King Abdullah Petroleum Studies and Research Center

Discussion Paper

Saudi Arabia Net Zero GHG Emissions by 2060

Transformation of the Electricity Sector

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Abstract

Under its Vision 2030 targets, Saudi Arabia is working to steer the nation toward a sustainable future. The Kingdom has recently amplified its sustainability goals, announcing its intention to achieve net zero greenhouse gas (GHG) emissions by 2060. As part of this renewed commitment, Saudi Arabia aims to have 50% of its electricity capacity from renewable sources by 2030. This pledge reflects the country's strategic move toward a greener and more sustainable energy landscape.

In this study, we use an integrated assessment modeling (IAM) framework to assess the long-term impact of Saudi Arabia's commitment to reach net zero GHG emissions by 2060 on the power sector. The modeling framework uses the levelized cost of electricity as the main driver for deploying different generation technologies in the absence of a typical season/daily demand curve. Hence, this paper aims to assess the long-term critical transformational impact of different decarbonization pathways on the power sector in Saudi Arabia.

Keywords: Net Zero, GHG emissions, Saudi Arabia, GCAM-KSA, Scenario Analysis, Climate Change, Power Sector, Renewable Energy

Introduction: Saudi Arabia's Electricity Sector and Sustainability Initiatives

Saudi Arabia's electricity sector is critical to the nation's bustling economy. Endowed with rich oil and gas reserves, Saudi Arabia is a prominent player in the region's electricity production, with an installed capacity of approximately 90 GW in 2020 (WERA Annual Statistics 2020). Nearly 55% of this capacity is relatively new, installed within the past decade. The Saudi Electricity Company (SEC) is the nation's primary electricity producer and distributor. It operates under Water and Electricity Regulatory Authority (WERA) supervision, ensuring the industry aligns with the nation's interests. The National Grid SA, under SEC's aegis, guarantees stability and interconnectedness across Saudi Arabia.

Historically, Saudi Arabia has heavily relied on fossil fuels for electricity generation. By 2019, natural gas constituted 57% of electricity generation, marking a considerable increase from 34% in 2010. The remainder was generated from liquid fuels, with crude and heavy fuel oil each accounting for 20% and diesel contributing 3% (Elshurafa et al. 2021). However, this reliance on fossil fuels in the power sector has led to a significant environmental impact, with 44% of Saudi Arabia's CO_2 emissions in 2016 stemming from electricity generation, including desalination (Saudi Arabia 2022).

To address these challenges, Saudi Arabia launched Vision 2030, an ambitious plan to steer the nation toward a sustainable future. The Kingdom has recently introduced its sustainability goals, announcing its intention to achieve net zero greenhouse gas (GHG) emissions by 2060 (Saudi Vision 2016). As part of this renewed commitment, Saudi Arabia aims to build 50% of its electricity capacity from renewable sources by 2030 (Saudi Gazette 2020). This pledge reflects the country's strategic move toward a greener and more sustainable energy landscape.

A vital component of reaching net zero GHG emissions involves transforming the electricity sector toward cleaner sources of generation (Kamboj et al. 2023). However, the path toward a sustainable future presents numerous challenges. The technological complexities of constructing a green power infrastructure, significant capital investment requirements, and issues related to energy storage and grid stability represent substantial obstacles to be overcome. A few studies have assessed the impact of various policies on Saudi Arabia's power sector expansion in a relatively short time horizon. For example, Elshurafa et al. (2021) evaluated the effects of renewable deployment on Saudi Arabia's emissions from the power sector until 2040. These studies have used different capacity expansion models with a high special and temporal resolution suitable to find the optimal power plant mix to meet future electricity demand, considering costs, regulations and grid reliability. However, there is still a gap in understanding the long-term implications for Saudi Arabia's power sector in reaching net zero GHG emissions by 2060.

In this study, we use an integrated assessment modeling (IAM) framework to assess the long-term impact of Saudi Arabia's commitment to reach net zero GHG emissions by 2060 on the power sector. Using an IAM provides a more holistic perspective by exploring the interactions between electricity and other end-use and economic sectors. They have lower spatial and temporal resolution, focusing more on long-term dynamics and interactions. The following sections of the paper briefly define the modeling framework for the Saudi Arabia version of the Global Change Analysis Model (GCAM-KSA), the methodology for the electricity sector, the scenario framework, assumptions, results and a discussion of key takeaways.

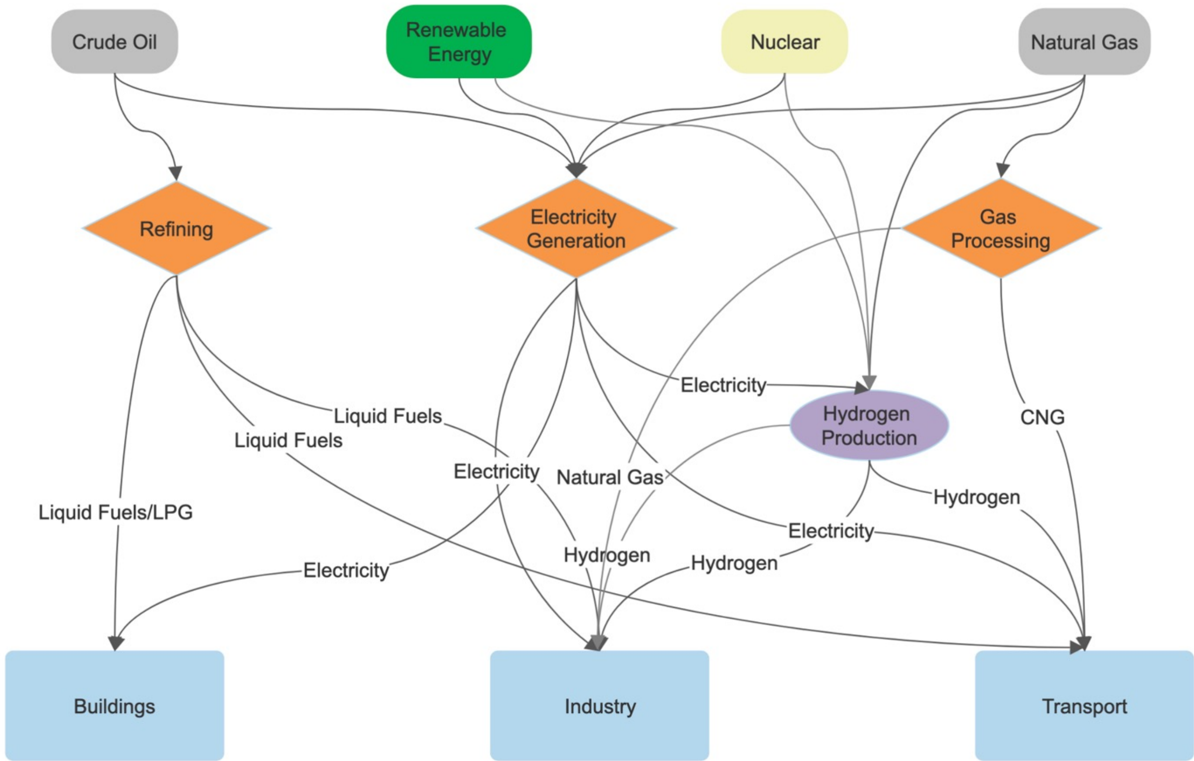
GCAM-KSA: Methodology and Scenario Framework

We use a modified version of the Global Change Analysis Model (GCAM v6.0), an integrated assessment model representing the behavior and interactions between the energy system, water, agriculture and land use, the economy and the climate (Calvin et al. 2019, 677-698). GCAM is an open-source community tool that has been utilized to support policymakers for over 30 years analytically and is documented through hundreds of peer-reviewed publications (Edmonds & Reilly 1983; Kim et al. 2006; Calvin et al. 2019, 677-698). For example, GCAM was the primary model for developing scenarios for the U.S. Mid-Century Strategy and supporting the State Department during the Paris Negotiations (U.S. Mid-Century Strategy 2021). GCAM was also one of the core models utilized in China's recent carbon neutrality report (Energy Foundation China, 2020).

For this study, we have separated the Kingdom of Saudi Arabia (KSA) as a separate energy-economy region, i.e., GCAM-KSA includes 33 energy-economy regions (32 original regions plus KSA). GCAM-KSA operates in five-year time-steps from 2015 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various markets in each time period. GCAM-KSA is a dynamic recursive model. Hence, solutions for each modeling period depend largely on conditions in the current modeling period. GCAM-KSA tracks emissions of 24 gases, including GHGs (i.e., CO_2, N_2O, CH_4, F-gases), short-lived species, and ozone precursors, endogenously based on the resulting energy, agriculture, land use and water systems.

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

Figure 1. Schematic of Energy System for Saudi Arabia in GCAM-KSA.



Note: CNG stands for compressed natural gas, and LPG stands for liquified petroleum gas. For more detailed structure and methodology of the end-use sectors, please refer to the series of sectoral papers from GCAM-KSA v1.0 (Kamboj, et al. 2023).

GCAM-KSA's electricity sector models electricity supply and demand annually, solving for the market equilibrium price where electricity supply equals evolving annual demands across building, industry and transportation end-use sectors dynamically. GCAM-KSA represents converting six primary energy carriers (natural gas, liquid fuels, nuclear, wind, solar and geothermal) into electricity for Saudi Arabia, with multiple power plant technologies represented for most fuels. Carbon capture and storage (CCS), combined with natural gas power plants, is a future technology for Saudi Arabia. Power sector technologies are vintage, with 20-50 years of technical lifetime. Investment in new capacity is determined based on relative levelized costs of electricity (inclusive of a range of costs — capital, fixed operation and maintenance, variable operation and maintenance, fuel, cooling water and policy — or subsidies) using GCAM's probabilistic (logit-based) choice function. Once invested, technology continues to operate until the end of its technical lifetime unless it becomes sufficiently unprofitable (i.e., variable costs such as fuel, water and emissions penalties exceed revenues) to merit premature retirement. The logit-based choice function is well-established for modeling multiple alternatives with a distribution of attributes competing for market share and helps avoid a winner-takes-all response.

The deployment of technologies primarily but not exclusively depends on relative costs. For example, electricity demand can be satisfied by solar, wind, combined-cycle natural gas-fired power plants or other technologies. GCAM-KSA calculates market shares for each technology based primarily on the cost of providing electricity with each technology.

However, in the real world, costs are not uniform within a country or region, and factors other than direct costs, e.g., local regulatory costs, variation in input costs within a region, unavailability of specific technology in regions, etc., can influence the choice between economic substitutes. It is accounted for by using a probabilistic choice function designed to represent decision-making among competing options when only some characteristics can be observed (Clarke and Edmonds 1993, 123-129). The following choice function reflects that the single best choice does not capture the entire market. A variety of factors not captured in the model, such as individual preferences, local variations in cost and simple happenstance, cause some of the market share to go to alternatives that, based on their indicator alone, are theoretically inferior choices.

$$s_i = \frac{\alpha_i \exp(\beta p_i)}{\Sigma_{j=1}^{N} \alpha_j (\beta p_j)}$$

In the above expression, s is the market share of technology, p is the cost of technology, β is the logit coefficient, which determines how large a cost is needed to produce a given difference in the market share of generation technology, and α is the share weight. Share weights serve two purposes in the model. First, they are used to calibrate the model to observe historical values. This calibration procedure absorbs regionally specific preferences for choice alternatives (arising, for example, from societal preferences, existing infrastructure, barriers to market entry, or the like) into the share weight parameters. For instance, Saudi Arabia aims to achieve half of its generation capacity as renewable energy and the remaining half as natural gas power plants by 2030. Share weights are also used to allow new technologies to be phased in gradually.
Exogenous socioeconomic drivers (population and GDP) set the initial trajectory for energy service demands in building, industry and transportation end-use sectors (GCAM v6.0 Documentation, 2022). The demands vary endogenously in scenarios according to price and income elasticities. Each of the sectors in the model has a detailed technology representation, and each technology competes for market share based on the technology's levelized cost. The cost of technology in any time period depends on three components:

1. Exogenous assumption of non-energy cost includes overnight capital cost amortized over the lifetime of technology, fixed and variable operations and maintenance costs.

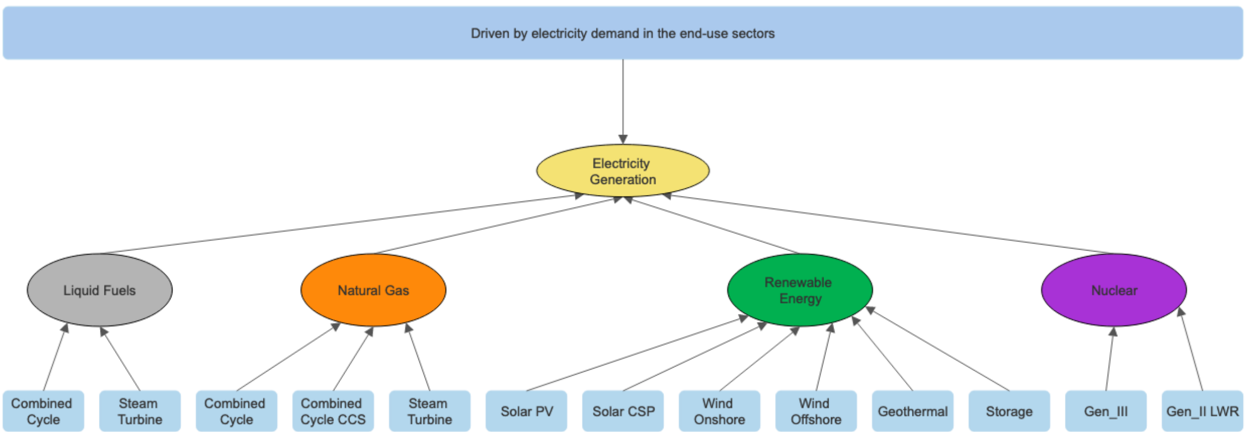
2. Fuel costs where historical prices are calibrated to the actual prices in Saudi Arabia based on the respective scenario, and the future price trajectory is endogenously determined by the model.

3. Cost of emissions in terms of a carbon price as determined by defined climate policy.

Figure 2 shows the structure of the electricity generation sector for Saudi Arabia in GCAM-KSA. For the electricity generation from different energy carriers, the levelized cost of electricity (LCOE expressed in \$/MWh) is estimated as

$$LCOE = \frac{C_f}{\eta} + \frac{1000 * C_I}{8766 * CF} * i + \frac{C_{O\&Mfix}}{8766 * CF} + C_{O\&Mvar}$$

Figure 2. Structure of the electricity sector for Saudi Arabia in GCAM-KSA.



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 8,766 hours in a year;
i is the fixed charge rate defined as the percentage of the total plant cost required over the 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.

The cost of individual technologies in the power sector includes amortized capital costs, operation and maintenance, and fuel costs, which are endogenously estimated based on the fuel supply curves for the region. In GCAM-KSA, the fossil fuel resource curves are represented at the national level based on the assessment of global hydrocarbon resources (Rogner 1997, 217-262). Distinct from generation technologies reliant on exhaustible resources, renewable energy technologies lack fuel-associated costs. However, they incorporate escalating costs contingent on resource curves, primarily because the most economically efficient resources are prioritized (Iyer et al. 2019; Zhou et al. 2012, 7857-7864). It is postulated that the incremental costs pertinent to large-scale solar technologies do not surge in tandem with deployment scales. Moreover, renewable energy systems devoid of storage components factor in intermittency costs. These costs mirror the diminishing returns to electrical capacity reserves as the proportion of intermittent technologies in the power grid increases (GCAM v6.0 Documentation 2022).

Currently, the contribution of renewable energy to electricity generation in the Kingdom is minimal. Nevertheless, numerous projects are at different phases of development, spanning from initial announcements to active construction. Due to the lack of specific cost data related to these projects in Saudi Arabia, technological progress within the model is depicted through exogenously decreasing costs over time. For this research, we sourced future cost projections from the National Renewable Energy Laboratory (NREL)'s 2022 Annual Technology Baseline database, referencing their median scenario (NREL 2022). It is worth noting that these global cost estimations might not accurately capture the actual project expenses in Saudi Arabia.
Each technological solution possesses a designated lifespan, and upon capital allocation, these technologies are operational until they reach the end of their lifespan. They may also be decommissioned if the operational cost surpasses the market price, which is intrinsically determined by the model. A comprehensive catalog of these technologies, along with their associated cost assumptions, can be found in Appendix 1, Table A1.1.

Scenario Framework and Critical Assumptions

This study considers four scenarios out to 2060 using GCAM-KSA. The design of these scenarios is aimed at capturing plausible long-term impacts of various policies and mitigation efforts on Saudi Arabia's energy system. For all the scenarios, we assume a growing economy and an increasing population, with per capita income reaching USD 37,000 (2020 prices) in 2060 and a 60 million total population. We include the impact of COVID-19 on the GDP growth rate in 2020 and the recovery thereafter in 2025 as per the International Monetary Fund (IMF) projections (IMF 2023). The population and GDP growth rate thereafter aligns with the Shared Socioeconomic Pathways - Middle of the Road (SSP2) assumptions for the growth rate from the shared socioeconomic pathways database (Fricko et al. 2017, 251-267). Saudi Arabia-specific critical policies and mitigation targets that are used to characterize the scenarios in this study are:

- *No Policy* scenario is a counterfactual scenario where we assume no specific climate mitigation target, i.e., no nationally determined contribution (NDC) target. This scenario does not account for the recent policy-driven mitigation efforts of energy efficiency gains and price reforms in the end-use sectors. This scenario does not consider support for low-carbon technologies, and traditional hydrocarbons drive future development.

- *Current Policy*[1] scenario considers the gains of various energy efficiency measures taken by SEEC and the two rounds of energy price reforms conducted in 2016 and 2018 in the country. This scenario also considers fulfilling the target of equal power capacity of renewable and gas-based electricity generation by 2030. No new additional policies are assumed for the remaining decades after 2030.

- *NDCs Continued* scenario applies emissions constraints, in addition to the *Current Policy* scenario, to achieve an emissions reduction of 278 $MtCO_2eq$ by 2030 relative to the *No Policy scenario*. The emissions constraints beyond 2030 reflect the same rate of declining GHG intensity of GDP (4%) achieved from 2020 to 2030 to meet the NDC target.

- *NZ 2060* scenario assumes meeting the NDC target by 2030, as reflected in the *NDCs Continued* scenario, and a linear decline to net zero GHG emissions from 2030 to 2060.

For other model regions except for Saudi Arabia, in the emissions-constrained *NDCs* Continued and *NZ 2060* scenarios, we assume the fulfillment of other regions' NDC and net zero targets as reflected in the NDCs scenario (Iyer et al., 2022, 1129-1135). This assumption includes various countries' commitments during COP 26 and the continued ambition scenario presented by Ou et al. (2021).

Table 1. Scenario design and key assumptions.

Sc.No.	Scenario Name	Policies and mitigation target
1	No Policy	No energy efficiency gains in the end-use sectors
		No energy price reforms, i.e., subsidized fuel prices continue
		No climate mitigation policy, i.e., no NDC target
		No market/support for low-carbon technologies
2	Current Policy	Energy efficiency gains are reflected based on various initiatives by SEEC in the end-use sectors
		Reflects energy price reforms by calibrating the 2020 fuel prices in the model to the actual fuel prices in Saudi Arabia post two rounds of price reforms in 2016 and 2018
		Equal electricity generation capacity of renewable and gas-based plants
3	*NDCs Continued*	Includes the policies from the *Current Policy* scenario and meets NDC target of emissions reduction of 278 $MTCO_2eq$ by 2030 compared to the *No Policy* scenario[2]
		Beyond 2030, continuation of the same declining rate of GHG intensity of the economy as achieved from 2020 to 2030 to meet the NDC target
4	*NZ 2060*	In addition to the *NDCs Continued* scenario, the net GHG emissions beyond 2030 linearly decline to zero by 2060

Results: The Transformation of the Electricity Sector

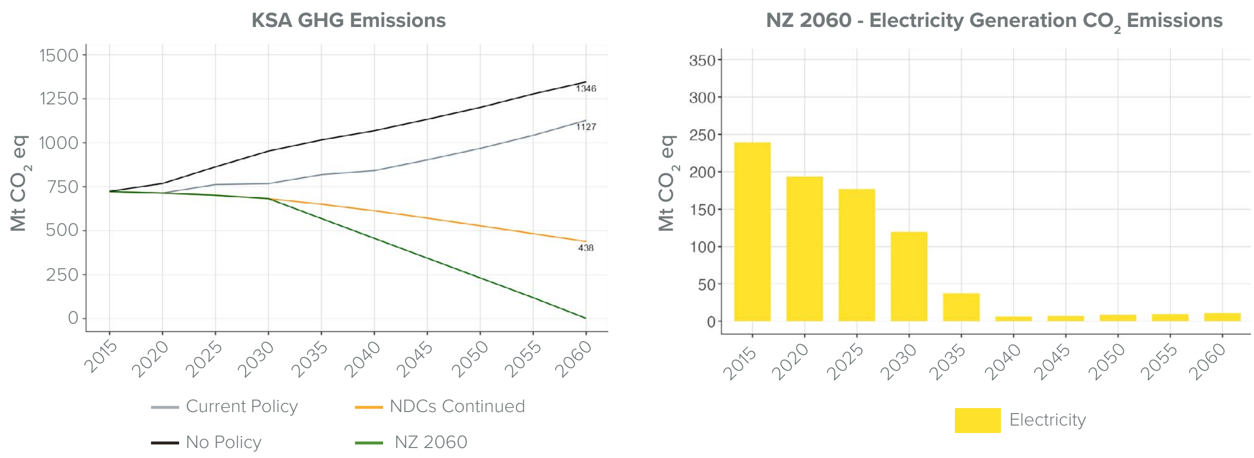
As highlighted earlier, we use an IAM framework that helps understand the long-term implications in the future of the policies implemented today. The modeling framework uses the levelized cost of electricity as the main driver for deploying different generation technologies in the absence of a typical season/daily demand curve. Hence, it is important to note that this paper aims to assess the long-term critical transformational impact of an economy-wide net zero pathway on the power sector in Saudi Arabia purely from an economic perspective (i.e., economic competition) rather than focusing on the technical feasibility of such scenarios from an operational capacity planning perspective.

Decarbonizing the Electricity Sector Is Central to Saudi Arabia's Ambitious Emissions Reduction Goals

In 2021, Saudi Arabia set a target of reducing 278 Mt of GHG emissions by 2030 in its updated NDC target submitted to UNFCCC. Figure 3 shows the modeled GHG emissions in all four scenarios and the breakdown of the sectoral contribution of emissions reduction in achieving the 278 $MtCO_2eq$ reductions (reflected in the *NDCs Continued* and *NZ 2060* scenarios) from the *No Policy* scenario in 2030. In the *No Policy* scenario, electricity generation is mainly driven by hydrocarbons, and our analysis shows that decarbonizing electricity generation can roughly contribute up to 55% of the NDC emissions reduction target by 2030.

This early decarbonization ensures a significant impact in the long term as it allows for a gradual and more manageable shift away from fossil fuels, providing ample time for the necessary infrastructure and policy changes required to decarbonize the other sectors. This early momentum of reducing emissions from electricity generation would mean that the electricity sector would be the earliest to decarbonize to achieve economy-wide net zero emissions by 2060 (Figure 3). With a decarbonized electricity sector, the electrification of other sectors, notably the transport sector, will have a knock-on effect of decarbonizing these sectors, in line with achieving the overall net zero target within the stipulated timeframe. Furthermore, early decarbonization of the electricity sector can stimulate innovation and the development of new technologies, such as carbon removal technologies, that could accelerate the transition to a carbon-neutral economy. Additionally, the growth of the renewable energy industry can create numerous jobs, fostering economic growth while achieving environmental goals.

Figure 3. Economy-wide modeled GHG emissions across four scenarios and CO_2 emissions from electricity generation in NZ 2060.



Source: Authors analysis based on GCAM-KSA v1.0.

Net Zero Journey Highlights a Massive Surge in Renewable Energy Capacity, Requiring Significant Investments and Grid Upgrades

In the *No Policy* scenario — a situation in which no reforms or climate policies are implemented — electricity generation continues to be dominated by hydrocarbons, with natural gas as the primary generation source. On the other hand, the *Current Policy* scenario, which includes price reforms and a target of achieving 50% renewable generation capacity by 2030, presents a different picture.

Electricity production from liquid fuels is entirely phased out in this scenario, with natural gas continuing to serve as the primary electricity generation source. The proportion of renewable energy generation increases, although it remains relatively low due to the lower capacity factors associated with these sources. Figure 4 shows the electricity generation and the technology mix for the *Current Policy* and *NZ 2060* scenarios.

In the *NDCs Continued* and *NZ 2060* scenarios, the total electricity generated and share of generation from renewable energy sources increase significantly. Particularly in the *NZ 2060* scenario, by 2060, the share of electricity generated from solar photovoltaic (PV) technology escalates to 75% of the total generation as it becomes increasingly cost-effective compared to other zero-carbon technologies. Additionally, electricity production from natural gas plants with CCS capabilities serves as the firm power source in this scenario.

Figure 4. Electricity generation by technology across scenarios.

Source: Authors analysis based on GCAM-KSA v1.0

In the *NZ 2060* scenario, a significant portion of the energy generation is expected to come from renewable resources, substantially increasing the total installed capacity. The installed capacity, which stands at 120 GW in 2030, is projected to expand to over 600 GW by 2060 under this scenario (as depicted in Figure 5). In terms of renewable power additions, this corresponds to an annual increase of 6 GW from 2020 to 2030. This rate escalates to a yearly addition of 16 GW of renewable power post-2030 to meet the net zero target. Putting this in the historical context for a better understanding, from 2010 to 2020, Saudi Arabia added roughly 5 GW of capacity annually; by 2020, the total installed capacity in the Kingdom was 90 GW. Renewables accounted for a negligible share of 341 MW out of the total installed capacity. However, since the announcement of the Saudi Green Initiative, around 11.4 GW of renewable capacity is under various stages of construction and is expected to be connected to the national grid soon.

The steep growth trajectory in capacity requirements implies an investment exceeding $500 billion for adding new capacities from 2030 to 2060. This translates into an annual investment of roughly $17 billion and would require a significant jump in the efforts required. A recent study by Yilmaz et al. (2023) identifies investment gaps based on differences between the required annual investment in the power sector to meet global net zero emissions targets and current investment flows. The study highlights that the investment gaps are particularly large in developing countries where access to conventional finance is already limited (Yilmaz et al. 2023).

Figure 5. Cumulative capacity by technology and the cumulative investment required (2020 USD) for adding new capacity.

Source: Authors analysis based on GCAM-KSA v1.0

As Saudi Arabia progresses toward achieving net zero emissions, the role of renewable energy sources, particularly intermittent ones such as wind and solar, becomes increasingly vital. However, the inherent intermittency of these sources presents a challenge to maintaining grid stability. Strengthening grid infrastructure and investing in energy storage solutions is essential to accommodate a significant share of intermittent renewable generation, ensuring a reliable power supply while progressing toward a sustainable, low-carbon future.

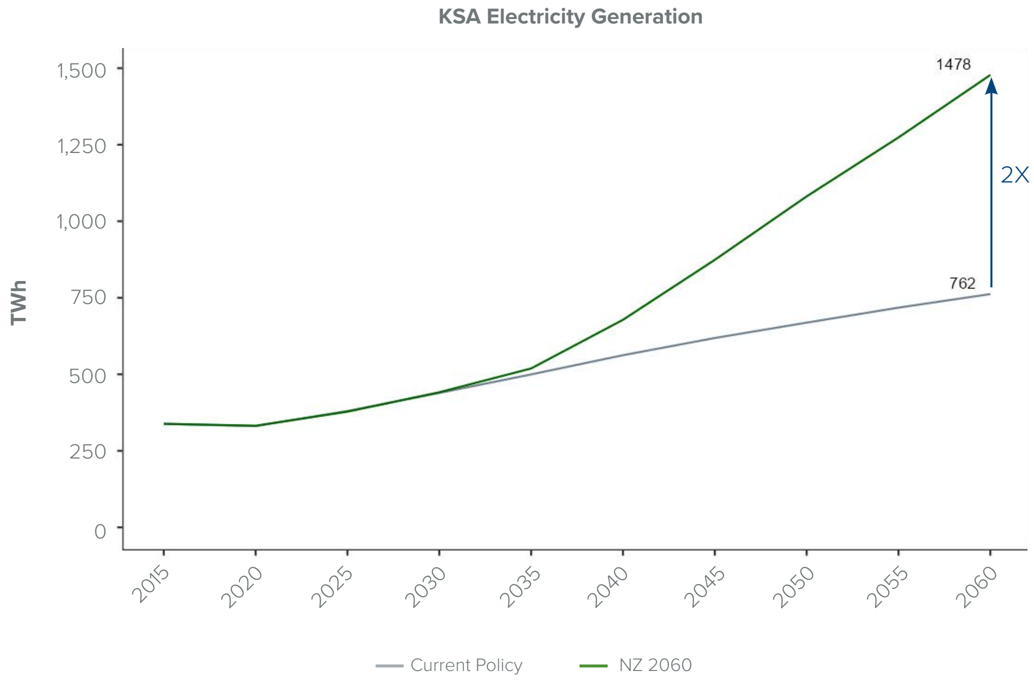
The Need for Carbon Removal Technologies (CDRs) Will Have a Significant Impact on the Electricity Demand To Achieve Net Zero GHG Emissions

In the *NZ 2060* scenario, CDRs are crucial in achieving net zero GHG emissions. Our current modeling framework for Saudi Arabia includes CCS and direct air capture (DAC) as the main technologies for capturing carbon dioxide (CO_2) from the emission sources or the atmosphere and storing it underground. However, the implementation and operation of these technologies are energy-intensive. Relying on these technologies could significantly increase the electricity requirement in Saudi Arabia to achieve net zero GHG emissions. Our analysis shows that in 2060, the electricity requirement in the *NZ 2060* scenario is double compared to the *Current Policy* scenario (Figure 6). A part of this increased requirement is due to the electrification to decarbonize the end-use sectors, and a significant share of this increased demand is due to the need for CDRs to offset emissions.

CCS technology, mainly applied to large-scale power plants, requires substantial energy for capturing, compressing, transporting and storing CO_2. The energy requirement for carbon capture can account for approximately 10-30% of a power plant's output, known as the "energy penalty." This energy penalty increases the overall electricity demand and may necessitate additional power generation capacity. Also, DAC, another promising carbon removal technology, uses chemical processes to capture CO_2 directly from the ambient air. Although it can potentially remove CO_2 irrespective of the source, DAC is currently a highly energy-intensive process. The energy required for DAC is primarily electrical, leading to a significant rise in electricity demand as the technology is scaled up.

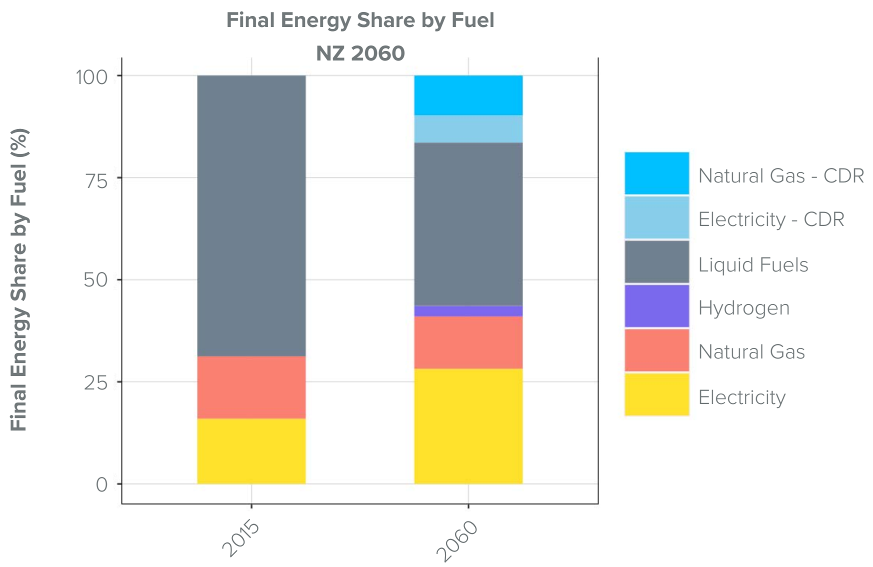
Hence, while carbon removal technologies are crucial in achieving net zero emissions, their energy-intensive nature necessitates first exploiting other carbon offsetting options. By prioritizing other options, Saudi Arabia can achieve immediate and cost-effective emissions reductions, reduce future reliance on carbon removal technologies and deliver additional environmental and social benefits. This integrated approach can enhance the feasibility and sustainability of Saudi Arabia's path to net zero emissions.

Figure 6. Total electricity generation (TWh) for the Current Policy and NZ 2060 scenario.



Source: Authors analysis based on GCAM-KSA v1.0

Figure 7. Modeled final energy by fuel share for the NZ 2060 scenario.



Source: Authors analysis based on GCAM-KSA v1.0

The Way Forward

In the evolution of Saudi Arabia's power sector toward its objective of achieving net zero emissions by 2060, the pivotal significance of delineating the country's energy trajectory becomes evident. This transition, from an erstwhile reliance on hydrocarbons for electricity generation to an emphasis on renewable energy sources, epitomizes the transformative measures essential for realizing a comprehensive net zero economy. Within this energy transition in the Saudi context, the nexus between water resources and electricity generation is accentuated, especially considering the nation's distinctive dependence on desalination processes. The ramifications of this shift in water demands must be rigorously examined..

This transition trajectory is multifaceted. While the ascent of renewable energy forms marks a laudable progression, it simultaneously presents complexities that necessitate judicious navigation by the power sector. The augmentation of renewables demands significant capital allocation toward grid modernization and energy storage solutions, particularly to counteract the intermittency inherent to solar and wind energy sources. The substantial financial requisites of this paradigm shift mandate a diversified portfolio of capital acquisition strategies. Thus, avenues such as foreign direct investments, international synergies and public-private consortiums might become indispensable.

Furthermore, despite their prospective benefits, the onset and emphasis on carbon removal technologies, such as DAC, underscores the energy-intensive nature of such modalities. Clearly, their role in the energy matrix necessitates prudence and a diversified approach to counterbalance residual carbon without imposing undue strain on the power sector. The potential of afforestation, as envisioned by the Saudi Green Initiative, along with alternate strategies such as emissions trading, warrants meticulous exploration to optimize capabilities before a decisive shift toward CDR technologies.

From the vantage point of the power sector, the ambition of net zero emissions transcends mere ecological responsibility: it embodies an economic and infrastructural transformation. This endeavor extends beyond merely reducing the ramifications of climatic shifts, endeavoring instead to instigate innovation, usher in novel market avenues and lay the foundation for a robust, sustainable energy framework.

Saudi Arabia's power sector is at the forefront of this evolution, signaling to economies worldwide that with strategic foresight, investment and commitment, the electricity industry can be the linchpin in the quest for a sustainable future. As the sector continues its transformative journey, it serves as a beacon for other economies, illustrating the tangible possibilities and pathways in the global endeavor to combat climate change.

Endnotes

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

[2] As Saudi Arabia has not officially defined the baseline emissions in their updated NDCs, we have assumed the *No Policy* scenario as the baseline emissions in this study.

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Appendix 1

Table A1.1. Socioeconomic Assumptions.

	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	Units
GDP	2.58	2.46	2.99	3.57	4.23	4.95	5.72	6.55	7.43	8.37	Trillion 2020 SAR
Population	31	35	39	43	46	50	53	56	58	60	million

Table A1.2. Assumed overnight capital costs of different electricity generation technologies for Saudi Arabia in GCAM-KSA, 2020 USD.

Technology	Parameter	Units	2020	2030	2060
Gas_CC	**Capital**	**$/kW**	1036	910	805
Gas_ST	**Capital**	**$/kW**	920	773	674
Gas_CCS	**Capital**	**$/kW**	2709	2061	1492
Liquids_CC	**Capital**	**$/kW**	1263	1263	1263
Liquids_ST	**Capital**	**$/kW**	1263	1263	1263
CSP	**Capital**	**$/kW**	6492	4333	3675
PV	**Capital**	**$/kW**	1331	750	556
Wind	**Capital**	**$/kW**	1459	948	671
Wind_offshore	**Capital**	**$/kW**	3620	2645	2117
Nuclear_Gen_III	**Capital**	**$/kW**	7427	6797	5446
Geothermal	**Capital**	**$/kW**	5794	5219	4418

Table A1.3 Assumed O&M costs of different electricity generation technologies for Saudi Arabia in GCAM-KSA, 2020 USD.

Technology	Parameter	Units	2020	2030	2060
Gas_CC	**Fixed**	**$/kW/year**	28	28	28
	Variable	**$/MWh**	2	2	2
Gas_CCS	**Fixed**	**$/kW/year**	69	64	0
	Variable	**$/MWh**	6	6	0
Liquids_CC	**Fixed**	**$/kW/year**	21	21	21
	Variable	**$/MWh**	3	3	3
Liquids_ST	**Fixed**	**$/kW/year**	25	25	25
	Variable	**$/MWh**	3	3	3
Gas_ST	**Fixed**	**$/kW/year**	21	21	21
	Variable	**$/MWh**	5	5	5
CSP	**Fixed**	**$/kW/year**	66	57	56
	Variable	**$/MWh**	3	3	3

PV	**Fixed**	**$/kW/year**	23	15	12
	Variable	**$/MWh**	0	0	0
Wind	**Fixed**	**$/kW/year**	43	39	30
	Variable	**$/MWh**	0	0	0
Wind_offshore	**Fixed**	**$/kW/year**	111	86	65
	Variable	**$/MWh**	0	0	0
Nuclear_Gen_III	**Fixed**	**$/kW/year**	146	146	146
	Variable	**$/MWh**	3	3	3
Geothermal	**Fixed**	**$/kW/year**	200	200	200
	Variable	**$/MWh**	0	0	0

Table A1.4. Assumed capacity factors and technology lifetime of different electricity generation technologies for Saudi Arabia in GCAM-KSA.

Technology	Capacity Factor	Lifetime
Gas_CC	0.8	35
Gas_ST	0.8	20
Gas_CCS	0.8	35
Liquids_CC	0.8	20
Liquids_ST	0.8	20
CSP	0.3	30
PV	0.25	25
Wind	0.3	25
Wind_offshore	0.4	25
Nuclear_Gen_III	0.9	50
Geothermal	0.9	30

Table A2.1. Modelled electricity generation in TWh by technology across all scenarios.

Scenario	Technology	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Current Policy	CSP	-	-	0	0	0	0	0	0	0	0
	Gas	189	224	258	328	365	373	414	472	554	597
	Liquid Fuels	149	105	86	-	-	-	-	-	-	-
	Nuclear	-	-	-	0	0	0	0	0	0	0
	Other RE	-	-	0	0	0	0	0	1	1	1
	PV	0	1	33	102	123	175	188	182	151	152
	Storage	-	-	-	0	1	1	2	2	3	4
	Wind	-	-	4	9	10	13	14	12	8	8
NDCs Continued	CSP	-	-	0	0	0	0	0	0	0	0
	Gas	189	223	245	289	233	165	103	52	29	15
	Gas_CCS	-	-	0	0	12	40	78	127	183	237
	Liquid Fuels	149	108	88	-	-	-	-	-	-	-
	Nuclear	-	-	-	0	0	0	1	1	2	3
	Other RE	-	-	0	0	1	1	1	1	1	2
	PV	0	1	40	140	240	365	489	604	691	779
	Storage	-	-	-	1	2	4	6	10	16	23
	Wind	-	-	5	12	18	25	31	34	35	35
No Policy	Gas	190	203	239	290	342	407	465	517	573	633
	Liquid Fuels	150	159	179	197	204	192	193	191	181	154
	PV	0	1	4	12	26	53	74	99	129	169
	Storage	-	-	0	0	0	0	0	0	0	0
	Wind	-	-	0	1	2	4	5	7	8	10
NZ 2060	CSP	-	-	0	0	0	0	0	0	0	0
	Gas	189	223	245	289	101	4	2	2	1	0
	Gas_CCS	-	-	0	0	74	124	159	202	247	295
	Liquid Fuels	149	108	88	-	-	-	-	-	-	-
	Nuclear	-	-	-	0	0	1	1	2	3	4
	Other RE	-	-	0	0	1	1	1	2	2	2
	PV	0	1	40	139	318	510	661	815	952	1,096
	Storage	-	-	-	1	2	5	9	14	22	33
	Wind	-	-	5	12	23	33	41	45	47	48

Table A2.2. Modelled GHG emissions for Saudi Arabia.

GHG Emissions ($MtCO_2eq$)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
No Policy	722	768	863	952	1016	1068	1133	1201	1277	1346
Current Policy	722	714	762	767	818	841	903	968	1042	1127
NDCs Continued	722	713	701	681	649	612	571	527	482	437
NZ 2060	722	713	701	681	568	456	343	230	118	0

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About the Project

This study is a part of the Climate Adaptation and Mitigation Partnership (CAMP) project.

The CAMP project is very timely and direly important for Saudi Arabia given the mounting risks associated with climate change impacts, the urgency of pushing toward low carbon futures while maintaining economic growth nationally, and the potential economic ramifications of global mitigation efforts on the Saudi energy sector and economy. Against this backdrop, the CAMP project investigates (1) the climate conditions over Saudi Arabia, (2) the sectoral impacts and the role of adaptation measures, and (3) the pathways of the Saudi economy to achieve low carbon futures or climate neutrality by mid-century. (4) The study will also adopt the circular carbon economy (CCE) concept in characterizing the Saudi government's efforts to decarbonize its own economy while meeting its growth aspirations.

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