCS – compete for the provision of process heat via the model's cost-based logit mechanism. Importantly, electricity does not compete with process heat because the two serve intrinsically different functions and are represented through fixed input-output coefficients that ensure physical consistency with real-world cement manufacturing processes. This structure aligns with industrial energy modeling literature emphasizing the limited substitutability between thermal and electrical energy in cement kilns (Hasanbeigi, Price, and Lin 2012).

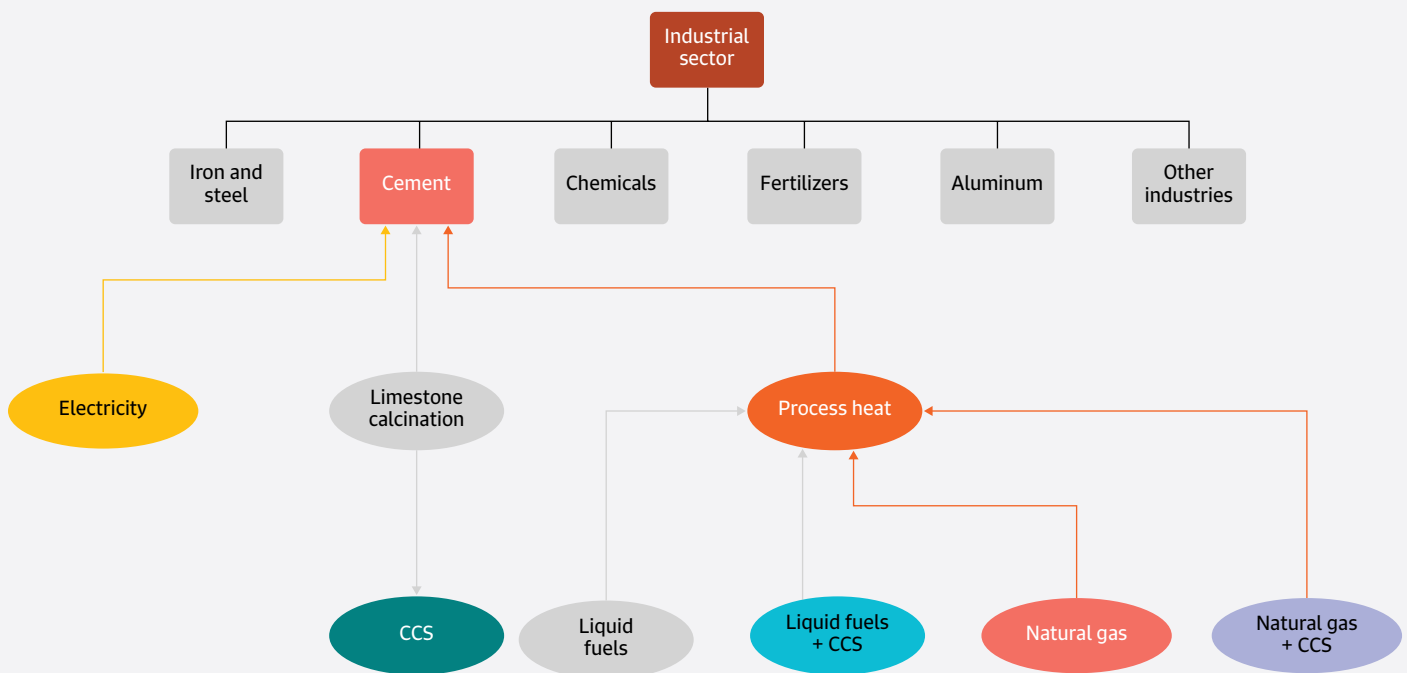
Future cement demand in region r and time period t is modeled following the model's standard elasticity-based construction:

$$D_{r,t} = D_{r,t-1} \left(\frac{Y_{r,t}}{Y_{r,t-1}} \right)^{\alpha} \left(\frac{P_{r,t}}{P_{r,t-1}} \right)^{\beta} \left(\frac{N_{r,t}}{N_{r,t-1}} \right) \quad (13)$$

where $D_{r,t}$ is cement demand; $Y_{r,t}$ is per capita GDP; $P_{r,t}$ is the aggregated cement service price; $N_{r,t}$ is population; and α and β represent income and price elasticities, respectively.

This formulation reflects three empirical regularities: (i) cement demand rises with urbanization and infrastructure investment, both of which scale with income; (ii) price sensitivity remains

Figure 8. Structure of the cement industry for Saudi Arabia in GCAM-KSA.



Source: Authors' adaptation.

modest, consistent with findings from global industrial demand studies (van Ruijven et al. 2016); and (iii) population growth contributes proportionally to construction material requirements. These drivers collectively shape long-term cement demand trajectories in GCAM-KSA, enabling the model to represent the evolution of construction material needs in line with Saudi Arabia's expected economic development trajectory.

Energy consumption for each model period is subsequently determined by combining projected cement output with technology- and fuel-specific energy intensities. These intensities evolve through exogenous technological change rates that reflect incremental efficiency improvements common to modern kiln technologies and structural shifts among fuel types – particularly under emissions constraints. This formulation ensures that GCAM-KSA accurately captures the coupled dynamics between cement demand, process heat requirements, and potential shifts to lower-emission fuels or CCS-enabled production routes.

3.5.3 Chemicals

The chemicals subsector in GCAM-KSA encompasses both energy use and feedstock consumption across the Kingdom's chemical and petrochemical industries. In contrast to subsectors such as cement, aluminum, fertilizers, or iron and steel, where physical production volumes (e.g., Mt of output) are explicitly tracked, the chemicals subsector in GCAM-KSA is represented in terms of energy service output (expressed in EJ). This modeling choice reflects the inherent diversity and complexity of chemical production pathways, as well as the lack of a standardized physical metric that can capture the wide range of intermediate and final chemical products produced in Saudi Arabia's petrochemical economy. As a result, the chemicals sector behaves as a service-based industrial category, where energy and feedstock demand respond to macroeconomic drivers rather than to explicit product-level activity indicators.

Historical calibration for chemicals is based on IEA energy balances (IEA 2021), which provide data on sectoral consumption of natural gas, liquids, electricity, and non-energy feedstocks such as natural gas and liquid fuels. These balances serve as the basis for establishing fuel shares and energy intensities for the 2015 base year. Future chemical sector service output is determined through an elasticity-based demand model, where output grows with per capita GDP and total population, moderated by price elasticities that capture

the responsiveness of industrial demand to energy service costs. This formulation is consistent with GCAM-Core and widely applied IAM representations of the chemical sector (Calvin et al. 2019).

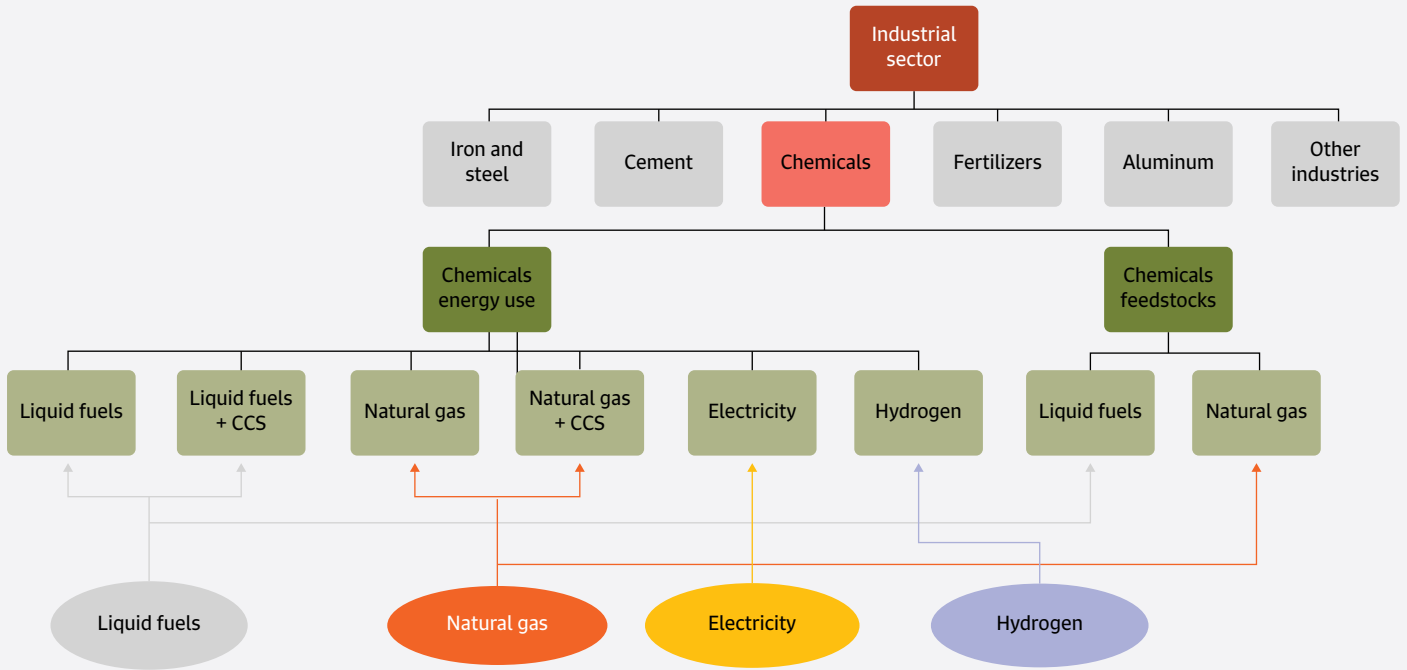
The chemicals sector in GCAM-KSA is divided into two main functional components (Figure 9):

- Energy use, which includes fuel combustion for process heat, steam, and electricity for industrial plant operations.
- Feedstock use, where fossil-derived inputs serve as material inputs for chemical transformation processes rather than energy carriers.

This distinction is crucial because feedstock consumption does not necessarily correlate with energy use, and emissions associated with feedstock use exhibit different mitigation characteristics than combustion-based emissions. Feedstock emissions are often inherent to chemical reactions and may require specialized carbon management technologies – such as CCS, methane reforming, or low-carbon hydrogen – to mitigate effectively, none of which are fully represented in GCAM's default chemical module. As such, emissions mitigation potential in the chemicals subsector in GCAM-KSA is more limited than in other industries and largely depends on changes in output demand, fuel switching for energy use, and carbon pricing effects on combustion-related processes.

Because GCAM-KSA does not model specific product streams (such as polyethylene, polypropylene, ammonia-based chemicals, aromatics, or methanol), the technology substitution space available to the chemicals sector is more constrained than in physically modeled subsectors. While GCAM-KSA can simulate switching between fuels (e.g., gas to electricity or gas to hydrogen for energy uses), process-level mitigation options (including alternative chemical pathways, electrified cracking, or bio-based feedstocks) are not yet represented.

Despite these constraints, GCAM-KSA's treatment of the chemical sector provides useful insights into how macroeconomic forces, energy prices, and carbon constraints affect energy and feedstock demand in one of Saudi Arabia's most economically significant industries. Under strong mitigation scenarios, rising carbon prices induce modest reductions in energy-related emissions through fuel switching and efficiency gains; however, emissions stemming from inherent feedstock use remain comparatively resistant to

Figure 9. Structure of the chemicals industry for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

change. Accordingly, mitigation in the chemicals subsector in GCAM-KSA tends to be less pronounced relative to other energy-intensive industries, underscoring the need for enhanced sectoral representation in future model development.

3.5.4 Nitrogenous Fertilizers (N Fertilizer)

The nitrogen fertilizer sector in GCAM-KSA captures both physical fertilizer production (in Mt of fixed N) and the associated energy and feedstock requirements that characterize ammonia and urea manufacturing. In line with the model's global industrial structure, the sector is represented as a process-based transformation system in which natural gas (primarily methane) serves as both an energy source and a chemical feedstock through SMR. Production outputs and technology shares in the base year 2015 are calibrated using IEA energy balances (IEA 2021) and international fertilizer industry statistics.

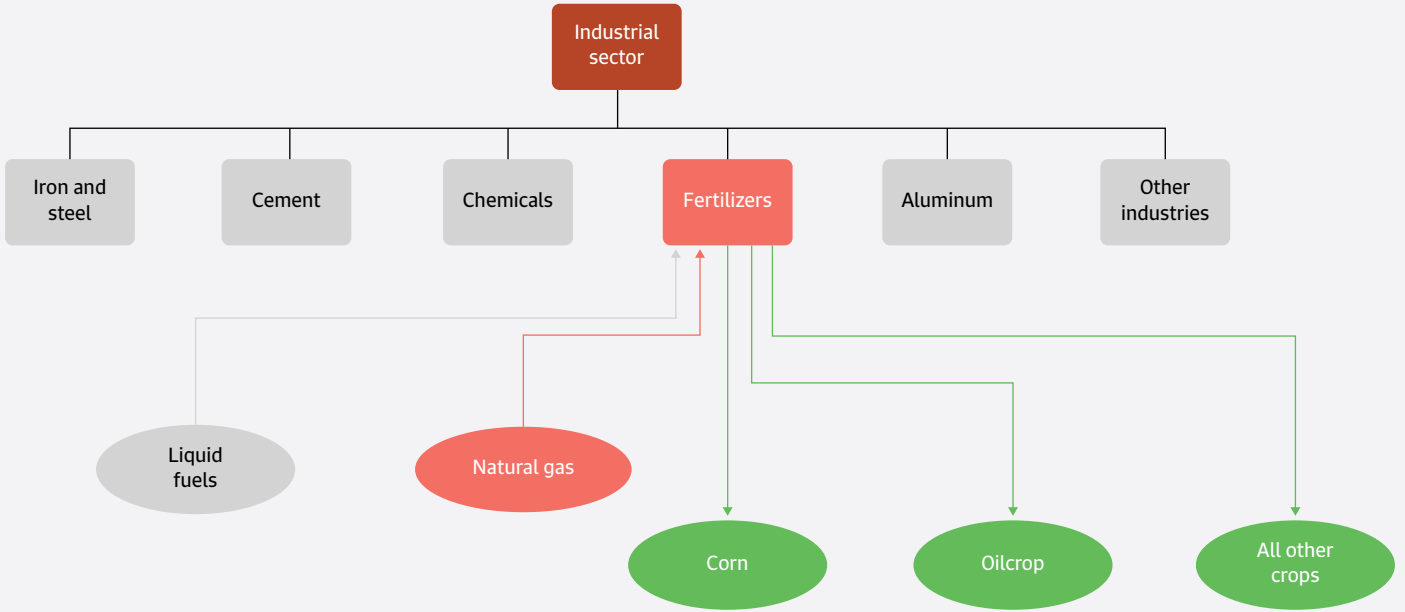
Fertilizer production in GCAM-KSA is closely linked to agricultural demand, as the model allocates fertilizer consumption to crop categories based on input-output coefficients. These coefficients

specify the fertilizer required per unit of crop output and evolve exogenously over time to reflect improvements in crop nitrogen-use efficiency (Tilman et al. 2011). Total fertilizer demand for the region r and time t is given by:

$$F_{r,t} = \sum_{k \in K_r} (\theta_{k,t} \cdot q_{k,r,t}) \quad (14)$$

where $Q_{k,r,t}$ is the output of crop k , and $\theta_{k,t}$ is the crop-specific fertilizer input coefficient. This formulation ensures that fertilizer requirements respond directly to agricultural expansion and land-use allocations in GCAM-KSA, linking agricultural and industrial systems through endogenous demand for nitrogen.

On the supply side, GCAM-KSA represents multiple hydrogen and heat sources for ammonia production, including natural gas, electricity, and hydrogen from low-carbon pathways. The model captures the energy implications of shifting between feedstocks and energy carriers. Under mitigation scenarios, carbon pricing increases the competitiveness of hydrogen pathways with lower upstream emissions intensities.

Figure 10. Structure of the fertilizers industry for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

3.5.5 Aluminum

The aluminum sector in GCAM-KSA is modeled as a physical output industrial subsector in which primary aluminum production (in Mt) determines energy consumption and associated CO₂ emissions. Saudi Arabia's aluminum industry is characterized by electricity-intensive smelting processes, reflecting the predominance of the electrolytic reduction process (Figure 11). GCAM-KSA calibrates aluminum output and sectoral energy use using IEA datasets and regional industrial statistics for the 2015 base year. Total aluminum demand for the region r and time t is given by:

$$q_{r,t} = q_{r,t-1} \times \left(\frac{Y_{r,t}}{Y_{r,t-1}} \right)^{\alpha} \quad (15)$$

$$Q_{r,t} = q_{r,t} \times N_{r,t} \quad (16)$$

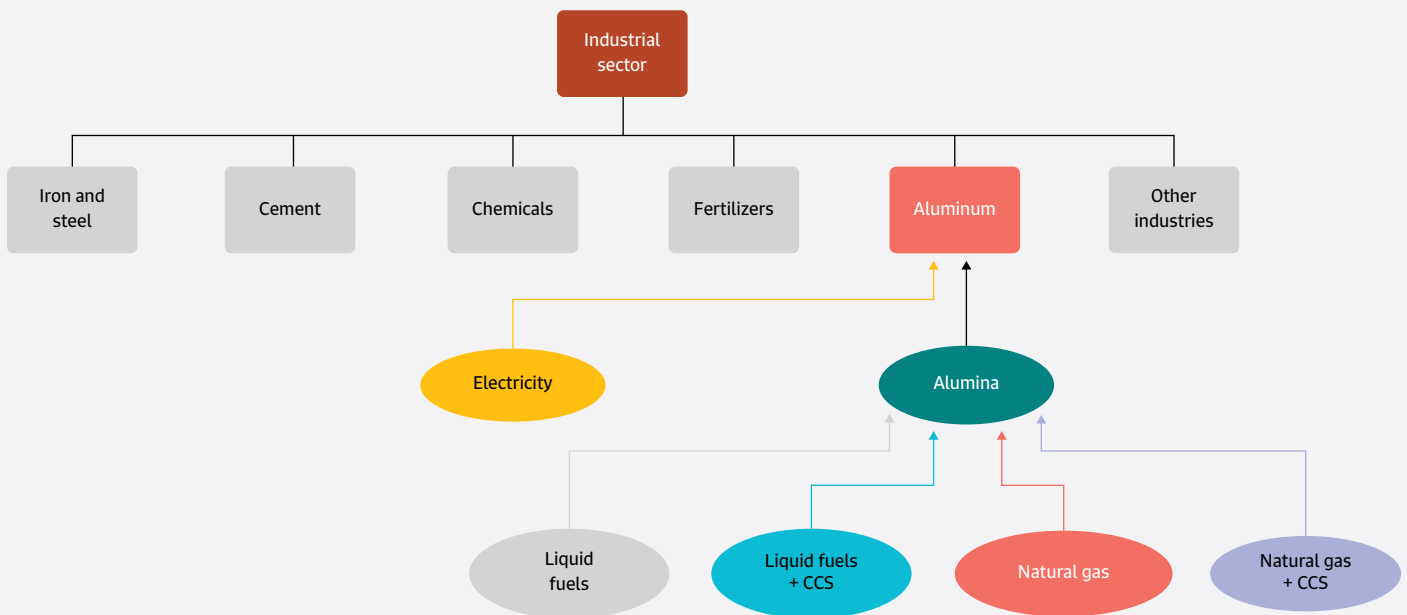
where $q_{r,t}$ is the aluminum demand per capita for region r in time t , $Y_{r,t}$ is the per capita GDP, α is income elasticity, $Q_{r,t}$ is the total aluminum demand for region r in time t , and $N_{r,t}$ is the total population of region r in time t .

Aluminum demand evolves over time according to the model's elasticity-based output model, driven by GDP growth, income

levels, and price effects. As aluminum production increases over time, GCAM-KSA multiplies production volumes by exogenous energy-intensity values to estimate associated electricity and thermal energy demands. These intensities decline modestly over time, reflecting improvements in smelting efficiency and heat recovery.

3.5.6 Other Industries

The "Other Industries" category serves an important calibration role by absorbing energy and feedstock use not attributed to the five explicitly modeled subsectors. However, this aggregation also reflects a limitation in the availability of detailed, facility-level data for small and medium industries in Saudi Arabia. Because GCAM-KSA cannot assign precise technology portfolios to these diverse activities, their fuel use is represented generically, limiting the model's ability to simulate process-specific mitigation options. As shown in Section 5: Results, this structural constraint manifests as higher residual emissions in the "Other Industries" category under mitigation scenarios – an artifact of data sparsity rather than an inherent inability of these industries to decarbonize.

Figure 11. Structure of the aluminum industry for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

3.6 The Water Sector

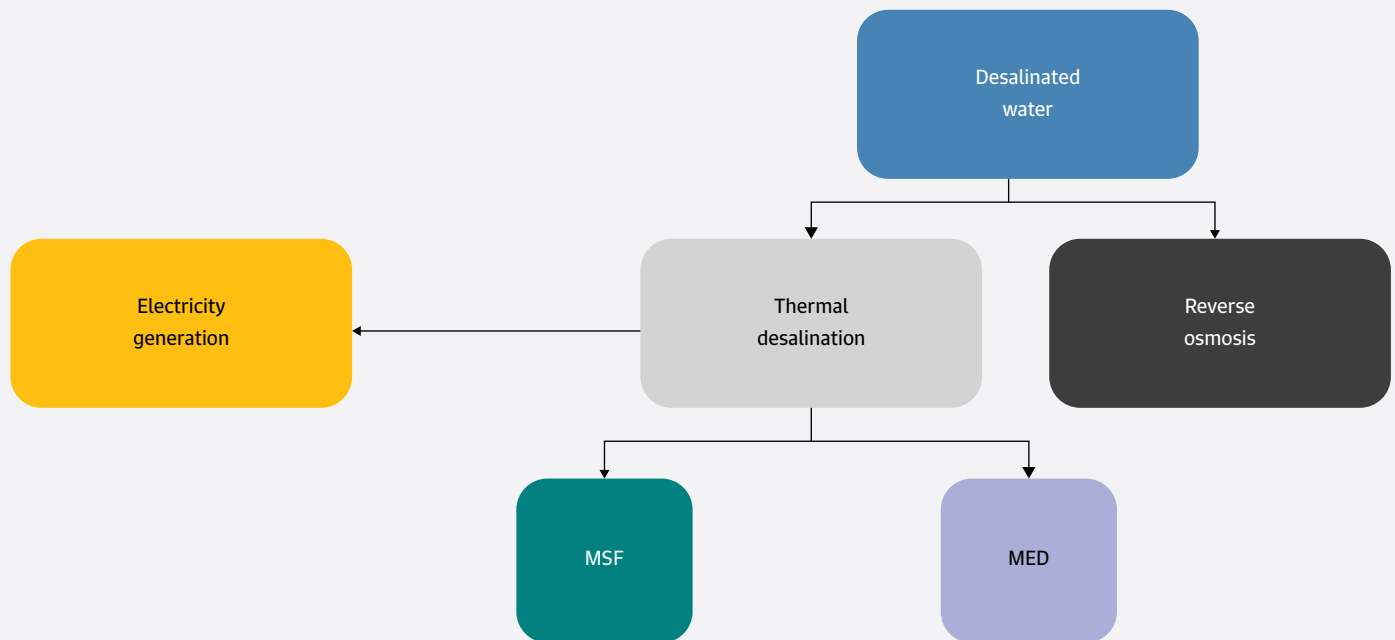
GCAM-KSA represents the water sector as an integrated system that connects energy, land-use, and economic modules within a unified modeling framework. In the model, water is treated as both a finite natural resource and an economic good, the availability and cost of which simultaneously influence multiple sectors. The model captures water dynamics through linked supply and demand components, resolved at the level of major water basins. Within each basin, a market equilibrium mechanism ensures that water prices adjust to balance supply and demand, thereby reflecting scarcity, cost, and intersectoral competition (Hejazi et al. 2014; Kim et al. 2016).

The water supply in the model is characterized by three primary sources: renewable freshwater, nonrenewable groundwater, and desalinated water. Renewable supplies derive from natural runoff and baseflow within each basin and are subject to environmental flow requirements, which reserve a portion of available water for ecological needs. Non-renewable groundwater refers to deep aquifers with very slow recharge rates and is considered a depletable resource. Desalinated water is considered a technologically intensive

source, typically serving the municipal or industrial sectors in regions with limited freshwater availability. All three sources are modeled using cost curves, where marginal extraction costs increase with higher withdrawal levels, representing the escalating difficulty and energy intensity of accessing additional water (Turner et al. 2019).

In GCAM-KSA, desalinated water production for Saudi Arabia has been updated to match reported values by the Food and Agriculture Organization's AQUASTAT (FAO AQUASTAT) for the calibration year of 2015. This update enables the model to scale desalination growth in future periods more accurately. Additionally, the representation of combined water and power plants (CWPs) has been improved, reflecting the co-production of desalinated water as a secondary output from oil and gas power plants. In Saudi Arabia, desalinated water is produced either through dedicated reverse osmosis (RO) or as a co-product from CWPs associated with oil and gas power plants (Figure 12).

On the demand side, the model distinguishes five end-use categories: irrigation, livestock, industry, municipal, and energy (Figure 13). Water use in each category is determined

Figure 12. Structure of the desalinated water sector for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

by sector-specific coefficients that describe consumption intensity per unit of activity or output. Irrigation water demand is closely linked to the area of irrigated cropland and crop type, accounting for both application efficiency and field losses. Livestock water demand depends on animal population and species characteristics, while industrial and municipal demands are tied to economic output and population growth, respectively (Hejazi et al. 2013; Hejazi et al. 2014). The energy sector, which includes electricity generation, refining, and fuel production, consumes water for cooling and processing. Technological choices within the energy system – such as the adoption of dry cooling or renewable power generation – affect overall water-use intensity and create dynamic feedback within the model.

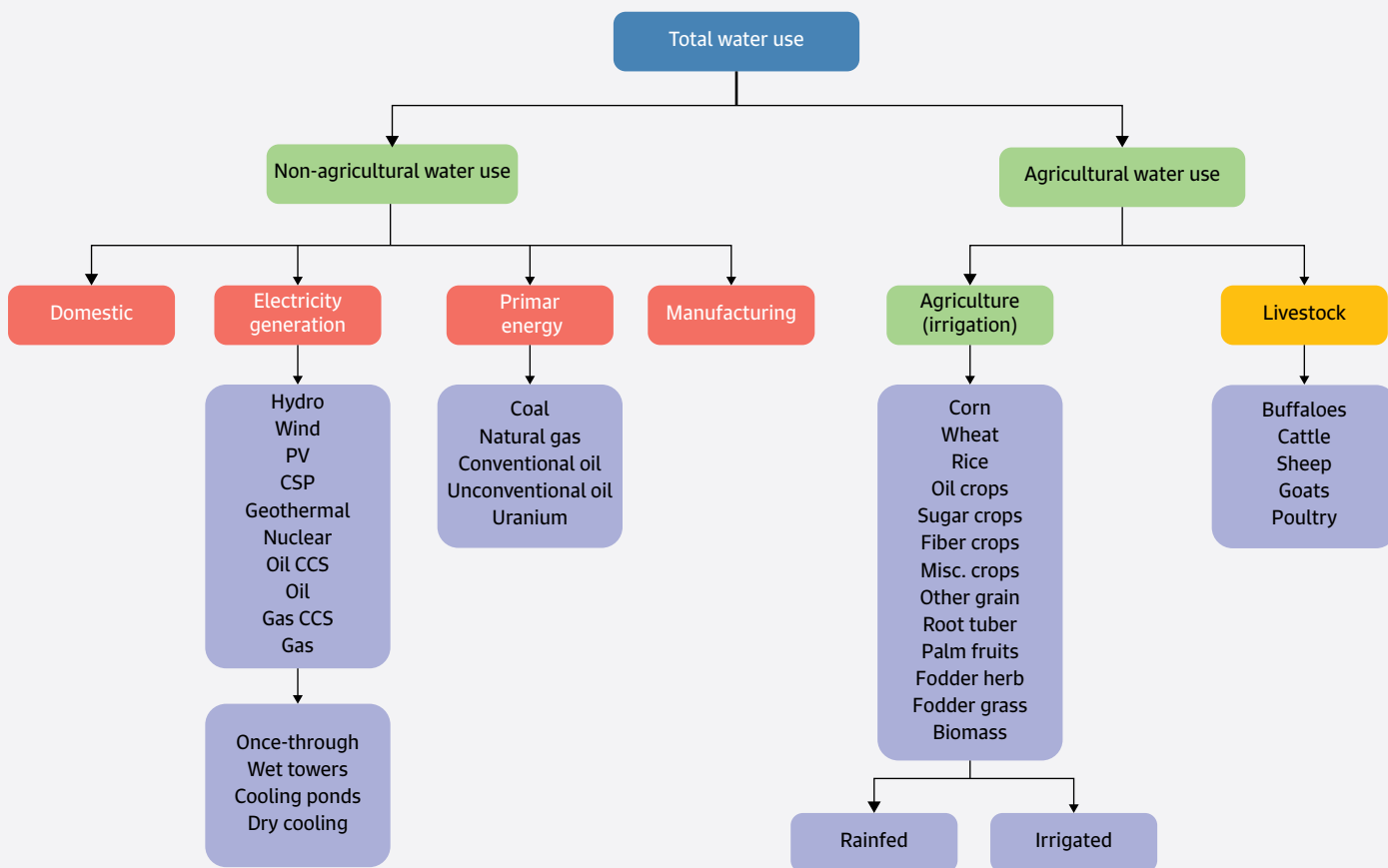
The model resolves water supply and demand at the river basin scale through an equilibrium mechanism. As water scarcity rises, prices increase, encouraging conservation, efficiency improvements, or adoption of more expensive supply sources (such as desalination). Conversely, abundant water availability reduces prices, stimulating greater use. Demand from multiple sectors within a basin competes for the same supply, allowing the model to capture trade-offs between agricultural, municipal, and industrial uses. The spatial representation links regional

economic activity to specific hydrological basins, enabling the model to simulate water competition among regions that share the same basins.

The water module interacts dynamically with the energy and land-use systems. In agriculture, irrigation demand and costs affect land allocation decisions, influencing both crop production and trade. Within the energy system, water availability shapes the choice of power generation technologies and cooling systems. Conversely, land-use changes and energy production affect water demand and quality. Through these interdependencies, GCAM-KSA provides a consistent framework for exploring the water-energy-land nexus, enabling analysis of how changes in technology, policy, and climate in one domain propagate across others.

3.7 Agriculture and Land-Use Sectors

GCAM-KSA incorporates agriculture and land-use sectors into a unified, multi-sector modeling framework that links terrestrial processes with the energy system, economic development,

Figure 13. Structure of the water sector demand for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

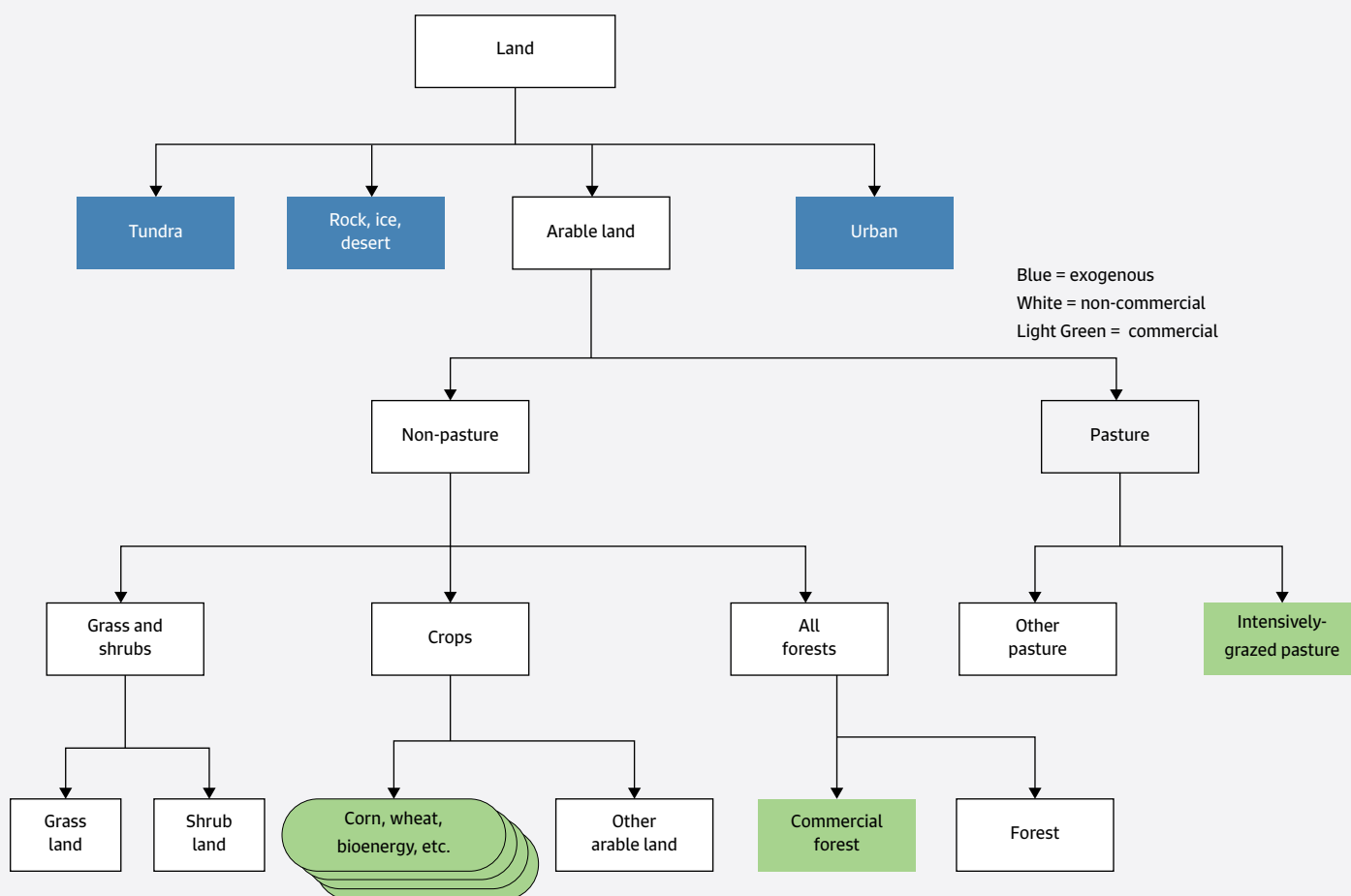
water availability, and climate outcomes. As in GCAM-Core, agriculture and land-use systems in GCAM-KSA are jointly shaped by demand-side drivers – such as food, feed, fiber, and non-food agricultural demands – and supply-side constraints related to land allocation, crop productivity, water availability, and carbon stock changes (Calvin et al. 2019; Wise et al. 2009). This integrated representation (Figure 14) enables the model to examine how demographic change, income growth, technological evolution, and resource limitations propagate through Saudi Arabia's agriculture and land-use sectors.

Food system dynamics begin with the estimation of demand for food, feed, and non-food agricultural commodities across regions. Historical calibration establishes baseline consumption patterns by commodity category, including cereals, fruits and vegetables, fodder crops, and livestock products. Future trajectories evolve based on regional per capita GDP growth, population expansion, commodity prices,

and income and price elasticities, consistent with the global agricultural demand structures used in GCAM-Core (Calvin et al. 2014; Edmonds et al. 2017).

Feed demand for livestock is modeled using a logit-sharing mechanism that distributes feed use among alternatives such as fodder grasses, fodder herbs, and grains, with shares determined by relative costs and livestock production levels. Non-food agricultural demand, including industrial crops and bioenergy feedstocks, is modeled analogously through elasticity-based demand equations.

On the supply side, GCAM-KSA allocates land among competing uses, including food crops, feed crops, bioenergy crops, pasture, managed forests, unmanaged forests, and shrubland, using a profit-based logit land-allocation framework developed initially for global GCAM applications (Wise et al. 2009). Land shares are determined by the relative profitability of each use,

Figure 14. Structure of the land-use and agriculture sector for Saudi Arabia in GCAM-KSA.

Source: Authors' adaptation.

incorporating revenues, production costs, water availability, and land-conversion costs.

The nested land framework distinguishes between irrigated and rainfed systems, and between low- and high-input management, enabling the model to capture both intensification (increased inputs on existing land) and extensification (area expansion) responses to changing economic signals. Land conversion incurs carbon costs and may be restricted by exogenous policy parameters, such as protected areas or biomass deployment limits.

These features allow GCAM-KSA to represent realistic land dynamics in arid regions with substantial water constraints.

The land-use sector in GCAM-KSA has been adjusted to reflect local conditions better. Non-land variable costs for fodder herbs have been reduced to limit future expansions, and biomass crop

exports have been eliminated, as such exports are considered highly unlikely for Saudi Arabia. Furthermore, water demands per unit of production for fodder crops have been updated using a study specific to Saudi Arabia (Mutsch et al. 2013).

Additionally, renewable water supply inputs have been modified to reduce the volume of water derived from the global hydrologic model Xanthos (Liu et al. 2018), aligning model inputs with historical observations. This adjustment improves the representation of water scarcity and availability, which are critical factors in Saudi Arabia's land-use dynamics.

3.8 Climate System

The climate system (Hector) in GCAM-KSA links anthropogenic emissions from energy, land-use, agricultural,

and industrial activities to atmospheric GHG concentrations, radiative forcing, and climate responses. This module mirrors the climate representation used in GCAM-Core and is based on simplified carbon-cycle and climate-response equations that map emissions to temperature outcomes over time (Calvin et al. 2019; Meinshausen et al. 2011). By embedding this system within the broader GCAM-KSA framework, the model can trace how human decisions related to energy production, land management, biomass use, and industrial activity influence long-term climate trajectories, and, conversely, how climate feedback pathways affect resource systems.

GCAM-KSA's climate component incorporates representations of CO₂ and non-CO₂ GHGs, including methane and nitrous oxide, and aggregates emissions into atmospheric concentration pathways. Radiative forcing is computed from these concentrations, and global mean temperature change is derived using an impulse-response climate model consistent with established integrated assessment practices. Although

GCAM-KSA is not a full Earth system model, its climate module captures the essential dynamics needed to evaluate climate outcomes of mitigation strategies, explore alternative emissions trajectories, and assess consistency with global climate targets.

The model's sectors interact with the carbon-cycle climate module, Hector, via emissions. At every time step, emissions from GCAM-KSA are passed to Hector, which converts these emissions into concentrations (where necessary) and calculates the associated radiative forcing, as well as the resulting climate and Earth system responses.

By integrating climate responses within a unified modeling system, GCAM-KSA provides a framework for examining how sectoral transitions – such as decarbonization of electricity, shifts in transport technologies, industrial CCS deployment, or land-use changes – affect long-term climate outcomes. This integrated climate representation also ensures consistency between global and regional scales by aligning national-scale emissions trajectories with broader carbon-budget pathways.

Socioeconomic Assumptions and Scenario Framework

04



4.1 Socioeconomic Assumptions

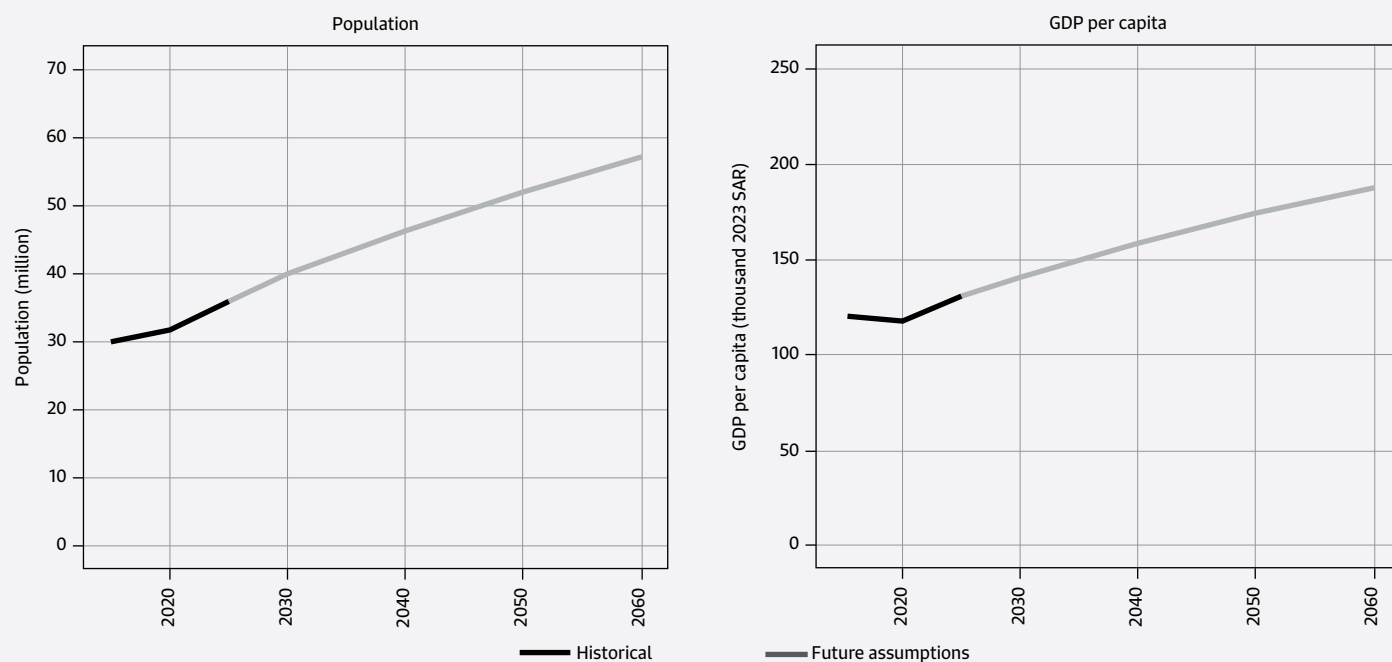
GCAM-KSA incorporates a set of long-term socioeconomic trajectories defined by population growth and GDP per capita evolution, which together determine regional income levels and drive energy service demand across all sectors. The projections used in the model are harmonized with internationally recognized demographic and economic scenarios to ensure consistency with global integrated assessment frameworks while preserving fidelity to Saudi Arabia's national statistics.

Population projections follow the United Nations World Population Prospects (UN WPP) "medium scenario" for Saudi Arabia, which describes a moderate long-term demographic pathway. To ensure short- and medium-term alignment with national demographic trends, GCAM-KSA calibrates historical population through 2022 using the most recent General Authority for Statistics (GASTAT 2022) census and extends near-term population growth to 2030 using the International Monetary Fund's projections (IMF 2025). These adjustments ensure that the demographic trajectory reflects both official statistical data and widely used international projections.

GDP per capita projections are constructed using long-run growth rates consistent with the OECD-SSP2 ("Middle of the Road") scenario for Saudi Arabia. The shared socioeconomic pathway (SSP2) is widely employed in integrated assessment modeling due to its moderate assumptions regarding technological progress, institutional development, and social

change (IIASA 2025; O'Neill et al. 2017; Riahi et al. 2017). Historical GDP per capita is calibrated using data from the Saudi Central Bank and the International Monetary Fund through 2025 (SAMA 2025; IMF 2025). This calibration ensures continuity between historical economic conditions and the model's forward-looking projections.

By combining updated national statistics with internationally harmonized SSP-based trajectories, GCAM-KSA constructs a socioeconomic pathway that is both globally comparable and locally grounded. These projections form the basis for estimating long-term energy service demands in buildings, transport, and industry; agricultural and food consumption; and the scale of economic activity influencing emissions, water use, and land demand. Figure 15 presents the resulting socioeconomic pathway for population and GDP per capita in GCAM-KSA.

Figure 15. Historical and projected population and GDP per capita trajectories for Saudi Arabia.

Source: Authors' analysis.

4.2 Scenario Framework

This subsection introduces the scenario framework used to explore alternative long-term pathways for Saudi Arabia. Two scenarios are considered: a Current Policy (2025) scenario, which reflects existing and announced domestic policies and targets, and a Net-Zero scenario, which imposes an economy-wide emissions constraint consistent with achieving net-zero greenhouse gas emissions by 2060. Table 1 summarizes the key policy and implementation assumptions applied within Saudi Arabia under each scenario.

Outside Saudi Arabia, global trajectories follow exogenously specified pathways consistent with GCAM-Core. The Current Policy (2025) scenario reflects SSP2, while the Net-Zero scenario aligns with global mitigation implied by updated Nationally Determined Contributions and net-zero commitments announced through COP26. No additional regional policy shocks are imposed, allowing the analysis to isolate Saudi-specific policy effects within a consistent global context.

Table 1. Key scenario assumptions for Saudi Arabia.

Scenario	Policies	Implementation
Current Policy (2025)	Energy price reforms	The prices of all energy fuels, including the end-use consumer prices, are calibrated to reflect the latest revision of fuel prices announced in January 2025, which incorporates the ongoing energy price reforms in the Kingdom.
	Electricity generation	Calibrated to reflect the generation mix in 2025. No specific target for renewable energy generation after 2025; the model follows a least-cost pathway.
	Buildings	Ongoing improvements in energy efficiency are assumed to continue at the same rate in the future, particularly for cooling, due to ongoing appliance labeling programs and building insulation standards.
	Transport	Ongoing improvements in vehicle fuel efficiency, as a part of corporate average fuel economy standards, continues at the same rate in the future. In line with recent initiatives to develop infrastructure for public transport, the model assumes an exogenous shift toward public transport.
	Industry	Ongoing improvements in industrial processes and energy efficiency are assumed to continue at the historical rate.
Net-Zero		Includes all Current Policy (2025) assumptions.
	Net-zero target	The scenario is constrained to achieve net-zero GHG emissions, with a linear decline starting in 2030 and reaching zero emissions by 2060.



The results presented in this section illustrate how the GCAM-KSA framework responds to scenario assumptions through its internal equilibrium mechanisms and sectorally linked structure. Because GCAM-KSA simultaneously resolves energy, economic, land, water, and climate subsystems, the model produces a coherent set of trajectories in which socioeconomic drivers, technology costs, resource availability, and emissions constraints interact to shape system evolution.

The results are presented as a comparison between the Current Policy (2025) and Net-Zero scenarios, highlighting how the model allocates mitigation effort, how structural features condition the pace and direction of transitions, and how endogenous substitution processes unfold across multiple sectors. Rather than evaluating policy performance, the focus is on how model structure and parameterization generate the observed dynamics, as well as on the role of cross-sectoral linkages in determining long-term outcomes.

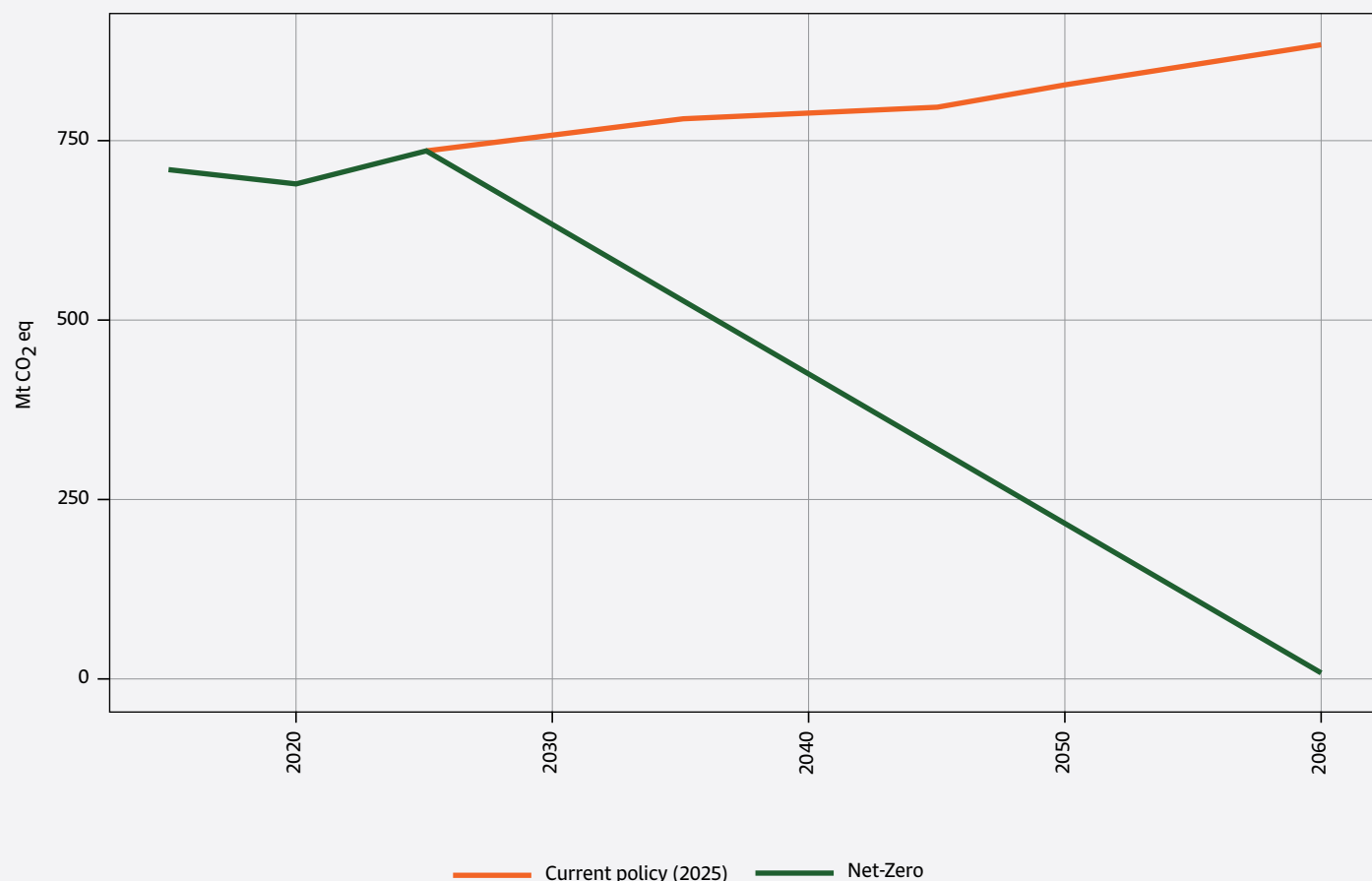
5.1 Economy-Wide Emissions and Sectoral Decomposition

The evolution of greenhouse gas emissions across the two scenarios highlights how GCAM-KSA's structure distributes mitigation effort across the economy and how sectoral interactions shape the aggregate emissions path. Under the Current Policy (2025) scenario, total emissions rise gradually over time (Figure 16), reflecting the combined influence of

population growth, increasing energy service demand, and a continued reliance on fossil-based technologies whose relative costs remain favorable in the absence of climate policy.

Because GCAM-KSA determines technology adoption through logit-based cost competition calibrated to the historical energy system, fossil technologies – particularly in industry, electricity generation, and transport – retain a substantial market share. This structural persistence generates the upward emissions trajectory observed in the aggregate results, demonstrating the inertia inherent in an energy system governed by existing cost structures and constrained substitution elasticities.

The sectoral decomposition of emissions (Figure 17) further illustrates how this aggregate trend arises from the internal distribution of emissions across activities. In the Current Policy (2025) scenario, industry remains the largest contributor throughout the projection period, reflecting both increasing levels of activity and the limited availability of cost-competitive low-carbon technologies in many industrial processes.

Figure 16. Total greenhouse gas emissions for Saudi Arabia under the Current Policy (2025) and Net-Zero scenarios.

Source: Authors' analysis.

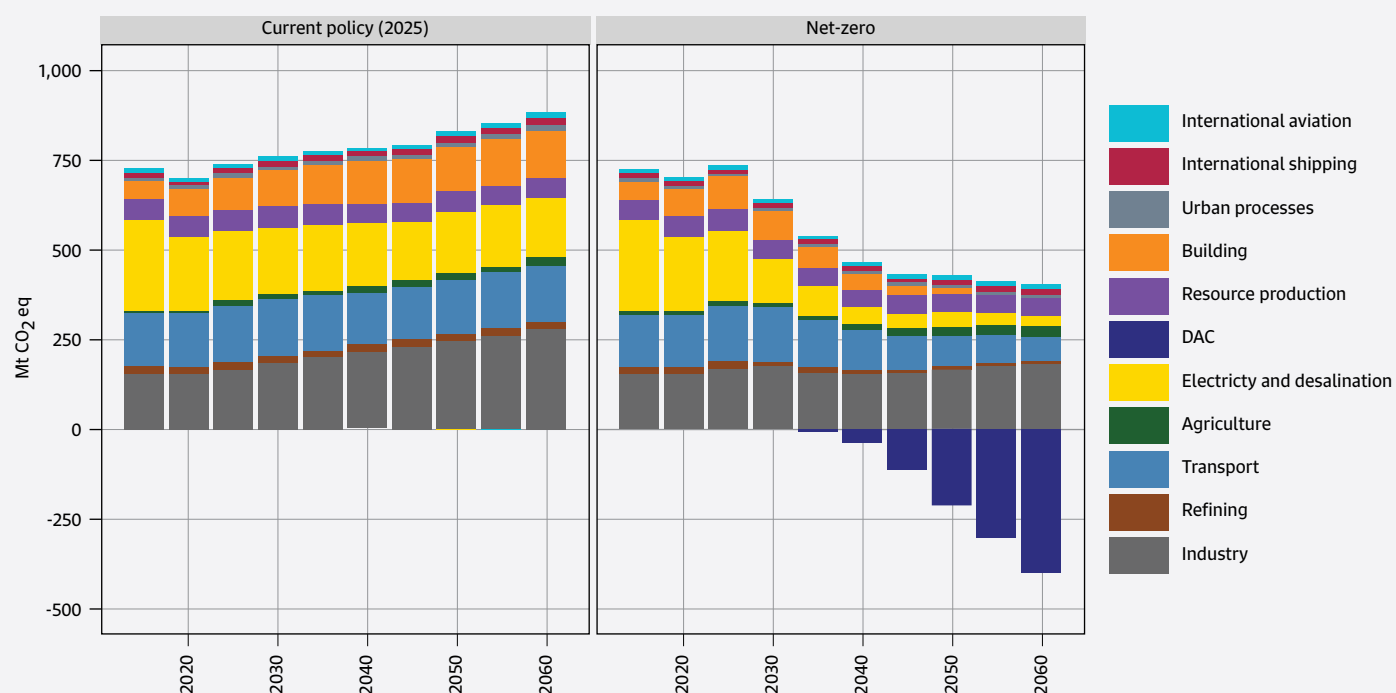
Electricity and desalination constitute another substantial share of emissions, driven by continued deployment of natural gas-based generation technologies, which remain the least-cost option under prevailing conditions. Transport emissions also grow steadily, with liquid fuels maintaining dominance across modes due to calibrated demand elasticities and cost parameters that do not induce large-scale electrification.

Emissions from buildings, resource production, and agriculture exhibit more modest increases but nonetheless contribute to the cumulative upward trend. Collectively, these sectoral patterns underscore how, in the absence of a binding climate policy, GCAM-KSA's equilibrium mechanism yields incremental adjustments in technology portfolios rather than structural shifts.

By contrast, the emissions trajectory under the Net-Zero scenario shows a rapid departure from historical patterns

beginning in the 2030s and converging to zero by 2060. The imposition of an economy-wide constraint introduces carbon penalties that alter relative technology costs, prompting the model to reallocate technology shares across multiple sectors. This reallocation becomes progressively more pronounced as the constraint tightens, producing an emissions path characterized by sustained, steep reductions.

The sectoral breakdown reveals how these adjustments occur in practice. Emissions from electricity and desalination decline sharply as renewable technologies and gas with CCS gain market share, reflecting the strong substitutability of electricity generation technologies and the competitiveness of low-carbon electricity once emissions penalties are internalized. Industrial emissions fall more gradually due to limited immediate substitutability, but CCS deployment and process shifts eventually generate substantial reductions.

Figure 17. Sectoral decomposition of GHG emissions under Current Policy (2025) and Net-Zero scenarios.

Source: Authors' analysis.

Building and transport emissions also diminish as electrification becomes increasingly cost-effective relative to fossil-based technologies. Emissions from agriculture and other non-energy sectors contract more slowly, consistent with biophysical constraints and limited mitigation options in those domains.

A notable feature of the Net-Zero sectoral emissions profile is the emergence of large negative emissions in later decades, driven by the deployment of direct air capture (DAC) technologies. GCAM-KSA activates DAC when the marginal cost of abatement in conventional sectors exceeds the cost of removal, allocating an increasing share of mitigation to engineered removals as the net-zero constraint tightens. The substantial negative emissions observed in 2050 and 2060 therefore reflect not only the model's technology cost structure but also its internal logic for distributing mitigation across sectors and technologies to satisfy a binding constraint while minimizing system-wide costs.

Together, the economy-wide and sectoral emissions trajectories demonstrate how GCAM-KSA integrates technological, economic, and resource considerations within

a unified system. The contrast between the two scenarios highlights that structural transformation does not arise from exogenous assumptions about specific sectoral pathways but from the collective effect of endogenous substitution patterns, cost evolution, and emissions accounting within the model's recursive dynamic equilibrium framework. The sectoral emissions breakdown thus provides essential insight into how GCAM-KSA operationalizes decarbonization across an integrated multisector system and how sector-specific structural characteristics condition responses to long-term constraints.

5.2 Primary and Final Energy Consumption

The evolution of primary and final energy use reveals how the model translates scenario assumptions into the allocation of fuels and energy carriers across the economy. These trajectories are particularly informative because GCAM-KSA's internal mechanisms propagate energy service demands, technology

choices, fuel substitutions, and emissions constraints across multiple layers of the energy system.

In the Current Policy (2025) scenario, primary energy demand (Figure 18) grows moderately and remains dominated by oil and natural gas through 2060. This reflects the joint influence of historically calibrated shares, relative fuel prices, and the absence of a binding constraint that would alter cost competition. Although solar and wind expand slowly due to declining capital cost assumptions, their penetration remains limited in this scenario because hydrocarbon-based electricity retains a competitive advantage under prevailing market prices. The stability of the primary energy structure indicates that endogenous substitution occurs gradually when driven only by technological learning and energy price trajectories.

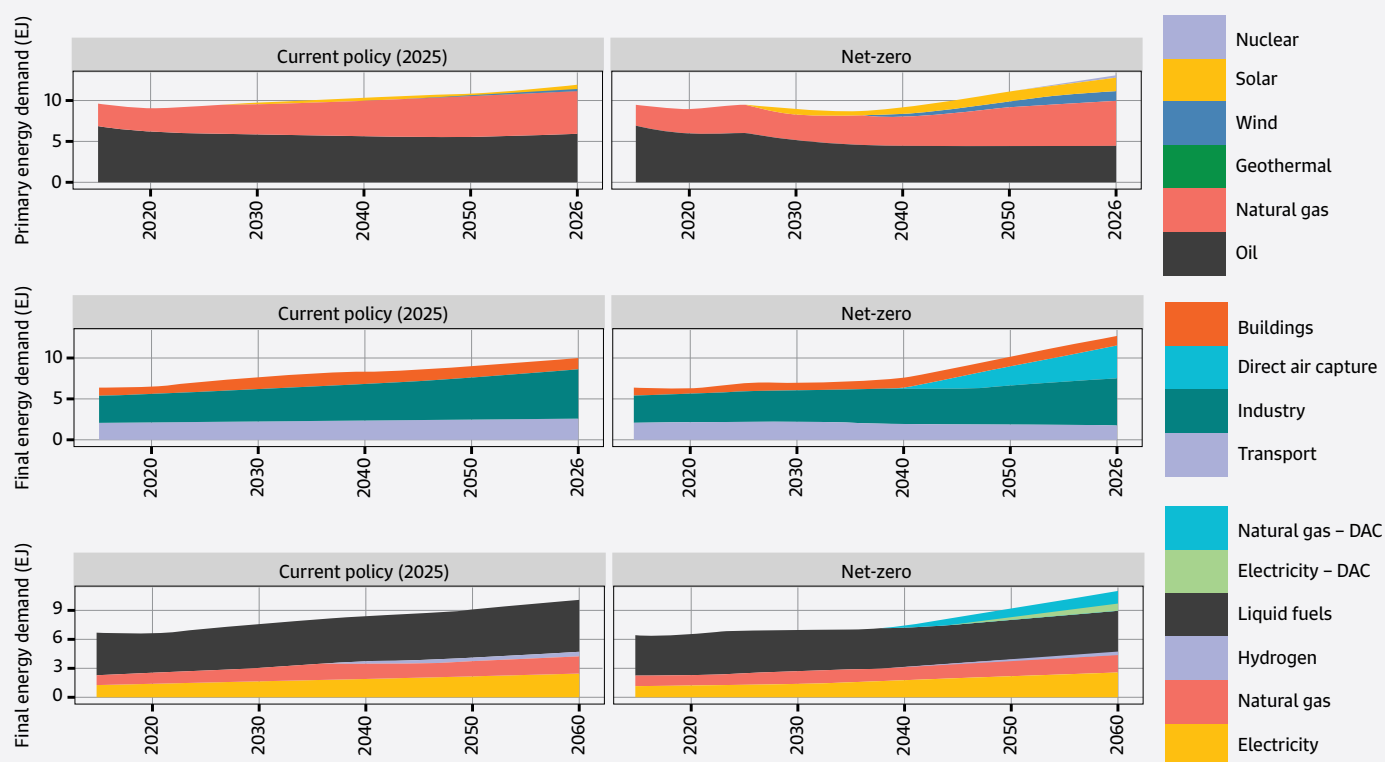
Under the Net-Zero scenario, however, primary energy supply becomes increasingly diversified (Figure 18), and the relative use of hydrocarbon energy carriers declines. Oil use

falls substantially as the transport and industrial sectors shift toward electrification, hydrogen, and CCS-equipped processes. Natural gas maintains a presence but increasingly flows into technologies employing carbon capture, while solar and wind expand rapidly in response to emissions penalties that make low-carbon electricity cost-competitive. Nuclear generation emerges in small quantities late in the modeling horizon, consistent with long lead-time assumptions and high capital costs.

The resulting structure demonstrates how the model resolves the emissions constraint primarily through fuel substitution and reconfiguration of the electricity system, rather than through significant reductions in total energy service demand.

Final energy trajectories (Figure 18) further illustrate the interaction between sectoral demand patterns and GCAM-KSA's technology competition mechanisms. Under the Current Policy (2025) scenario, final energy consumption grows across

Figure 18. Primary energy and final energy demand by fuel type and aggregated sectors under Current Policy (2025) and Net-Zero scenarios.



Source: Authors' analysis.

buildings, industry, and transport, with liquid fuels retaining a dominant role in transport and industrial processes. Electricity demand rises steadily but without transformative shifts, and hydrogen remains marginal due to cost disadvantages. The absence of large-scale structural change is consistent with GCAM-KSA's elasticity-driven demand formulation and historically calibrated technology shares.

In contrast, the Net-Zero scenario displays clear signs of structural reconfiguration. Electrification accelerates across transport and parts of industry, reflecting the increasing competitiveness of low-carbon electricity as the power sector decarbonizes. Hydrogen demand grows as cost thresholds are crossed in specific industrial and transport subsectors.

Most notably, energy consumption associated with DAC (both electricity- and gas-based) becomes substantial after 2040, illustrating the reliance on engineered removals in the absence of alternative technologies to meet the binding net-zero constraint, once marginal abatement costs rise in hard-to-abate sectors, such as industrial processes, aviation, and shipping. The final energy structure under the Net-Zero scenario therefore reflects both the direct effects of electrification and the indirect

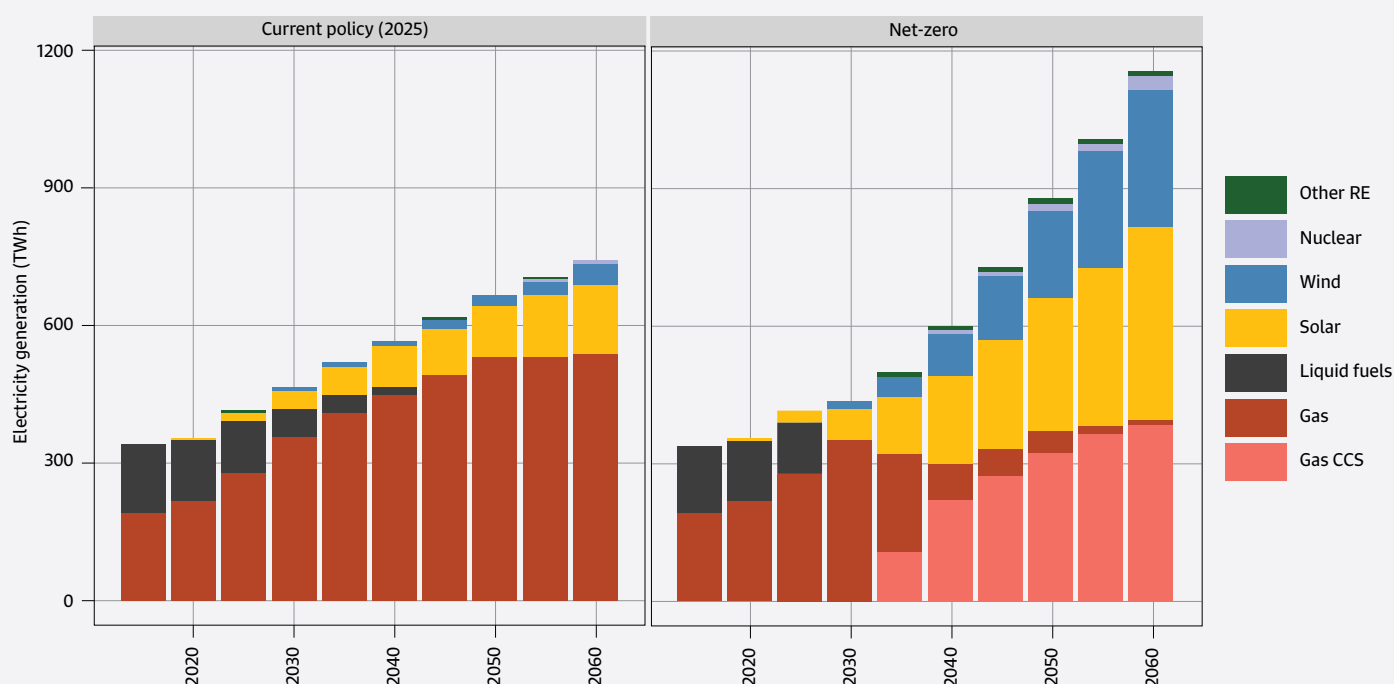
effects of negative emissions deployment, showing how GCAM-KSA balances competing energy and emissions dynamics through its integrated framework.

5.3 Dynamics in the Electricity Sector

Electricity generation is one of the most responsive sectors of the GCAM-KSA energy system because the model includes a wide array of generation technologies with varying cost structures, resource constraints, and emissions characteristics. The contrasting trajectories of the two scenarios highlight how the model endogenously reconfigures the power system through price signals and cost-based allocation.

Under the Current Policy (2025) scenario, electricity generation expands steadily to accommodate rising service demands, but the generation mix remains heavily dominated by natural gas (Figure 19). This outcome is consistent with the relatively low cost of gas-based technologies, the historical calibration of technology shares, and the absence of emissions penalties

Figure 19. Electricity generation mix under Current Policy (2025) and Net-Zero scenarios.



Source: Authors' analysis.

that would shift the cost competition. Solar generation grows gradually as declining capital costs improve its competitiveness, yet the expansion remains modest relative to hydrocarbon-based generation. Liquid-fuel generation decreases slowly over time and eventually phases out due to the natural retirement of plants. Overall, the electricity mix under the Current Policy (2025) scenario evolves incrementally, with endogenous cost reductions driving slow diversification but without inducing structural transformation.

The Net-Zero scenario, by contrast, produces a rapid and pronounced restructuring of the power system (Figure 19). Solar generation expands sharply as cost declines compound with emissions penalties applied to hydrocarbon-based generation. Wind generation also grows substantially, supported by its favorable cost trajectory and resource availability. Natural gas without CCS declines as carbon prices increase its effective cost. In contrast, gas with CCS becomes a major contributor to generation, particularly in the midcentury, reflecting the model's mechanism for allocating mitigation effort across technologies with different abatement cost profiles. Nuclear generation emerges late in the century, albeit on a small scale, consistent with its high capital costs and lengthy construction periods.

The overall scale of electricity generation grows more rapidly under the Net-Zero scenario because end-use sectors increasingly electrify and because DAC facilities introduce significant new electricity demand.

5.4 Dynamics in the Building Sector

The buildings sector in GCAM-KSA exhibits sustained growth in both service demand and electricity consumption across the Current Policy (2025) and Net-Zero scenarios. These dynamics arise from the model's structural representation of building energy use, in which service demands for cooling and other end uses are functions of floorspace, income, and price elasticities, while technology adoption follows a logit-based cost competition framework.

Because the Kingdom's climatic conditions generate a high cooling load and socioeconomic development drives significant increases in built area, the buildings sector becomes one of the principal sources of electricity demand growth across both scenarios. Floorspace expansion is the primary driver of

building energy demand (Figure 20). Residential floorspace increases from under 1 billion square meters in 2020 to nearly 2 billion by 2060, reflecting continued population growth and rising per capita income. Commercial floorspace also expands substantially, more than doubling over the projection period.

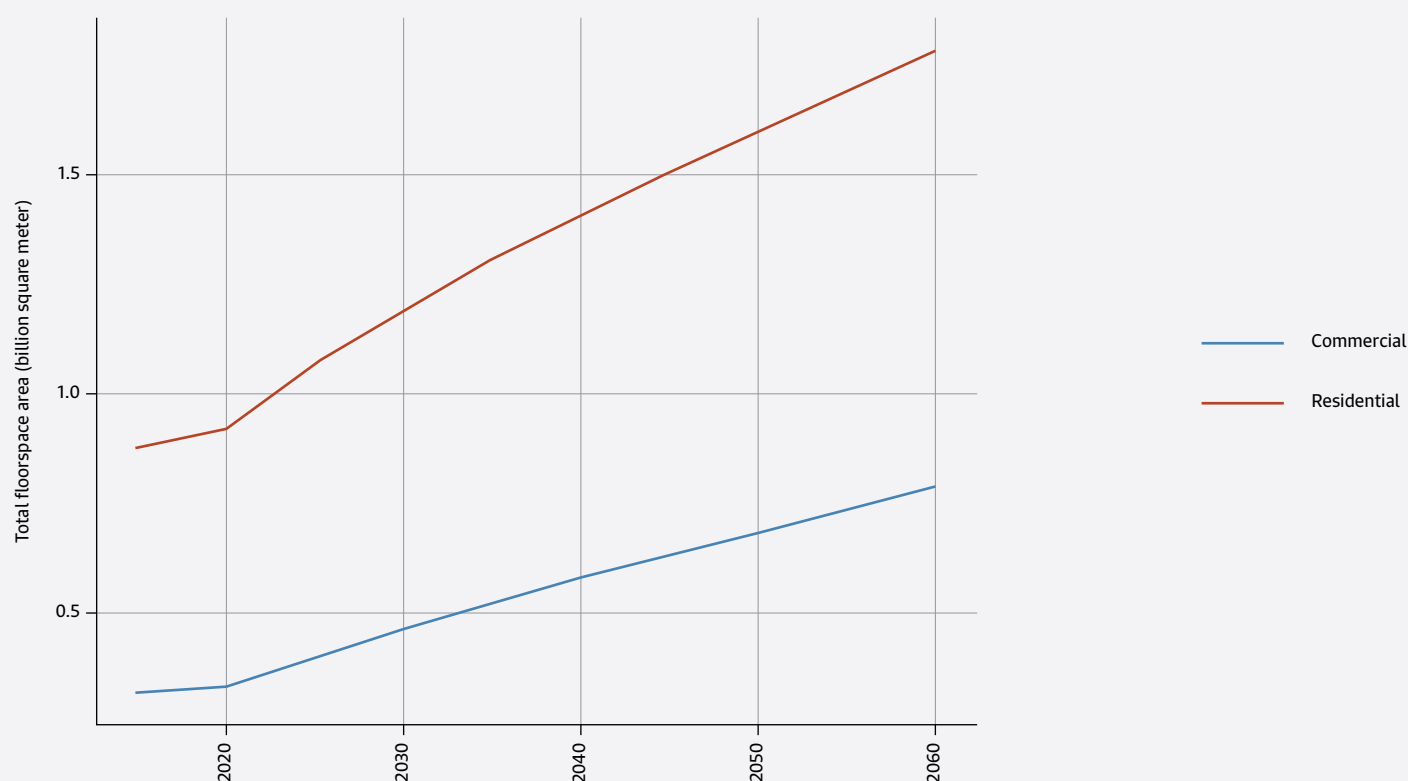
In GCAM-KSA, floorspace supply responds to income-driven demand while incorporating price effects associated with building operation. As energy prices evolve differently across scenarios, the affordability of building services – particularly the cost of cooling – can subtly influence the rate of floorspace expansion. However, the overarching trend of substantial growth in residential and commercial built area is driven primarily by demographic and economic fundamentals, with scenario differences exerting only second-order influence. This growth in floorspace creates a structural increase in the demand for building energy services that persists across both scenarios.

Service demand trajectories reflect these underlying floorspace expansions. Residential cooling demand grows rapidly, accelerating through midcentury as both floorspace and income rise. Commercial cooling follows a similar trajectory, becoming the single largest component of total building service demand by 2060 (Figure 21).

These patterns arise from GCAM-KSA's saturation-adjusted formulation for cooling, which captures the increasing service intensity associated with higher comfort levels as incomes grow. Service demand for “other” end uses – such as lighting, appliance use, heating, and miscellaneous services – increases more gradually but still contributes substantially to overall energy requirements as floorspace expands.

Electricity consumption in the buildings sector mirrors these service demand trends (Figure 21). Under the Current Policy (2025) scenario, electricity use for residential and commercial cooling rises sharply over time, with residential cooling becoming the largest single category of building electricity demand. Commercial cooling and non-cooling electricity use also grow steadily, reflecting the dominance of electricity-based end-use technologies in the buildings sector. Because the model calibrates electricity prices to historical values and allows them to evolve based on supply-side dynamics, buildings increasingly rely on electricity as floorspace expands and service demands intensify.

In the Net-Zero scenario, electricity consumption in buildings exhibits a similar upward trend but grows slightly differently

Figure 20. Residential and commercial floorspace expansion under both scenarios.

Source: Authors' analysis.

across individual end uses (Figure 21). As the electricity system decarbonizes and emissions penalties weaken the competitiveness of fossil-based fuels, electricity becomes even more cost-competitive in relative terms, reinforcing its dominance as the primary energy carrier for building services. Although buildings are not directly subject to mitigation constraints, they respond indirectly to decarbonization through this shift in relative technology costs. The result is a further strengthening of the structural coupling between floorspace growth and electricity demand. Cooling remains the most significant load, reflecting the model's linkage of cooling demand to climate-driven temperature indicators and building envelope characteristics.

Taken together, the buildings sector results highlight GCAM-KSA's internal consistency in linking socioeconomic drivers, floorspace expansion, climatic conditions, and technology adoption. Floorspace growth emerges as the principal driver of building energy demand, with cooling dominating the overall service and electricity load profile. Scenario differences in electricity system decarbonization and relative energy prices influence the technological mix but do not fundamentally alter

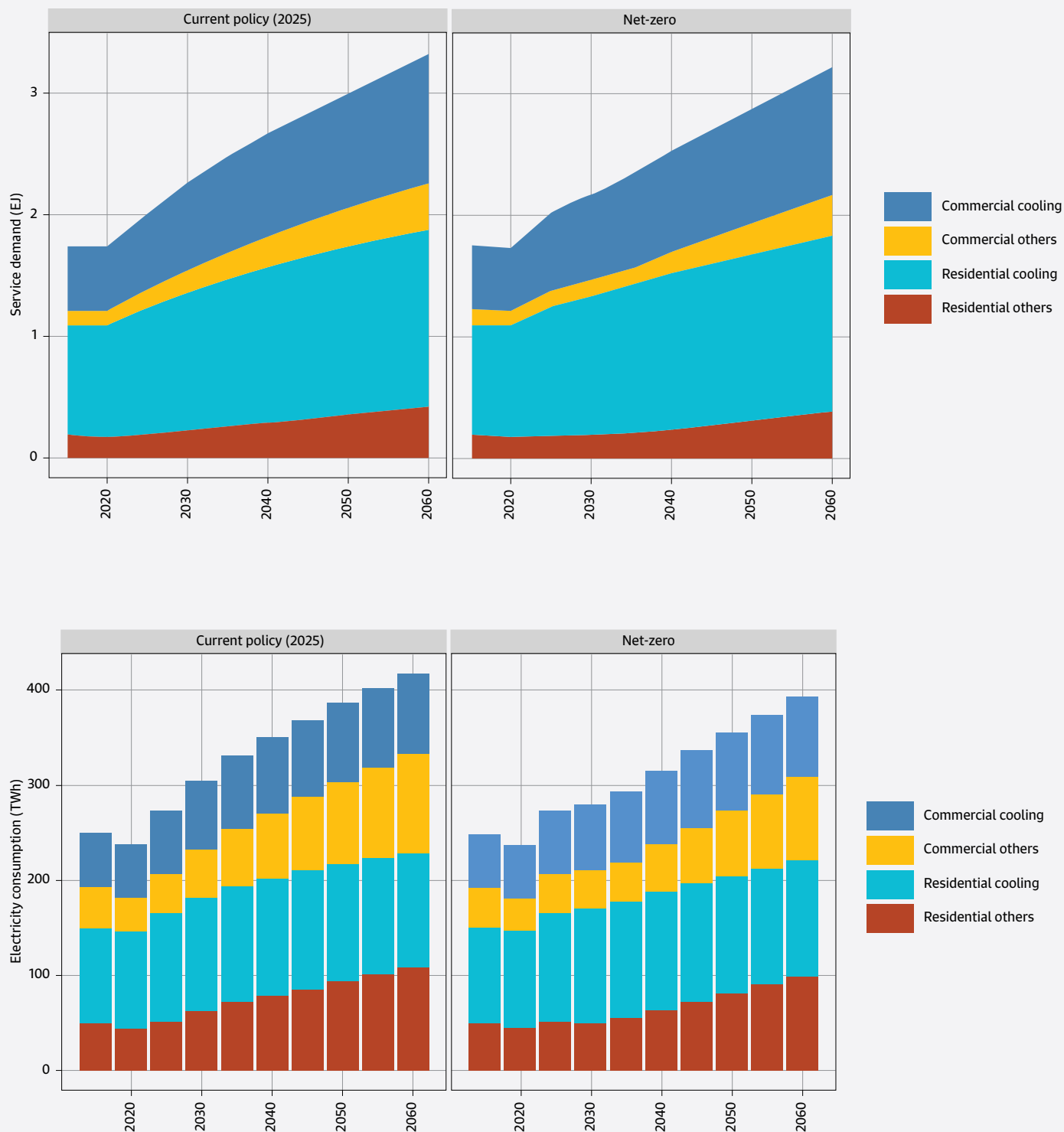
the long-term pattern of rising electricity consumption driven by the expansion of the built environment. These findings underscore the importance of capturing building sector dynamics accurately within integrated assessment models for regions where climatic and demographic factors exert substantial pressure on long-term energy demand.

Although this analysis focuses on demographic and structural drivers, future climate change could significantly influence cooling demand.

5.5 Dynamics in the Transport Sector

The transport sector in GCAM-KSA exhibits distinct patterns of evolution across the Current Policy (2025) and Net-Zero scenarios, reflecting the combined influence of service demand growth, technology competition, fuel substitution, and emissions constraints. Because transport technologies

Figure 21. Building service demand and electricity consumption by end use (cooling and other services).



Source: Authors' analysis.

in GCAM-KSA compete within nested choice structures – first across modes and then among fuels within modes – the sector provides a clear illustration of how substitution elasticities and cost trajectories interact with rising mobility demand to produce heterogeneous outcomes across scenarios.

Figures 22 and 23 illustrate how service demand, fuel use, and emissions adjust endogenously in response to rising mobility demand and stringent mitigation constraints.

Under the Current Policy (2025) scenario, both freight and passenger service demands increase steadily, primarily driven by population and income growth. The composition of demand remains relatively stable, with liquid-fuel technologies maintaining overwhelming dominance in both passenger mobility demand (pkm) and freight movement demand (tkm). The prevalence of liquid fuels reflects several structural factors: historical mode shares, the relatively low cost of internal combustion technologies, and the limited incentives for electrification or hydrogen adoption in the absence of climate policy.

Although electric and hybrid technologies begin to appear in the passenger sector, they remain marginal due to cost disadvantages and the persistent infrastructural barriers captured in the model's logit-based choice mechanism. Freight transport is even more resistant to transformation, with heavy and medium trucks continuing to rely predominantly on liquid fuels. The stability in fuel use translates into emissions trajectories in which four-wheel vehicles, heavy trucks, and international aviation continue to be major contributors. The emissions profile thus mirrors the service demand structure, demonstrating how, without a binding mitigation policy, the transport system evolves through incremental efficiency improvements rather than structural technological change.

In contrast, the Net-Zero scenario introduces a substantial departure from these trends, with emissions constraints fundamentally altering both the composition of service supply and the technological structure of fuel use. Although total service demand grows at rates similar to the Current Policy (2025) scenario – indicative of GCAM-KSA's treatment of transport demand as primarily income-driven – a pronounced shift in the technologies providing that service becomes evident beginning in the 2030s.

In the passenger sector, battery electric vehicles (BEVs) emerge as the dominant technology by midcentury, reflecting their increasing cost competitiveness once electricity becomes

substantially decarbonized and hydrocarbon fuels face emissions penalties. Hybrid vehicles and hydrogen fuel-cell vehicles also expand, albeit at smaller scales, illustrating the model's endogenous logit-based competition among technologies by cost and the influence of non-economic barriers, such as infrastructure availability, on the pace of adoption. Liquid fuels do not disappear entirely but decline in both absolute and relative terms, consistent with the model's inertia in long-lived capital stocks and cost competition frameworks.

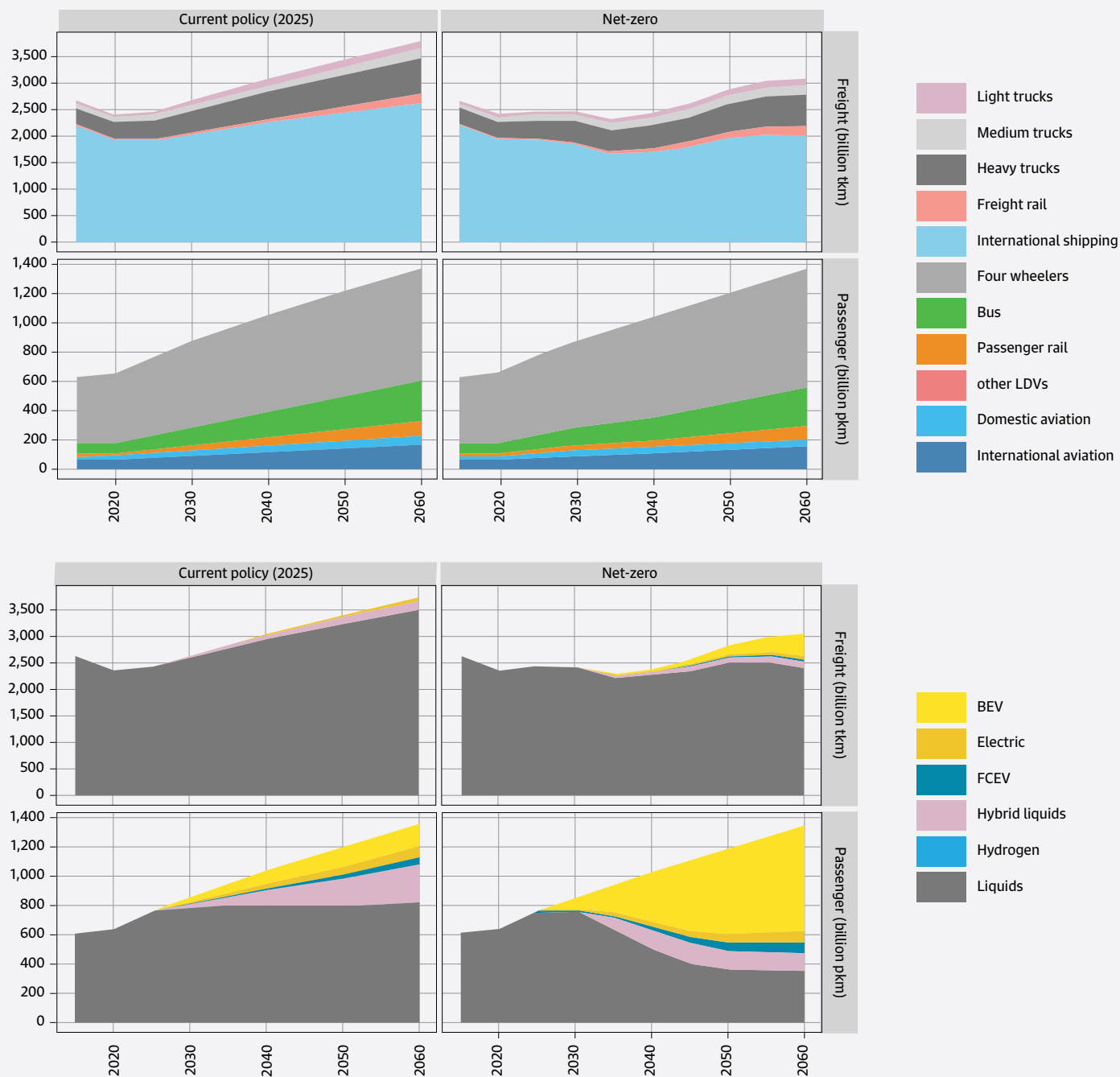
Freight transport exhibits a more gradual transformation due to its higher energy intensity and the more limited set of substitutable technologies available in modes such as shipping. Nonetheless, electric freight vehicles – including BEV trucks and electric rail – gain share as emissions constraints tighten, and hydrogen begins to appear as a supplementary fuel for specific heavy-duty freight segments. Service supplied by liquid-fuel technologies declines but remains significant in 2060, highlighting the structural rigidity of freight transport and the slower rate of technological turnover in heavy-duty applications.

The implications of these technological shifts are evident in the emissions decomposition across transport modes. Under the Net-Zero scenario, emissions from four-wheel vehicles and heavy trucks decline steadily, with sharp reductions occurring once electrification accelerates and electricity generation shifts decisively toward low-carbon sources. International and domestic aviation emissions also decrease but at a slower pace, reflecting the limited availability of fully cost-competitive zero-carbon aviation fuels in the model. Rail emissions fall modestly as electrification deepens, while international shipping continues to contribute a notable share due to limited fuel-switching options.

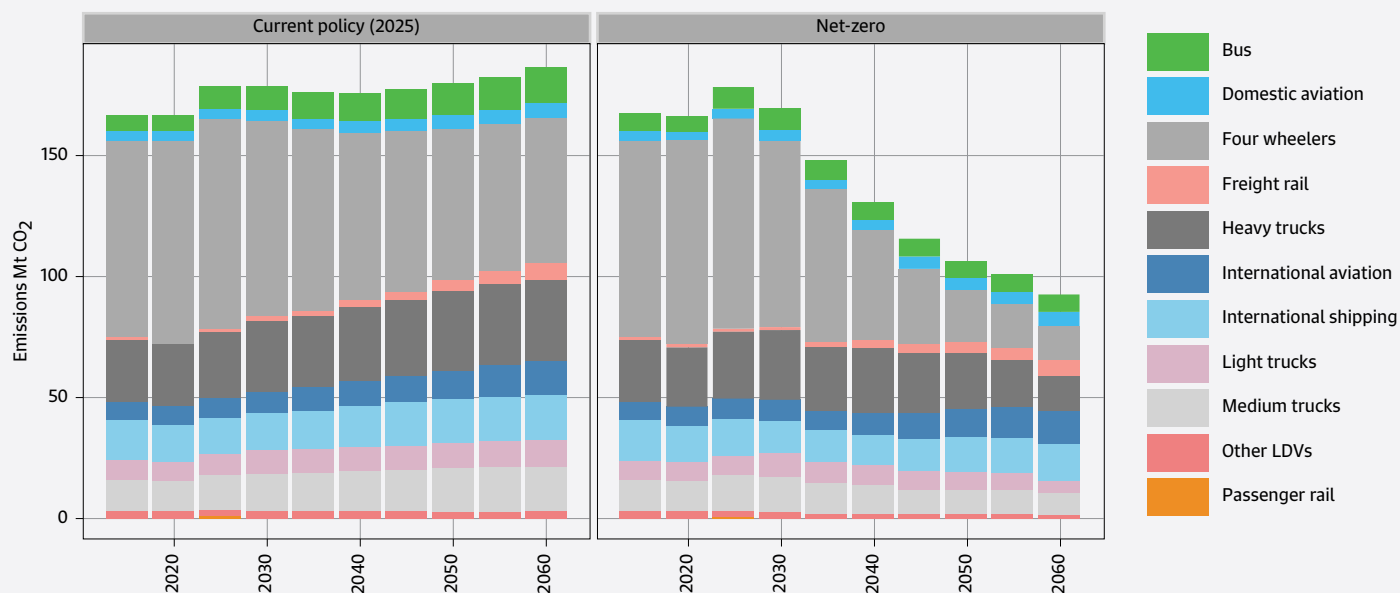
By the 2050s, total transport-sector emissions undergo a substantial decline, and by 2060, several subsectors approach zero emissions, consistent with the economy-wide constraint and the model's activation of alternative low- or zero-carbon fuel technologies.

A comparison of modal service levels across scenarios further demonstrates that reductions in emissions emerge not from declines in transport demand but from shifts in the modes and technological systems that supply that demand. Freight and passenger activity levels remain high across both scenarios, yet the carbon intensity of supplying those services diverges substantially.

Figure 22. Transport service demand by mode and technology type across freight and passenger modes.



Source: Authors' analysis.

Figure 23. Transport sector CO₂ emissions by mode under Current Policy (2025) and Net-Zero scenarios.

Source: Authors' analysis.

This reflects the model's heavily nested structure, in which economic growth drives rising transport service demand, while mitigation occurs through fuel substitution, efficiency improvements, and electrification rather than demand suppression.

5.6 Dynamics in the Industrial Sector

Industrial activity in GCAM-KSA includes several explicitly represented sub-industries (i.e., cement, chemicals, iron and steel, aluminum, nitrogen fertilizers, and refining), alongside a broad aggregated category, "Other Industries." The model captures the behavior of these sub-industries differently depending on the availability of data and the nature of the underlying industrial processes. Notably, cement, iron and steel, fertilizers, and aluminum are modeled with physical production units (Mt), enabling the model to link output growth directly to energy use and associated emissions.

In contrast, the chemical sector is not represented in terms of physical output, but rather through energy service demand, reflecting the absence of a standardized physical metric

capable of capturing the wide range of chemical products and processes. This structural difference has consequences for the emissions pathways and substitution options available to the sector. Parallel to these explicitly represented industries, the "Other Industries" category aggregates small and medium manufacturing activities for which detailed energy consumption data are not available, limiting the model's ability to map technological alternatives and capture subsector-specific mitigation potential.

Industrial output trajectories highlight these representational differences (Figure 24). For cement, iron and steel, aluminum, and fertilizers – each modeled with explicit physical output – the model shows rising production across both scenarios, driven by economic and demographic growth. In the Net-Zero scenario, these subsectors achieve a clear decoupling between output and emissions through the deployment of CCS and the substitution of electricity or hydrogen for fossil fuels. This effect is particularly pronounced in the iron and steel sector, where output increases at a faster rate, primarily due to trade dynamics in the model, as other regions also follow emissions target as per the scenario design.

The chemical sector also shows increased service demand across the projection horizon, but because output is not tied to

physical production units, the observed decoupling manifests through shifts in energy carriers rather than through identifiable process innovations. For “Other Industries,” output grows with income and population, but emissions remain more rigid due to technological aggregation that prevents the introduction of process-specific mitigation options.

Under the Current Policy (2025) scenario, emissions from cement, iron and steel, aluminum, and nitrogen fertilizers rise steadily as their physical output grows in response to GDP-driven demand (Figure 25). These sub-industries exhibit well-defined relationships between production volume, energy intensity, and emissions, allowing the model to scale energy use proportionally as output increases.

The chemical sector also shows increasing emissions, but its behavior stems from rising energy service requirements rather than growth in tracked physical production. Because the chemical sector is represented through an aggregated energy service function, the model cannot attribute emissions reductions to specific chemical processes or material-efficiency improvements and instead responds primarily to shifts in fuel costs.

Across all sub-industries, refining maintains a persistent contribution to emissions, linked to continued domestic fuel processing. In contrast to these explicitly modeled industries, the “Other Industries” category also shows rising emissions but for different reasons: lacking detailed structural information on the constituent industrial activities, GCAM-KSA represents this category using generic technology and energy intensity assumptions. As a result, the subsector retains a fossil-intensive technology mix with limited scope for low-carbon substitution, leading to emissions that grow proportionally with economic activity.

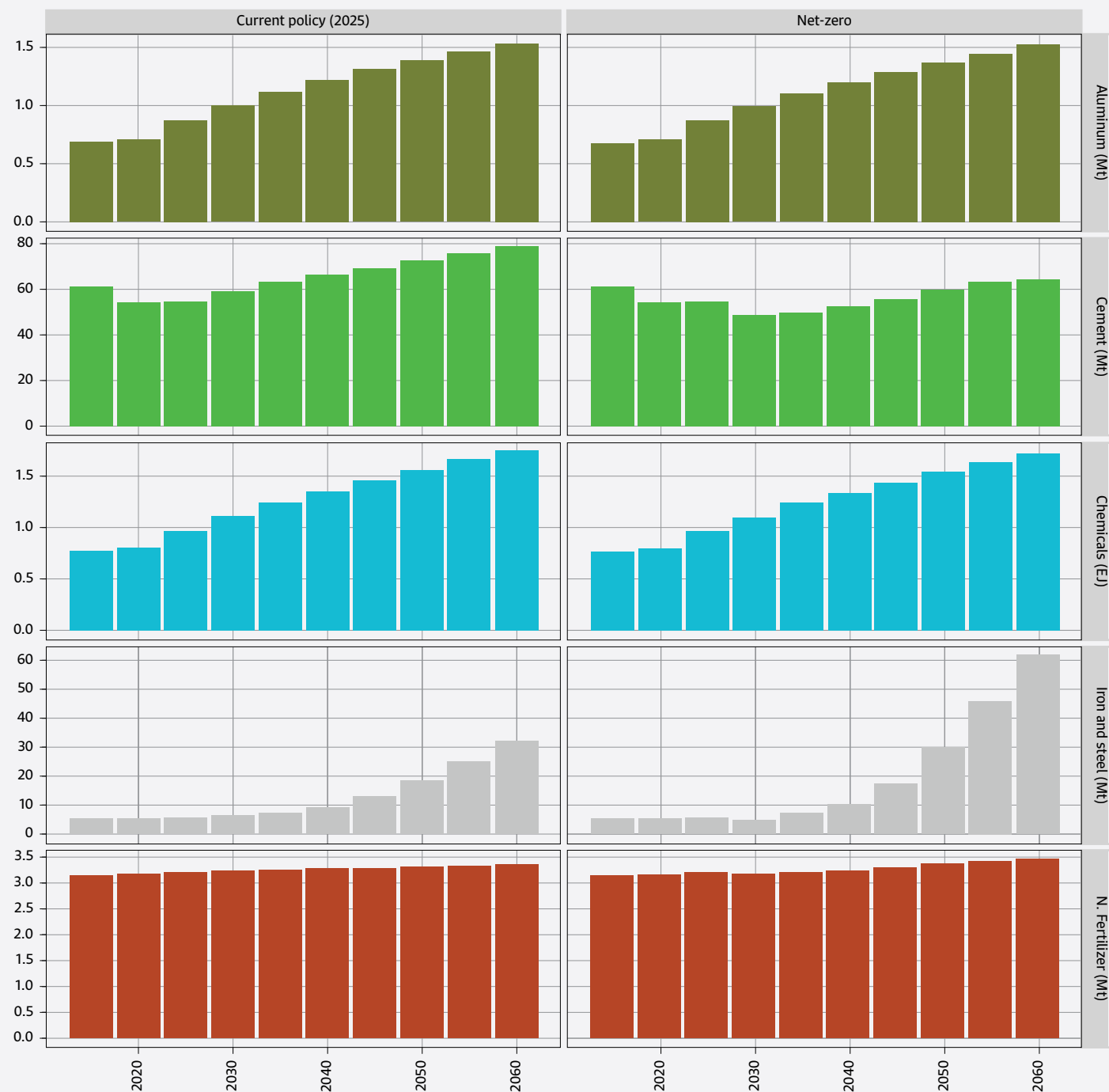
In the Net-Zero scenario, emissions from the explicitly represented industries decline substantially due to the availability of process-specific low-carbon substitutes (Figure 25). Cement transitions toward CCS-equipped clinker production, reducing both energy-related and process emissions. Iron and steel production shifts toward CCS-enabled EAF pathways, reflecting the sector’s relatively well-defined technological substitution options. Aluminum experiences emissions reductions through increased electrification and improved energy intensity over time. Nitrogen fertilizer production also decarbonizes as the model substitutes hydrocarbon-based hydrogen inputs with low-carbon

alternatives or deploys CCS in ammonia production routes. Refining emissions fall as fuel demand declines and CCS is introduced into remaining refining operations.

The chemical sector also exhibits declining emissions, but the mechanism differs from the other industries. Because the model captures chemicals through energy service demand rather than physical production processes, emissions reductions occur through fuel switching and the introduction of CCS for thermal energy services, not through process-level technological substitution. This difference underscores a representational limitation: the model cannot specify carbon-saving innovations in chemical feedstocks or processes, leading to more generalized mitigation pathways.

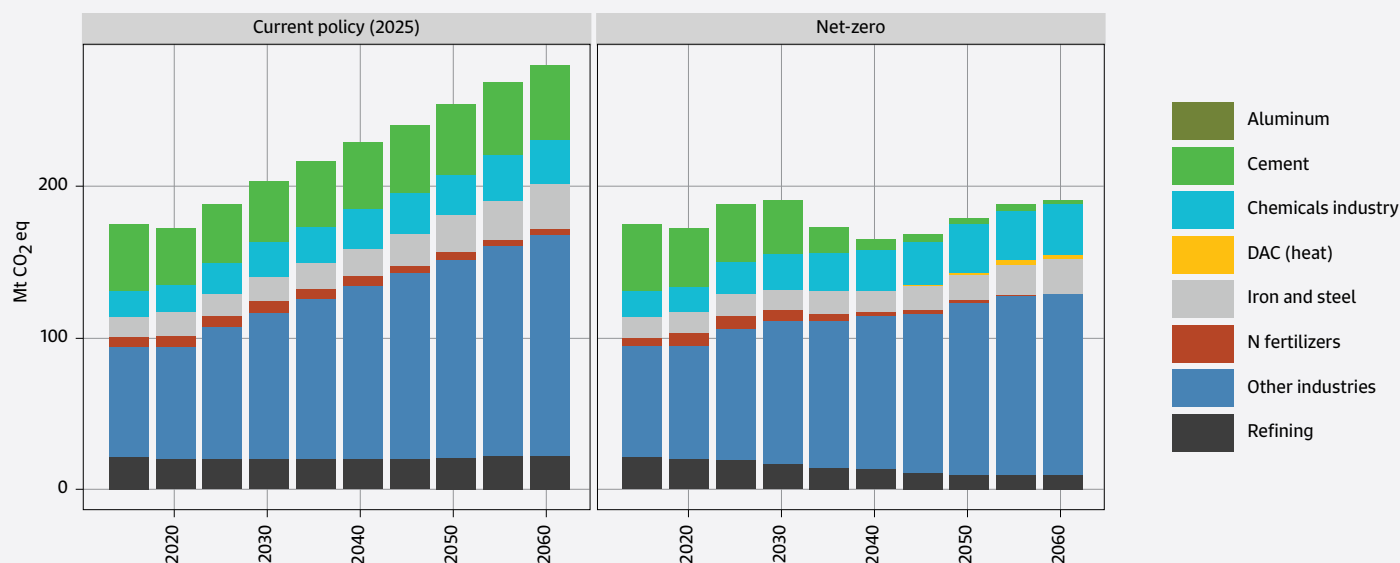
The “Other Industries” category behaves differently. Although emissions decline modestly under the Net-Zero scenario, the reductions are significantly smaller than those observed in the physically tracked sub-industries. Because GCAM-KSA lacks process-level data for small and medium industries, the model cannot assign appropriate low-carbon technologies. This structural limitation – stemming from data availability rather than inherent technological constraints – prevents the model from substituting hydrocarbon-intensive processes with cleaner alternatives, leading to a large share of persistent residual emissions concentrated in this aggregated category. In effect, the inability to map detailed industrial processes translates into limited technological flexibility, producing an emissions pattern in which “Other Industries” remains disproportionately carbon-intensive even under stringent mitigation requirements.

Collectively, the industrial sector results illustrate how GCAM-KSA’s structural representation, technological database, and calibration constraints determine emissions trajectories. Sub-industry-specific decarbonization emerges where the model has well-defined production processes and associated low-carbon technologies, whereas aggregated sub-industries with limited data availability – particularly “Other Industries” – exhibit more persistent emissions due to the inability to map granular technological alternatives. The divergence in behavior between physically modeled industries and the chemical and aggregated categories underscores the importance of improved energy-demand and technology data for small and medium industries, as well as the need for enhanced process-level characterization of the chemical sector in the future development of GCAM-KSA.

Figure 24. Industrial output by subsector under Current Policy (2025) and Net-Zero scenarios.

Note: Units of each industry's output are mentioned in parentheses next to each industry on the right axis.

Source: Authors' analysis.

Figure 25. Industrial CO₂ emissions by subsector under Current Policy (2025) and Net-Zero scenarios.

Source: Authors' analysis.

5.7 Interlinked Dynamics of Water Use, Agricultural Production, and Land-Use Patterns

The evolution of water use, agricultural production, and land allocation in GCAM-KSA highlights the strong interdependencies among these systems and illustrates how the model resolves resource competition through its integrated equilibrium structure. Because GCAM-KSA links sectoral water demands, crop yields, land conversion costs, and irrigation intensities within a unified framework, shifts in one domain (such as agriculture) propagate directly into water withdrawals and land-use allocations. The differences between the Current Policy (2025) and Net-Zero scenarios therefore reflect not only socioeconomic drivers but also the structural assumptions and data constraints embedded in the representation of the water-energy-land nexus.

Under the Current Policy (2025) scenario, agricultural production increases steadily across almost all crop categories. Fiber crops, fodder grasses, fodder herbs, and miscellaneous crops exhibit the strongest growth, consistent with rising domestic food and feed demand driven by population and

income growth (Figure 27). Wheat, corn, oil crops, and rice also rise, but at a more gradual pace.

Because GCAM-KSA models agricultural production through crop-specific yield trajectories and land-use intensification parameters, these increases are met through a combination of yield improvements and incremental expansion of irrigated cropland. This expansion, in turn, drives the steady rise in irrigation-related water consumption and withdrawals (Figure 26), which account for the majority of total water use over the projection period. Municipal and industrial water demands grow more modestly, as they respond primarily to population and income growth.

The Net-Zero scenario shares these broad structural tendencies but introduces more variability in agricultural production. Several crops – particularly fiber crops, fodder grasses, and fodder herbs – expand more rapidly after 2040, reflecting interactions among agricultural demand, reduced competition for land from energy crops, and subtle shifts in the relative cost of water as the energy system decarbonizes.

However, an important nuance arises in the case of fodder grass and pasture expansion. Although the model exhibits increased production of these water-intensive feed crops, this behavior does not correspond to current or emerging agricultural

trends in Saudi Arabia, where ongoing water scarcity concerns and national policy directions prioritize reducing domestic production of highly water-intensive fodder crops and replacing them with imports.

The modeled expansion is not a prediction of real-world outcomes but rather an artifact of data limitations in the calibration of crop-specific constraints. Because detailed information on limits to fodder production, policy restrictions, and feed import dynamics is not yet available for full integration into GCAM-KSA, the model treats these crops similarly to other irrigated crops and allocates land based solely on relative profitability and resource costs. Future versions of GCAM-KSA will incorporate more realistic constraints and improved data to better reflect the Kingdom's strategic shift away from water-intensive fodder production.

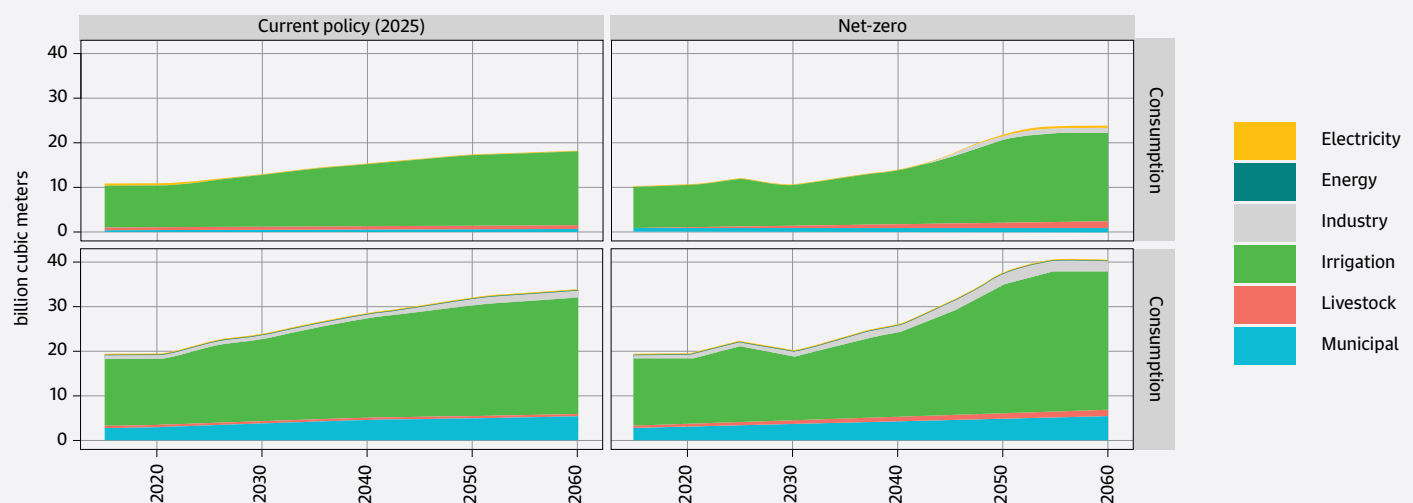
Despite this limitation, the broader water-use dynamics under the Net-Zero scenario remain informative. Overall, total water withdrawals increase in both scenarios, with the net-zero case showing a sharper rise after midcentury due to the combination of agricultural expansion and the additional water requirements associated with CCS and engineered carbon removal technologies.

Land-use patterns remain dominated by desert land across both scenarios, with cropland and pasture occupying relatively modest

shares of total land. Under both scenarios, cropland expands slightly in response to crop production needs, and pasture also grows somewhat within the model to reflect increased livestock feed requirements. However, as noted, the expansion of pasture and fodder crops likely overstates the plausible real-world extent of these land uses given water scarcity constraints and policy directions in Saudi Arabia. Forests and other natural land categories show limited changes, reflecting the high costs associated with land conversion and the absence of bioenergy-driven land competition within these scenarios.

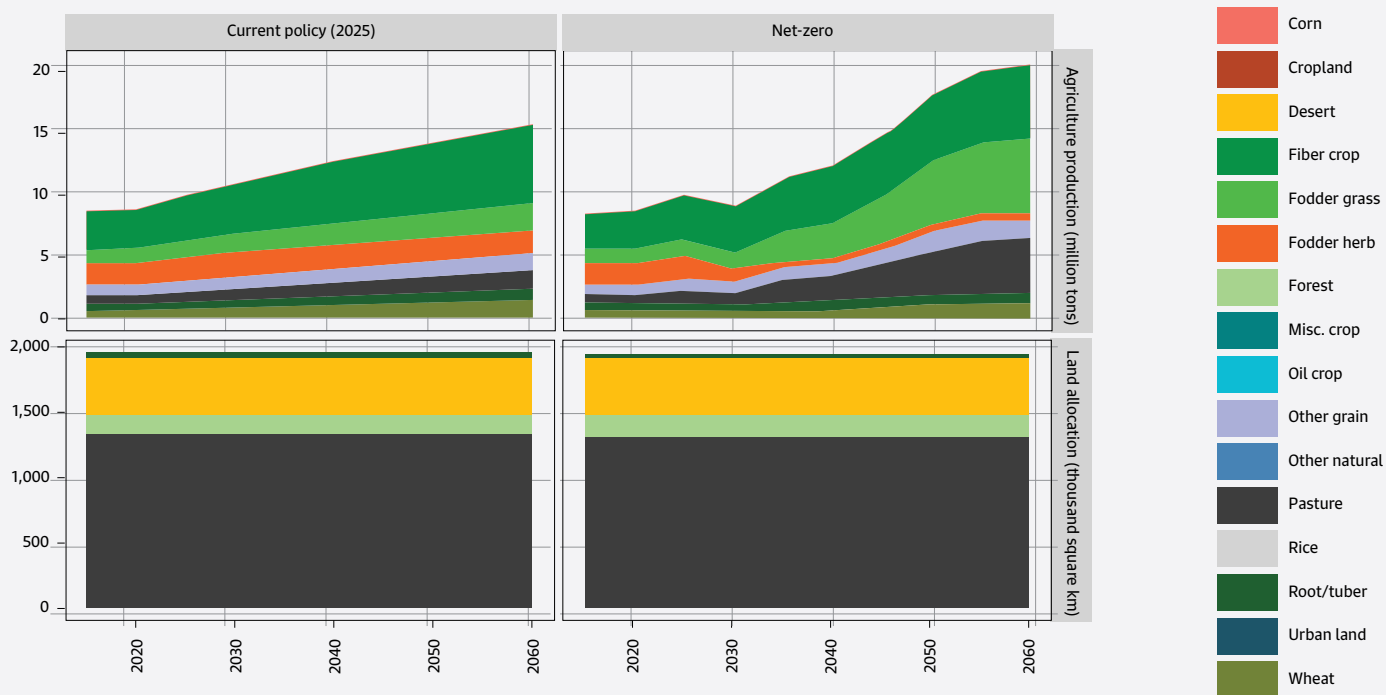
Taken together, the results demonstrate how GCAM-KSA's integrated modeling of water, agriculture, and land use captures systemic interactions that influence resource allocation and long-term trajectories. Irrigation demand remains the central driver of water use, agricultural production responds strongly to socioeconomic drivers, and land-use change is constrained by both biophysical and economic factors. At the same time, the model's behavior in specific crop categories – especially fodder grasses and pasture – highlights areas where further refinement of data and structural constraints is required to align modeled outcomes more closely with the realities of water scarcity and agricultural policy in the Kingdom. These insights underscore both the strengths of integrated assessment modeling for exploring cross-sectoral linkages and the importance of ongoing improvements to GCAM-KSA's agricultural and water data foundations.

Figure 26. Water consumption and withdrawals by sector under Current Policy (2025) and Net-Zero scenarios.



Source: Authors' analysis.

Figure 27. Agricultural production and land allocation under Current Policy (2025) and Net-Zero scenarios.



Source: Authors' analysis.

Conclusion and Further Model Development

06



The results from GCAM-KSA demonstrate the model's ability to generate internally consistent, system-wide trajectories for Saudi Arabia under alternative long-term socioeconomic and emissions pathways. As an integrated assessment model, GCAM-KSA captures how interactions across the energy system, industrial structure, land resources, water availability, and technological change co-evolve in response to scenario assumptions. The contrast between the Current Policy (2025) and Net-Zero scenarios confirms that system-wide outcomes in the model are not the product of isolated sectoral shifts but are instead shaped by cross-sectoral feedbacks transmitted through market prices, resource competition, technological substitutability, and the model's recursive dynamic equilibrium structure.

Emissions pathways highlight the degree of structural inertia embedded in the Kingdom's energy system. Under the Current Policy (2025) scenario, emissions rise gradually as population, income, and demand for energy services increase, and fossil fuels remain cost-competitive across multiple end-use sectors. When an economy-wide net-zero constraint is imposed, however, the model identifies a coordinated mitigation response featuring the rapid expansion of renewable electricity, substitution among end-use technologies, widespread deployment of CCS in industry and refining, and the activation of engineered carbon removal.

Sectoral decomposition reveals that the power sector and the passenger transport sector respond earliest to mitigation pressures, reflecting the availability of mature low-carbon technologies in these domains. Persistent residual emissions

occur primarily in subsectors where technological options are limited or data are insufficient – most notably the aggregated “Other Industries” category – underscoring the importance of accurate sectoral calibration for credible long-term mitigation analysis.

Energy system trajectories further illustrate the interplay between primary and final energy demand and transformations in electricity supply. Buildings, transport, and industry increasingly electrify across both scenarios, and this sustained rise in electricity demand requires significant expansion of low-carbon power generation under the Net-Zero conditions. Buildings contribute disproportionately to electricity growth due to the rapid expansion of residential and commercial floorspace and the high cooling load associated with the Kingdom's climatic conditions.

Transport demand also grows steadily, with liquid fuels retaining dominance for freight and aviation in the absence of stringent mitigation constraints. In the Net-Zero pathway, the sector undergoes more pronounced shifts toward cleaner modes for passenger travel, while freight decarbonization remains constrained by limited substitution options. These dynamics highlight the centrality of electricity in the Kingdom's long-term energy transitions as represented in GCAM-KSA.

The industrial sector results reveal differentiated behavior across subsectors depending on the maturity and specificity of their technological representations. Cement, iron and steel, fertilizers, and aluminum are modeled using physical production units, enabling GCAM-KSA to link output growth directly to energy use and emissions and to apply process-specific CCS pathways effectively under the Net-Zero conditions.

By contrast, the chemical sector is represented through energy service demand rather than physical production, limiting the model's ability to capture process-level emissions and feedstock substitution pathways. Emissions reductions in the chemical sector therefore reflect fuel and heat substitution rather than more fundamental transformations in industrial chemistry. The large "Other Industries" category, which aggregates numerous small and medium enterprises, remains a major source of residual emissions due to limited data on energy use, technology characteristics, and emissions sources. This aggregation constrains the model's representation of feasible decarbonization options and results in stylized emissions pathways that reflect structural data limitations rather than actual mitigation potential.

The interconnected dynamics of water use, agriculture, and land allocation further highlight the value of an integrated modeling framework. Irrigation remains the dominant driver of water withdrawals across both scenarios, reflecting the strong linkage between agricultural production and water demand in the Kingdom's arid environment. Under the Net-Zero conditions, changes in electricity costs and reductions in pressure on land for energy crops indirectly influence agricultural production patterns and water demand.

However, the model's representation of fodder grass and pasture expansion – driven by economic competitiveness and the absence of restrictive constraints – does not reflect ongoing national efforts to reduce domestic production of water-intensive feed crops. This divergence highlights the need for improved crop-specific water use constraints, groundwater

withdrawal limits, and feed import representations to align agricultural outcomes more closely with real-world policy and resource conditions. More detailed data on irrigation practices, crop management, and land-use regulation would significantly enhance GCAM-KSA's ability to represent Saudi Arabia's water-land-agriculture nexus.

Taken together, the results affirm that GCAM-KSA resolves long-term transitions through the integrated operation of coupled systems rather than through isolated sectoral adjustments. Emissions outcomes depend on co-evolving transformations in energy supply, land use, and industrial technologies; water withdrawals respond to agricultural patterns and desalination costs; floorspace growth drives electricity demand and cooling loads; and industrial technology adoption interacts with fuel prices and CCS availability. These interactions are emergent properties of the model's equilibrium structure and technology competition mechanisms, illustrating the necessity of integrated assessment modeling for exploring transitions in complex, resource-constrained economies.

A closer examination of model outputs identifies several areas for improvement that will strengthen GCAM-KSA's representation of the Kingdom's socioeconomic and resource systems. Foremost is the need for greater disaggregation in the industrial sector, particularly within the "Other Industries" category. Detailed data on energy use, technology types, and emissions sources in small and medium enterprises would enable a more realistic allocation of technologies and more accurate representation of future emissions pathways.

Similarly, the chemical sector would benefit from a shift away from a generic service-based representation toward tracking physical production volumes for key chemical products. Improved data on process emissions, feedstock use, and the potential for low-carbon chemical technologies would allow GCAM-KSA to better capture transition pathways in one of Saudi Arabia's most dynamic industrial sectors.

In the agricultural domain, improved representation of fodder crop constraints, water-use policies, and feed import strategies is essential for aligning model outcomes with the Kingdom's real-world responses to chronic water scarcity. Enhanced data on crop-specific irrigation requirements, spatial water availability, and land-use restrictions would strengthen the model's capacity to simulate water-land-agriculture interactions and ensure that modeled agricultural expansion reflects realistic biophysical and policy constraints.

It is important to acknowledge that the analysis presented in this paper does not account for the direct physical impacts of climate change or for macroeconomic shocks arising from climate and energy systems, or for specific regional policy developments outside Saudi Arabia. Global dynamics are captured within the model's framework through trade dynamics in selected sectors, such as oil, iron and steel, and agricultural trade. Future work will extend GCAM-KSA to explore climate impacts and international macroeconomic feedback.

Overall, GCAM-KSA provides a rigorous analytical platform for exploring long-term transformations in Saudi Arabia's

energy-water-land-economy systems. Its detailed sectoral disaggregation and integrated architecture enable the examination of cross-sectoral dynamics that are essential for understanding mitigation pathways in an energy-intensive, resource-constrained national context. At the same time, the analysis presented here highlights specific opportunities – industrial disaggregation, improved representation of chemical processes, and enhanced constraints for water-intensive agriculture – where further model development will enhance the fidelity and policy relevance of GCAM-KSA in future applications.

Alaqrnma, Mohammed, and Ansir Ilyas. 2025. "A Critical Overview: Evaluating Saudi Arabia's Progress on Renewable Energy Goals." King Abdullah University of Science and Technology (KAUST) Research Repository. <https://doi.org/10.25781/KAUST-DSCWT>.

Andrew, Robbie M. 2019. "Global CO₂ Emissions from Cement Production, 1928–2018." *Earth System Science Data* 11 (4): 1675–1710. <https://doi.org/10.5194/essd-11-1675-2019>.

Alwosheel, Abdulrahman, and Rubal Dua. Estimating Regional Variation in Saudi Arabia's Energy Usage and Carbon Emissions. Riyadh, Saudi Arabia: King Abdullah Petroleum Studies and Research Center, 2023.

Bauer, Nico, Katherine Calvin, Johannes Emmerling, Oliver Fricko, Shinichiro Fujimori, Jérôme Hilaire, Jiyong Eom, Volker Krey, Elmar Kriegler, Ioanna Mouratiadou, Harmen Sytze de Boer, Maarten van den Berg, Samuel Carrara, Vassilis Daioglou, Laurent Drouet, James E. Edmonds, David Gernaat, Petr Havlik, Nils Johnson, David Klein, and Detlef P. van Vuuren. 2017. "Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives." *Global Environmental Change* 42 (January): 316–330. <https://doi.org/10.1016/j.gloenvcha.2016.07.006>.

Calvin, Katherine, Leon Clarke, Volker Krey, Geoffrey Blanford, Kejun Jiang, Mikiko Kainuma, Elmar Kriegler, Gunnar Luderer, and P. R. Shukla. 2012. "The Role of Asia in Mitigating Climate Change: Results from the Asia Modeling Exercise." *Energy Economics* 34, Supp. 3 (December): S251–S260. <https://doi.org/10.1016/j.eneco.2012.09.003>.

Calvin, Katherine, Marshall Wise, Page Kyle, Pralit Patel, Leon Clarke, and Jae Edmonds. 2014. "Trade-Offs of Different Land and Bioenergy Policies on the Path to Achieving Climate Targets." *Climatic Change* 123: 691–704. <https://doi.org/10.1007/s10584-013-0897-y>.

Calvin, Katherine, Pralit Patel, Leon Clarke, Ghassem Asrar, Ben Bond-Lamberty, Ryna Yiyun Cui, Alan Di Vittorio, Kalyn Dorheim, Jae Edmonds, Corinne Hartin, Mohamad Hejazi, Russell Horowitz, Gokul Iyer, Page Kyle, Sonny Kim, Robert Link, Haewon McJeon, Steven J. Smith, Abigail Snyder, Stephanie Waldhoff, and Marshall Wise. 2019. "GCAM v5.1: Representing the Linkages Between Energy, Water, Land, Climate, and Economic Systems." *Geoscientific Model Development* 12 (2): 677–698. <https://doi.org/10.5194/gmd-12-677-2019>.

Chaturvedi, Vaibhav, Jiyong Eom, Leon E. Clarke, and Priyadarshi R. Shukla. 2014. "Long Term Building Energy Demand for India: Disaggregating End Use Energy Services in an Integrated Assessment Modeling Framework." *Energy Policy* 64 (January): 226–242. <https://doi.org/10.1016/j.enpol.2012.11.021>.

Clarke, Leon, Jiyong Eom, Elke Hodson Marten, Russell Horowitz, Page Kyle, Robert Link, Bryan K. Mignone, Anupriya Mundra, and Yuyu Zhou. 2018. "Effects of Long-Term Climate Change on Global Building Energy Expenditures." *Energy Economics* 72 (May): 667–677. <https://doi.org/10.1016/j.eneco.2018.01.003>.

Durand-Lasserve, Olivier. 2025. "Net Zero Emissions in Saudi Arabia by 2060: Least-Cost Pathways, Influence of International Oil Price, and Economic Consequences." *The Energy Journal* 46 (5): 57–84. <https://doi.org/10.1177/01956574251340006>.

Edmonds, James A., Robert Link, Stephanie T. Waldhoff, and Ryna Cui. 2017. "A Global Food Demand Model for the Assessment of Complex Human-Earth Systems." *Climate Change Economics* 8 (4): 1750012. <https://doi.org/10.1142/S2010007817500129>.

Elshurafa, Amro M., Hatem Alatawi, Salaheddine Soummame, and Frank A. Felder. 2021. "Assessing Effects of Renewable Deployment on Emissions in the Saudi Power Sector Until 2040 Using Integer Optimization." *The Electricity Journal* 34 (6): 106973. <https://doi.org/10.1016/j.tej.2021.106973>.

Eom, Jiyong, Leon Clarke, Son H. Kim, Page Kyle, and Pralit Patel. 2012. "China's Building Energy Demand: Long-Term Implications from a Detailed Assessment." *Energy* 46 (1): 405–419. <https://doi.org/10.1016/j.energy.2012.08.009>.

General Authority for Statistics (GASTAT). 2022. *Saudi Census*. <https://www.stats.gov.sa/en/home>.

Goodwin, Phil, Joyce Dargay, and Mark Hanly. 2003. "Elasticities of Road Traffic and Fuel Consumption with Respect to Price and Income: A Review." *Transport Reviews* 24 (3): 275–292. <https://doi.org/10.1080/0144164042000181725>.

Hasanbeigi, Ali, Lynn Price, and Elina Lin. 2012. "Emerging Energy-Efficiency and CO₂ Emission-Reduction Technologies for Cement and Concrete Production: A Technical Review." *Renewable and Sustainable Energy Reviews* 16 (8): 6220–6238. <https://doi.org/10.1016/j.rser.2012.07.019>.

- Hasanbeigi, Ali, Marlene Arens, and Lynn Price. 2014. "Alternative Emerging Ironmaking Technologies for Energy-Efficiency and Carbon Dioxide Emissions Reduction: A Technical Review." *Renewable and Sustainable Energy Reviews* 33 (May): 645–658. <https://doi.org/10.1016/j.rser.2014.02.031>.
- Hejazi, Mohamad, James Edmonds, Vaibhav Chaturvedi, Evan Davies, and Jiyong Eom. 2013. "Scenarios of Global Municipal Water-Use Demand Projections over the 21st Century." *Hydrological Sciences Journal* 58 (3): 519–538. <https://doi.org/10.1080/02626667.2013.772301>.
- Hejazi, Mohamad, James Edmonds, Leon Clarke, Page Kyle, Evan Davies, Vaibhav Chaturvedi, Marshall Wise, Pralit Patel, Jiyong Eom, Katherine Calvin, Richard Moss, and Son Kim. 2014. "Long-Term Global Water Projections Using Six Socioeconomic Scenarios in an Integrated Assessment Modeling Framework." *Technological Forecasting and Social Change* 81: 205–226. <https://doi.org/10.1016/j.techfore.2013.05.006>.
- IAMC Wiki. 2026. "The Common Integrated Assessment Model (IAM) Documentation." https://www.iamcdocumentation.eu/index.php/IAMC_wiki.
- International Energy Agency (IEA). 2018. *Technology Roadmap - Low-Carbon Transition in the Cement Industry*. <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>.
- International Energy Agency (IEA). 2021. *Global Extended Energy Balance*. <https://www.iea.org/data-and-statistics/data-product/world-energy-balances>.
- International Institute for Applied Systems Analysis (IIASA). 2025. *SSP Scenario Explorer*. <https://data.ece.iiasa.ac.at/ssp/#/login?redirect=%2Fworkspaces>.
- International Monetary Fund (IMF). 2025. "Saudi Arabia." <https://www.imf.org/en/countries/sau>.
- Isaac, Morna, and Detlef P. van Vuuren. 2009. "Modeling Global Residential Sector Energy Demand for Heating and Air Conditioning in the Context of Climate Change." *Energy Policy* 37 (2): 507–521. <https://doi.org/10.1016/j.enpol.2008.09.051>.
- Iyer, G.C., M. Brown, S.M. Cohen, J. Macknick, P. Patel, M. Wise, M. Binsted, and N. Voisin. 2019. "Improving Consistency Among Models of Overlapping Scope in Multi-Sector Studies: The Case of Electricity Capacity Expansion Scenarios." *Renewable and Sustainable Energy Reviews* 116. <https://doi.org/10.1016/j.rser.2019.109416>.
- Joint Global Change Research Institute (JGCRI). 2023. "GCAM v7 Documentation: Table of Contents." <https://jgcric.github.io/gcam-doc/v7.0/toc.html>.
- Kamboj, Puneet, Mohamad Hejazi, Yang Qiu, Page Kyle, and Gokul Iyer. 2024. "The Path to 2060: Saudi Arabia's Long-Term Pathway for GHG Emission Reduction." *Energy Strategy Reviews* 55: 101537. <https://doi.org/10.1016/j.esr.2024.101537>.
- Kim, Son H., Jae Edmonds, Josh Lurz, Steven J. Smith, and Marshall Wise. 2006. "The ObJECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation." *The Energy Journal* 27 (2): 63–91. <https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-4>.
- Kim, Son H., Mohamad Hejazi, Lu Liu, Katherine Calvin, Leon Clarke, Jae Edmonds, Page Kyle, Pralit Patel, Marshall Wise, and Evan Davies. 2016. "Balancing Global Water Availability and Use at Basin Scale in an Integrated Assessment Model." *Climatic Change* 136: 217–231. <https://doi.org/10.1007/s10584-016-1604-6>.
- Kyle, Page, and Son H. Kim. 2011. "Long-Term Implications of Alternative Light-Duty Vehicle Technologies for Global Greenhouse Gas Emissions and Primary Energy Demands." *Energy Policy* 39 (5): 3012–3024. <https://doi.org/10.1016/j.enpol.2011.03.016>.
- Leeson, D., N. Mac Dowell, N. Shah, C. Petit, and P.S. Fennell. 2017. "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as well as Other High Purity Sources." *International Journal of Greenhouse Gas Control* 61: 71–84. <https://doi.org/10.1016/j.ijggc.2017.03.020>.
- Liu, Yaling, Mohamad Hejazi, Hongyi Li, Xuesong Zhang, and Guoyong Leng. 2018. "A Hydrological Emulator for Global Applications - HE v1.0.0." *Geoscientific Model Development* 11 (3): 1077–1092. <https://doi.org/10.5194/gmd-11-1077-2018>.
- Matar, Walid. 2016. "The KAPSARC Energy Model (KEM) for Saudi Arabia." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). <https://doi.org/10.13140/RG.2.2.19405.33768>.
- Meinshausen, Malte, S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J-F. Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. Thomson, G. J. M. Velders, and D.P. P. van Vuuren. 2011. "The RCP Greenhouse Gas Concentrations and their Extensions from 1765 to 2300." *Climatic Change* 109: 213. <https://doi.org/10.1007/s10584-011-0156-z>.

Multsch, S., Y. A. Al-Rumaikhani, H.-G. Frede, and L. Breuer. 2013. "A Site-specific Agricultural Water Requirement and Footprint Estimator (SPARE:WATER 1.0)." *Geoscientific Model Development* 6 (4): 1043–1059. <https://doi.org/10.5194/gmd-6-1043-2013>.

Muratori, Matteo, Steven J. Smith, Page Kyle, Robert Link, Bryan K. Mignone, and Haroon S. Kheshgi. 2017. "Role of the Freight Sector in Future Climate Change Mitigation Scenarios." *Environmental Science & Technology* 51 (6): 3526–3533. <https://doi.org/10.1021/acs.est.6b04515>.

NREL. 2024. *Electricity Annual Technology Baseline (ATB) Data*. <https://atb.nrel.gov/electricity/2024/data>.

O'Neill, Brian C., Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. van Ruijven, et al. 2017. "The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century." *Global Environmental Change* 42: 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>.

Riahi, Keywan, Detlef van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir KC, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, and Kristie Ebi. 2017. "The Shared Socioeconomic Pathways and their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42: 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>.

Rogner, H-H. 1997. "An Assessment of World Hydrogen Resources." *Annual Review of Environment and Resources* 22: 217–262. <https://doi.org/10.1146/annurev.energy.22.1.217>.

SAMA. 2025. *Saudi Central Bank Portal for Open Data*. <https://www.sama.gov.sa/en-US/EconomicReports/pages/database.aspx>.

Samir, KC, and Wolfgang Lutz. 2017. "The Human Core of the Shared Socioeconomic Pathways: Population Scenarios by Age, Sex and Level of Education for All Countries to 2100." *Global Environmental Change* 181–192. <https://doi.org/10.1016/j.gloenvcha.2014.06.004>.

Saudi Electricity Regulatory Authority (SERA). 2024. *Annual Statistical Booklet for Electricity*. <https://www.sera.gov.sa/-/media/2edc2790b86043c9abb618796e94e285.ashx>.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. "Global Food Demand and the Sustainable Intensification of Agriculture." *Proceedings of the National Academy of Sciences* 108 (50). 20260–20264. <https://doi.org/10.1073/pnas.1116437108>.

Turner, Sean W. D., Mohamad Hejazi, Catherine Yonkofski, Son Kim, and Page Kyle. 2019. "Influence of Groundwater Extraction Costs and Resource Depletion Limits on Simulated Global Nonrenewable Water Withdrawals over the Twenty-First Century." *Earth's Future* 7: 123–135. <https://doi.org/10.1029/2018EF001105>.

van Ruijven, Bas J., Detlef P. van Vuuren, Willem Boskaljon, Maarten L. Neelis, Deger Saygin, and Martin K. Patel. 2016. "Long-Term Model-Based Projections of Energy Use and CO₂ Emissions from the Global Steel and Cement Industries." *Resources, Conservation and Recycling* 112: 15–36. <https://doi.org/10.1016/j.resconrec.2016.04.016>.

Wise, Marshall, Katherine Calvin, Allison Thomson, Leon Clarke, Benjamin Bond-Lamberty, Ronald Sands, Steven J. Smith, Anthony Janetos, and James Edmonds. 2009. "Implications of Limiting CO₂ Concentrations for Land Use and Energy." *Science* 324 (5931): 1183–1186. <https://doi.org/10.1126/science.1168475>.

Xu, Xun, Puneet Kamboj, Saif Almutairi, Thomas Gertin, Anvita Arora, and Mohamad Hejazi. 'Decarbonizing Road Freight Transportation in Saudi Arabia.' 2025. Riyadh: King Abdullah Petroleum Studies and Research Center. <https://doi.org/10.30573/KS-2025-DP10>.

Yao, Yuan, John Marano, William R. Morrow III, and Eric Masanet. 2018. "Quantifying Carbon Capture Potential and Cost of Carbon Capture Technology Application in the U.S. Refining Industry." *International Journal of Greenhouse Gas Control* 74: 87–98. <https://doi.org/10.1016/j.ijggc.2018.04.020>.

Appendix

Key Assumptions for GCAM-KSA

Table A1. Socioeconomic assumptions for Saudi Arabia in GCAM-KSA.

Variable	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	Units
GDP per capita	120,690	118,466	132,117	141,637	150,713	159,344	167,472	175,145	182,264	188,920	2023 SAR
Population	29.82	31.55	36.01	39.75	43.25	46.36	49.21	51.98	54.71	57.41	Million

Source: For population, calibrated to historical numbers as per Saudi Arabia Census 2022; future projection in the short-term aligned with IMF projections until 2030, and in the long-term aligned with the UN population's medium-scenario growth rate estimates for Saudi Arabia.

Table A2.1. Cost Assumptions for electricity generation technologies.

Capital cost and O&M fixed cost (CAPEX and OPEX) – 2022 US\$/kW									
Technology		2025	2030	2035	2040	2045	2050	2055	2060
Gas – single cycle	CAPEX	1,102.60	1,058.30	1,014.10	969.80	925.50	881.30	837.30	793.30
	OPEX	9.80	8.80	7.70	6.80	6.10	5.30	6.40	5.40
Gas – combined cycle	CAPEX	1,011.80	960.10	906.20	857.30	811.80	766.20	720.80	675.50
	OPEX	13.60	12.20	10.60	9.40	8.40	7.40	6.40	5.40
Gas-combined cycle with CCS	CAPEX	2,966.30	2,722.60	2,468.70	2,298.50	2,184.30	2,070.10	1,956.00	1,841.90
	OPEX	69.00	68.00	64.00	64.00	64.00	64.00	64.00	64.00
Solar PV	CAPEX	1,067.60	819.60	544.60	413.10	377.20	341.40	305.50	269.70
	OPEX	21.30	17.80	14.50	12.80	12.30	11.90	11.40	10.90
Solar CSP	CAPEX	6,210.50	4,736.70	4,014.60	3,793.50	3,572.50	3,351.40	3,130.30	2,909.30
	OPEX	65.30	55.70	51.80	51.80	51.80	51.80	50.30	47.80
Wind – onshore	CAPEX	1,484.30	1,251.90	1,147.50	1,080.80	1,014.00	947.30	880.40	813.30
	OPEX	28.80	25.20	22.50	20.40	18.30	16.30	13.70	10.80
Wind – offshore	CAPEX	4,625.60	4,042.60	3,838.40	3,698.60	3,592.00	3,505.70	3,427.70	3,350.90
	OPEX	83.50	75.10	70.10	66.40	63.60	61.20	59.10	57.10
Geothermal	CAPEX	8,880.90	7,980.50	7,377.90	7,081.10	6,905.80	6,734.90	6,566.50	6,398.10
	OPEX	169.00	169.00	169.00	169.00	169.00	169.00	169.00	169.00
Nuclear	CAPEX	5,324.00	4,740.80	4,581.50	4,426.90	4,275.50	4,115.50	3,888.80	3,643.10
	OPEX	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: NREL (2024) ATB database.

Table A2.2. O&M variable cost assumption for electricity technologies.

O&M variable cost – 2022 US\$/MWh	
Technology	US\$/MWh
Gas – single cycle	4.00
Gas – combined cycle	2.00
Gas – combined cycle with CCS	6.00
Nuclear	5.00

Source: NREL (2024) ATB database.

Table A2.3. Lifetime, efficiency, and capacity factor assumptions for electricity technologies.

Technology	Lifetime (years)	Efficiency	Capacity Factor
Gas – single cycle	25	38%	85%
Gas – combined cycle	25	45%	85%
Gas – combined cycle with CCS	25	45%	85%
Solar PV	25	-	25%
Solar CSP	25	-	25%
Wind – onshore	25	-	30%
Wind – offshore	25	-	45%
Geothermal	25	10%	90%
Nuclear	50	33%	90%

Table A3. Key assumptions for the building sector.

	2020	2025	2030	2035	2040	2045	2050	2055	2060	Units
Residential cooling	2.53	2.57	2.68	2.78	2.89	3.00	3.11	3.23	3.35	COP (unitless)
Commercial cooling	2.62	2.67	2.78	2.89	3.00	3.11	3.23	3.35	3.47	COP (unitless)
Residential shell conductance	1.14	1.12	1.09	1.06	1.03	1.00	0.98	0.95	0.92	watt per m2
Commercial shell conductance	1.15	1.13	1.10	1.08	1.05	1.02	1.00	0.97	0.95	watt per m2

Table A4.1. Assumption for non-energy cost (2022 US\$/vkm) for different modes and technologies for Saudi Arabia.

Mode	Technology	2025	2030	2040	2060
Passenger rail	Electric	28.70	28.70	28.70	28.69
	Liquid fuel	38.37	38.37	38.36	38.35
Bus	BEV	4.00	3.76	3.34	2.91
	FCEV	6.09	5.28	3.97	2.96
	ICE hybrid	3.02	3.02	3.00	2.99
	ICE	2.99	2.95	2.96	2.98
2W and 3W	BEV	0.11	0.11	0.11	0.11
	ICE	0.11	0.11	0.11	0.11
Car	BEV	0.57	0.55	0.52	0.51
	FCEV	0.66	0.63	0.57	0.56
	ICE hybrid	0.54	0.55	0.57	0.58
	ICE	0.51	0.52	0.54	0.57
Large car and truck	BEV	1.02	1.00	0.96	0.95
	FCEV	1.14	1.11	1.04	0.98
	ICE hybrid	0.99	1.00	1.00	1.01
	ICE	0.93	0.94	0.96	0.98
Mini car	BEV	0.24	0.21	0.20	0.20
	FCEV	0.30	0.27	0.21	0.21
	ICE hybrid	0.22	0.22	0.22	0.23
	ICE	0.21	0.21	0.21	0.22
Freight Rail	Electric	27.63	27.63	27.63	27.63
	Liquid Fuel	50.55	50.89	50.87	50.85
Heavy truck	BEV	2.73	2.13	1.30	0.76
	FCEV	1.76	1.51	1.12	0.79
	ICE hybrid	1.07	1.03	0.95	0.86
	ICE	0.78	0.76	0.72	0.67
Light truck	BEV	0.50	0.47	0.43	0.40
	FCEV	0.55	0.51	0.43	0.40
	ICE hybrid	0.49	0.46	0.44	0.41
	ICE	0.48	0.47	0.44	0.41
Medium truck	BEV	0.95	0.86	0.71	0.66
	FCEV	0.88	0.82	0.72	0.67
	ICE hybrid	0.79	0.75	0.70	0.64
	ICE	0.75	0.73	0.69	0.64

Source: NREL (2024) ATB database.

Table A4.2. Assumption for fuel efficiency improvements for key transport modes for Saudi Arabia (MJ per vehicle km).

Mini car	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
ICE	3.65	3.33	3.05	2.79	2.48	2.36	2.26	2.16	2.07	1.98
BEV	0.63	0.64	0.64	0.64	0.58	0.56	0.54	0.51	0.49	0.47
FCEV	1.33	1.31	1.29	1.27	1.19	1.17	1.14	1.12	1.10	1.07
ICE hybrids	3.68	3.26	2.89	2.56	2.35	2.24	2.15	2.06	1.98	1.89
Large car and SUV	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
ICE	5.36	4.82	4.33	3.90	3.57	3.42	3.28	3.16	3.03	2.92
BEV	0.99	0.99	0.99	0.99	0.87	0.84	0.82	0.79	0.76	0.73
FCEV	2.03	2.00	1.96	1.93	1.83	1.78	1.74	1.70	1.66	1.63
ICE hybrids	5.27	4.63	4.08	3.59	3.31	3.18	3.05	2.94	2.83	2.72
Car	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
ICE	4.64	4.15	3.71	3.32	3.05	2.92	2.80	2.69	2.59	2.48
BEV	0.81	0.81	0.81	0.81	0.72	0.70	0.68	0.66	0.64	0.62
FCEV	1.80	1.73	1.66	1.60	1.51	1.47	1.44	1.42	1.39	1.36
ICE hybrids	4.25	3.81	3.42	3.06	2.81	2.68	2.56	2.45	2.35	2.25
Buses	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
BEV	5.13	4.70	4.31	3.95	3.59	3.46	3.32	3.19	3.06	2.93
Diesel	12.73	11.73	10.81	9.96	9.29	9.03	8.79	8.56	8.34	8.12
Hybrids	12.31	11.26	10.29	9.41	8.60	8.30	8.02	7.75	7.50	7.25
FCEV	10.22	9.19	8.26	7.43	6.74	6.41	6.11	5.84	5.58	5.33
Light truck	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
BEV	1.88	1.74	1.61	1.49	1.37	1.32	1.27	1.22	1.17	1.13
ICE	7.06	6.52	6.02	5.56	5.21	5.06	4.92	4.78	4.65	4.52
ICE hybrids	5.20	4.73	4.30	3.91	3.57	3.43	3.31	3.19	3.08	2.98
FCEV	3.40	3.12	2.86	2.62	2.44	2.34	2.26	2.18	2.10	2.03
Medium truck	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
BEV	3.26	3.03	2.81	2.61	2.40	2.31	2.22	2.13	2.05	1.96
ICE	9.36	8.67	8.03	7.44	7.00	6.81	6.63	6.46	6.30	6.13
ICE hybrids	9.37	8.47	7.66	6.92	6.34	6.04	5.78	5.53	5.30	5.08
FCEV	5.94	5.46	5.01	4.61	4.28	4.10	3.94	3.80	3.65	3.51
Heavy truck	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
BEV	5.80	5.34	4.91	4.52	4.12	3.97	3.81	3.65	3.50	3.35
ICE	14.97	13.82	12.76	11.78	11.03	10.65	10.30	9.97	9.65	9.34
ICE hybrids	14.48	13.15	11.94	10.84	9.98	9.53	9.13	8.75	8.40	8.05
FCEV	11.21	10.16	9.21	8.34	7.64	7.28	6.96	6.66	6.38	6.11

Table A4.3. Assumptions for annual vehicle kms (vkm) traveled by different modes.

Mode	Annual VKM (km)	Source
All cars	25,300	Alwosheel and Dua (2023)
Buses	26,886	Assumed same as medium trucks
Light truck	30,683	Xu et al. (2025)
Medium truck	26,886	Xu et al. (2025)
Heavy truck	45,574	Xu et al. (2025)

About the Authors



Puneet Kamboj

Puneet Kamboj is a Lead in KAPSARC's Climate and Sustainability team, specializing in scenario analysis and deep decarbonization pathways. He brings over a decade of specialized experience in policy research, focusing on climate change mitigation, clean energy technologies, and the power sector. Before his tenure at KAPSARC, Puneet worked in India with multiple reputed global policy research institutions, where he engaged and advised stakeholders, including government, industry, and academia. Puneet has a rich portfolio of published papers, policy briefs, and reports. He also contributed to the Brookings Institution's anthology on India's coal sector. Puneet holds an M.Tech in Renewable Energy from TERI University, New Delhi, and an MBA in Power Management from UPES, Dehradun.



Yang Qiu

Yang Qiu is a Postdoctoral Researcher at the Pacific Northwest National Laboratory (PNNL). Yang has a Ph.D. in Environmental Science and Management from the University of California, Santa Barbara, two M.S. degrees – first in Applied Statistics from the Syracuse University, and second in Environment Science from the State University of New York College of Environmental Science and Forestry – and a B.S. in Forestry from the Beijing Forestry University.



Neal Graham

Neal Graham is an Earth Scientist at the Joint Global Change Research Institute in College Park, MD. His research interests include human-water system interactions and short- and long-term multisectoral impacts on the Human-Earth system. Neal holds a BS in Meteorology from Rutgers University and an MS and Ph.D. in Atmospheric and Oceanic Sciences from the University of Maryland.



Page Kyle

Page Kyle is an Earth Scientist at the Joint Global Change Research Institute, where he has been a developer for the Global Change Analysis Model since 2006. He has authored over 100 peer-reviewed journal articles on a variety of topics, including energy supply and demand, agriculture, land use, water, the atmosphere, climate change, and the interactions therein. He received a bachelor's degree from Dartmouth College, and a master's degree from Utah State University.



Raphael Apeaning

Raphael Apeaning is a Lead Researcher in the Climate and Sustainability Program at KAPSARC and an integrated assessment modeler with expertise in energy transition strategies and policy. Prior to joining KAPSARC, he was a Researcher at the Institute for Responsible Carbon Removal in Washington, DC, where he contributed to expanding the portfolio of carbon dioxide removal technologies for climate modeling and to developing market mechanisms for negative emission technologies.



Gokul Iyer

Gokul Iyer is an Earth Scientist at the Joint Global Change Research Institute (JGCRI), a partnership between Pacific Northwest National Laboratory (PNNL) and the University of Maryland. Gokul is a team leader for the Human-Earth Systems Science: Analysis team within JGCRI and has over a decade's worth of experience in integrated modeling of energy, economy, climate, water, agriculture, and land systems at global to national to subnational scales. Gokul has published over 70 peer-reviewed publications with more than a dozen in top journals, and was also a contributing author to the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC). Gokul has a Ph.D. in Environmental Policy from the University of Maryland, a master's degree in Energy Systems Engineering from Indian Institute of Technology – Bombay, and a bachelor's degree in Electrical and Electronics Engineering from the Visvesvaraya National Institute of Technology – Nagpur.



Mohamad Hejazi

Mohamad Hejazi is the Executive Director of Climate and Sustainability at KAPSARC, leading research on climate change adaptation and mitigation, scenario analysis and decarbonization pathways, integrated assessment modeling, and the energy-water-land nexus. With more than 100 journal publications, he has contributed to major projects with organizations including the World Bank, NASA, and the U.S. Department of Energy. Previously, he was a Senior Research Scientist at Pacific Northwest National Laboratory. He holds a Ph.D. from the University of Illinois at Urbana-Champaign and is contributing to major climate assessments, including the IPCC AR6 report.

About the Project

This study is part of the Climate Adaptation and Mitigation Partnership (CAMP) project. The CAMP project is both timely and crucial for Saudi Arabia, given the mounting risks associated with climate change impacts, the urgency of advancing toward a low-carbon future while maintaining national economic growth, and the potential economic ramifications of global mitigation efforts on the Saudi energy sector and economy. Against this backdrop, the project investigates (i) the climate conditions in Saudi Arabia, (ii) the sectoral impacts and the role of adaptation measures, and (iii) the pathways for the Saudi economy to achieve a low-carbon future or climate neutrality by midcentury. The study will also adopt the circular carbon economy concept in characterizing the Saudi government's efforts to decarbonize the economy while supporting continued growth.

