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Assessing the Impact of Energy Transition Initiatives on the Policy Cost of Saudi Arabia's Net-Zero Ambition

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ABSTRACT

Saudi Arabia's ambitious goal to achieve a net-zero economy by 2060 offers a unique opportunity to diversify away from fossil fuels while fostering long-term economic resilience and sustainability. Crucial to this transition are energy policies that guide the Kingdom from a fossil fuel-based economy toward carbon neutrality. This study uses GCAM-KSA, a multi-sectoral integrated assessment model tailored to Saudi Arabia's economic and energy systems, to evaluate the impact of early energy transition initiatives on the policy costs of achieving the Kingdom's net-zero target. These initiatives include ongoing and proposed energy efficiency measures, renewable energy deployment, and fuel displacement targets. The study highlights that early implementation of these initiatives can significantly reduce barriers to adopting low-carbon technologies, ultimately lowering the economic burden of achieving the net-zero goal. Compared to a delayed implementation scenario, early action reduces long-term policy costs by 38–72% over the period from 2025 to 2060, driven by accelerated energy system transformation. These findings provide valuable insights into how Saudi Arabia's energy policies can mitigate economic challenges, promote economic diversification, and contribute to global emission reductions, reinforcing the Kingdom's transition to a sustainable net-zero economy.

1. Background and Introduction

The global shift toward a net-zero economy represents an important response to mitigating the adverse impacts of human-induced climate change [1]. Nations across the globe are setting forth ambitious objectives aimed at attaining net-zero emissions within specified timeframes. Currently, countries with net-zero targets cover about 88% of global emissions, 92% of the global Gross Domestic Product and 89% of the global population [2]. Nevertheless, it's imperative to understand that despite these shared aspirations, each country's journey to net-zero is distinct, and the challenges that different countries confront can vary significantly.

The Kingdom of Saudi Arabia (KSA) in 2021 made a significant commitment to combat climate change by setting a target to achieve net-zero greenhouse gas (GHG) emissions by 2060, alongside its National Determined Contribution (NDC) goal of reducing emissions by 278 $MtCO_2e$ by 2030. This dual commitment reflects Saudi Arabia's recognition of the need for transformative action. However, the Kingdom's unique position as a leading global energy exporter, heavily reliant on hydrocarbon revenues, introduces significant economic challenges [3]. Further, recent studies have highlighted that achieving this climate target could represent a substantial financial burden for the Kingdom [4]. Estimates by Durand-Lasserve, [5] suggest Saudi Arabia's net-zero transition could exceed 10–12% of GDP by 2060. Such financial burdens underline the importance of identifying cost-effective strategies to meet these goals.

In addition to these economic challenges, the Kingdom faces transition risks due to its hydrocarbon-dependent economy, which makes it vulnerable to global energy market shifts and declining oil demand. Without proactive mitigation measures, such risks could strain economic growth, fiscal stability, and public welfare [3]. Conversely, Saudi Arabia's strong economic growth, coupled with untapped innovation potential, presents significant opportunities for diversification and resilience [4]. Early and effective energy transition strategies can mitigate these risks while unlocking opportunities for green job creation, economic diversification, and sustainable growth.

The energy sector of Saudi Arabia is currently responsible for nearly 80% of the country's total greenhouse gas emissions [6,7]. The significant emissions from this sector highlight the critical need for transitioning to cleaner energy sources to reach net-zero emissions. To

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navigate the challenges inherent in this energy transition, Saudi Arabia has implemented a range of forward-looking policies. One of the most significant initiatives is the Saudi Vision 2030 plan, which seeks to diversify Saudi Arabia's economy by reducing its dependence on oil and fostering a more resilient economic future [4]. In line with this vision, Saudi Arabia has implemented two notable energy price reforms in 2016 and 2018 [8]. These reforms were aimed at encouraging efficient energy consumption by aligning electricity, gasoline, and diesel prices more closely with international prices [9]. Within this vision, the Kingdom of Saudi Arabia also aims to achieve a power system that comprises 50% renewable technologies and 50% natural gas by 2030.

Saudi Arabia has embraced the Circular Carbon Economy (CCE) approach, aimed at reducing greenhouse gas emissions and driving the energy transition to combat climate change [10]. A core pillar of the CCE approach is to reduce energy demand through efficiency improvements. With this goal, the Saudi Energy Efficiency Program (SEEP) which was initiated in 2012 has played a key role in Saudi Arabia's CCE commitment. SEEP has already made significant strides in promoting efficiency in various sectors like industry, buildings, and transportation [11]. In industry, SEEP focuses on enhancing energy conservation practices in key manufacturing sectors such as iron production, cement factories, and petrochemical facilities. In the building sector, the government has introduced energy efficiency labels, stringent standards, and regulations [12]. Moreover, government buildings are undergoing retrofits to lower energy consumption and emissions [13]. Saudi Arabia has also launched several transportation sector initiatives, including energy efficiency labels for vehicles, tire standards, and the enforcement of Corporate Average Fuel Economy (CAFE) standards [14].

Numerous empirical and modeling studies have investigated the implications of energy transition policies in Saudi Arabia. Table 1 presents a selection of noteworthy journal and report publications about Saudi Arabia's energy transition policies. Empirical studies including [15,16] and [17] have assessed the effects of the energy price reforms (EPR) on various fronts, including energy demand reduction and associated benefits such as emission reduction and welfare gains. In the same vein, studies including [18] and [19] have applied energy and engineering models to gauge the impact of the energy price reforms. Furthermore, insights from studies such as [20–22] and [23] offer a comprehensive assessment of the economic and environmental consequences of building energy efficiency improvements within Saudi Arabia. In a related context, Belaïd and Massié, [11] employed an econometric model to evaluate the impact of economy-wide energy efficiency enhancements on carbon intensity in Saudi Arabia. Other energy modeling studies including Alshammari and Sarathy, [24], Alshammari, [25], Elshurafa and Peerbocus, [26] & Elshurafa et al., [27] have investigated the role of low-carbon solutions in decarbonizing Saudi Arabia's power and energy sectors. Several advanced general equilibrium studies, including those by Durand-Lasserve, [5,28], Blazquez et al., [29] and Almutairi et al., [30] have examined the interplay between the Saudi economy and global energy markets, with focus on understanding how domestic policies and international trends shape economic stability and growth in Saudi Arabia. Collectively, the aforementioned studies provide valuable insights into the pivotal role played by energy policy instruments and advanced technologies in steering the nation's energy transition journey.

Although previous studies on Saudi Arabia's energy transition have been valuable in enhancing our understanding of the journey towards a sustainable energy landscape, these studies are often limited in their scope of addressing the challenges and opportunities inherent in achieving net-zero emissions. Many of these studies tend to focus on specific facets of the transition, such as energy price reforms or sectoral decarbonization, hence missing key interactions and feedback across policies. In turn, the lack of sufficient representation of inter-sectoral interactions and feedback in the previous studies has resulted in a gap in the holistic understanding of the country's net-zero pathway. Furthermore, most of these studies have a short- to medium-term focus,

Table 1
Review of literature on Saudi Arabia's energy transition policies

Study	Sectoral/Policy Scope	Method	Notable policy insight
[20]	Building Energy Efficiency & Renewable	Energy Model	Adopting International Energy Conservation Code standards and incorporating solar technologies in Saudi homes can significantly reduce energy consumption.
[21]	Building & Renewable	Energy Model	Advanced solar panel tracking systems can boost power generation and cut costs for grid-connected solar PV systems.
[9]	Energy Price Reform	Econometrics Model	Saudi Arabia's recent reforms led to price and income inelasticity in energy demand, resulting in significant welfare gains and reduced consumption.
[24]	Economy-wide decarbonization	Energy Model	Achieving an 80% reduction in greenhouse gas emissions from the power generation sector requires implementing energy efficiency measures to enable a smooth transition to a low-carbon energy system.
[25]	Chemical sector decarbonization	Energy Model	Tackling industrial sector emissions, especially in chemical manufacturing, is crucial for climate action, and reaching this goal may involve a blend of carbon capture and solar tech.
[15]	Energy Price Reform	Econometric Model	Raising domestic energy prices in Saudi Arabia, particularly for gasoline, may not substantially curb demand due to price inelasticity. Thus, there's a need to improve energy efficiency and encourage alternative transportation modes.
[17]	Energy Price Reform	Input-Output Model	Energy price reforms in Saudi Arabia disproportionately burden low-income households due to higher energy-intensive product costs.
[11]	Economy-wide energy efficiency	Econometric Model	Economy-wide energy efficiency holds a pivotal role in Saudi Arabia's journey toward achieving its net-zero emissions goal, potentially contributing up to one-fifth of decarbonization by 2060.
[26]	Transport electrification (electric vehicle)	Energy Model	Adopting a low- or no-carbon energy source for charging electric vehicles in Saudi Arabia to ensure emissions reduction.
[27]	Power sector decarbonization	Energy Model	Saudi Arabia, renewable deployment can defer national gas supply expansion plans but not investments in expanding domestic gas transport capacities.
[18]	Energy Price Reform	Energy Model	Saudi Arabia's power generation expansion should consider fuel-price

(continued on next page)

Table 1 (*continued*)

Study	Sectoral/Policy Scope	Method	Notable policy insight
			reforms to minimize emissions, aiming for domestic retail prices above 20% of expected international wholesale fuel prices.
[22]	Building Energy Efficiency & Decarbonization	Energy Model	Substantial cost-effectiveness can be achieved by reducing electrical loads through energy efficiency measures in individual housing units.
[23]	Building Energy Efficiency & Decarbonization	Energy Model	Implementing energy retrofit programs tailored to different types, ages, and locations of residential buildings in Saudi Arabia can improve cost-effectiveness and yield multiple benefits.
[31]	Building Energy Efficiency & Decarbonization	Energy Model	Energy efficiency programs in Saudi Arabia's building sector, such as retrofits and optimized new designs, can result in significant energy savings, cost reductions, and positive environmental gains.
[19]	Electricity pricing	Energy Model	Time-of-use (TOU) pricing in Saudi Arabia's electricity sector can potentially influence household electricity consumption patterns and have wider economic effects.
[32]	Energy Price Reform	Energy Model	Alternative energy policies, such as deregulating fuel prices and incentivizing renewables, can lead to a more efficient energy system in Saudi Arabia, reducing oil and gas consumption and fostering economic growth.
(Matar et al, 2023)	Economy-wide decarbonization	Energy Model	A non-prescriptive scenario without energy price reform can achieve equivalent emission reduction at a lower cost compared to announced policies scenario.
[33]	Energy Price Reform	Price-gap Analysis	Saudi Arabia's energy subsidies, though initially aligned with socio-economic objectives, may hinder progress due to over-subsidization and poor implementation.
[16]	Energy Price Reform	Econometric Model	Saudi Arabia's vehicle fuel economy improvement is influenced by gasoline price elasticity, with the potential for progressive policies like feebates targeting income and household size.
[34]	Economy-wide decarbonization	Integrated Assessment Model	Early deployment of Direct Air Capture (DAC) driven by its early and rapid cost reduction could reduce climate mitigation cost relative to delayed DAC deployment.
[5]	Energy price deregulation & global oil market	General Equilibrium Model	Saudi Arabia's path to net zero emissions will be shaped by the deregulation of energy prices and the implementation of CO_2 caps, both essential for cutting carbon emissions and advancing sustainable energy technologies.
[30]	Energy Price & global oil market	General Equilibrium Model	Saudi Arabia's Vision 2030 enhances economic resilience to oil shocks by 10 to 60 percent through diversification and structural reforms, despite increasing volatility from changes in energy prices and tax policies.
[28]	Energy Price & global oil market	General Equilibrium Model	Saudi Arabia's Vision 2030 reforms, encompassing VAT introduction, energy price adjustments, and renewable energy deployment, collectively boost GDP and welfare, with energy price reforms showing the most substantial benefits.
[29]	Energy Price & global oil market	General Equilibrium Model	Saving domestically consumed oil in Saudi Arabia offers significant economic efficiencies by capitalizing on the price differences between domestic and international markets.

thus overlooking the long-term implications associated with energy policy instruments.

This research aims to address the existing gaps by evaluating of Saudi Arabia's energy transition, with a focused examination of the economic implications of current and prospective policies. This study focuses on the consequences of early intervention in the energy sector by assessing both existing and planned measures in terms of their financial impact. This study aims to shed light on the potential strategies to minimize economic losses by taking proactive mitigation actions within the energy system. Overall, this study offers actionable insights into how energy transition policies can steer the Saudi economy toward a more economically efficient net-zero pathway. To achieve this objective, this study utilizes a regionalized variant of the integrated model assessment tool called the Global Change Analysis Model (GCAM v6). This model (dubbed GCAM-KSA) is tailored to capture the unique characteristics and dynamics of Saudi Arabia's economy and energy systems. This study is structured as follows. In Section 2, an in-depth explanation of GCAM-KSA is provided, followed by highlighting the scenarios and their associated assumptions. Subsequently, the study delves into a discussion of the findings, focusing on primary energy and emissions transformations under alternative baseline scenarios. Finally, an exploration of net-zero emissions and their policy cost implications across various scenarios is conducted.

2. Methods

2.1. GCAM-KSA

To address the objectives of this paper, the study employs a regionalized version of the Global Change Analysis Model (GCAM v6) known as GCAM-KSA (Puneet et al, 2023). Building upon the technology-rich framework of GCAM v6, GCAM-KSA is tailored to capture the unique characteristics and dynamics of Saudi Arabia's economy and energy systems. While GCAM v6 provides detailed representations of water, agriculture, and land use systems, it's important to note that the version of GCAM-KSA used in this study, primarily focuses on the representation of KSA's energy systems and the resultant emissions.

In GCAM-KSA, the KSA is portrayed as a distinct geopolitical region alongside the existing 32 geopolitical regions of GCAM v6. The detailed representation of KSA energy system encompasses (see Fig. 1), the production of energy resources (i.e., oil, gas, uranium, and renewables), energy transformation and distribution (electricity, refining, gas processing & hydrogen production) and final energy demand sectors (buildings, industry, and transportation). The model tracks the emission of 24 different gases along the supply chain of the energy system from production through to final energy services. These gases include CO_2, N_2O, CH_4, and F-gases, as well as short-lived species and ozone precursors.

Similar to GCAM v6, GCAM-KSA operates in 5-year intervals, beginning with the calibration year of 2015 and continuing until 2100. During each time step, the model iterates until it identifies a set of prices that effectively balances all markets and meets all consistency requirements. As a dynamic recursive model, GCAM determines technology and market decisions by considering prevailing prices. Further, technology decisions are determined by a logit formulation, which allocates market share to technologies based on their levelized costs mediated by the influence of non-cost factors such as societal preferences, existing infrastructure, non-cost barriers to market entry and many more [35–37]. This formulation mimics decision-making processes among competing technologies, with technology options ranked according to the calibrated preferences regarding relative technology costs [35].

2.2. Mitigation Cost Computation in GCAM-KSA

This study aims to quantify the policy costs associated with net-zero scenario strategies of Saudi Arabia. GCAM employs a 'deadweight loss' approach to estimate the welfare losses resulting from these climate policies. In this context, the 'deadweight loss' refers to the loss of economic efficiency when the equilibrium outcome is not achievable due to market distortions, typically caused by suboptimal outcomes of policy interventions [38]. Notably, GCAM's policy cost calculations focus on the gross costs, which excludes the benefits of mitigation and the social and resource costs incurred by implementing the policy [39]. Instead, this computation only quantifies deadweight loss by measuring the costs incurred to meet GHG mitigation targets [40]. GCAM calculates policy costs by calibrating the marginal abatement cost for each period based on an endogenously calculated carbon price and the level of GHG emissions abated due to technology and socio-economic dynamics [41]. By default, GCAM calibrates the marginal abatement curve across five carbon price margins (0-20%, 20-40%, 40-60%, 60-80% and 80-100%) for each period. The deadweight loss at each level is determined by the impact of the carbon price on emissions relative to an emission pathway without a carbon price [42] (see Fig. 1A in the appendix). The carbon price levels (i.e. P) at the margins and the corresponding abated GHG emissions (E) form the marginal abatement cost curve for a given period (T). The mitigation cost (C_T) for a given period is then determined by computing the area under the curve. Specifically, this is done by integrating the carbon price, as a function of abated emissions, over the emissions range that is affected by the policy (see equation 1). The cumulative policy cost is calculated by interpolating the estimated mitigation costs between time steps, discounting them using a rate 'r', and summing them up to the target year (see equation 2).

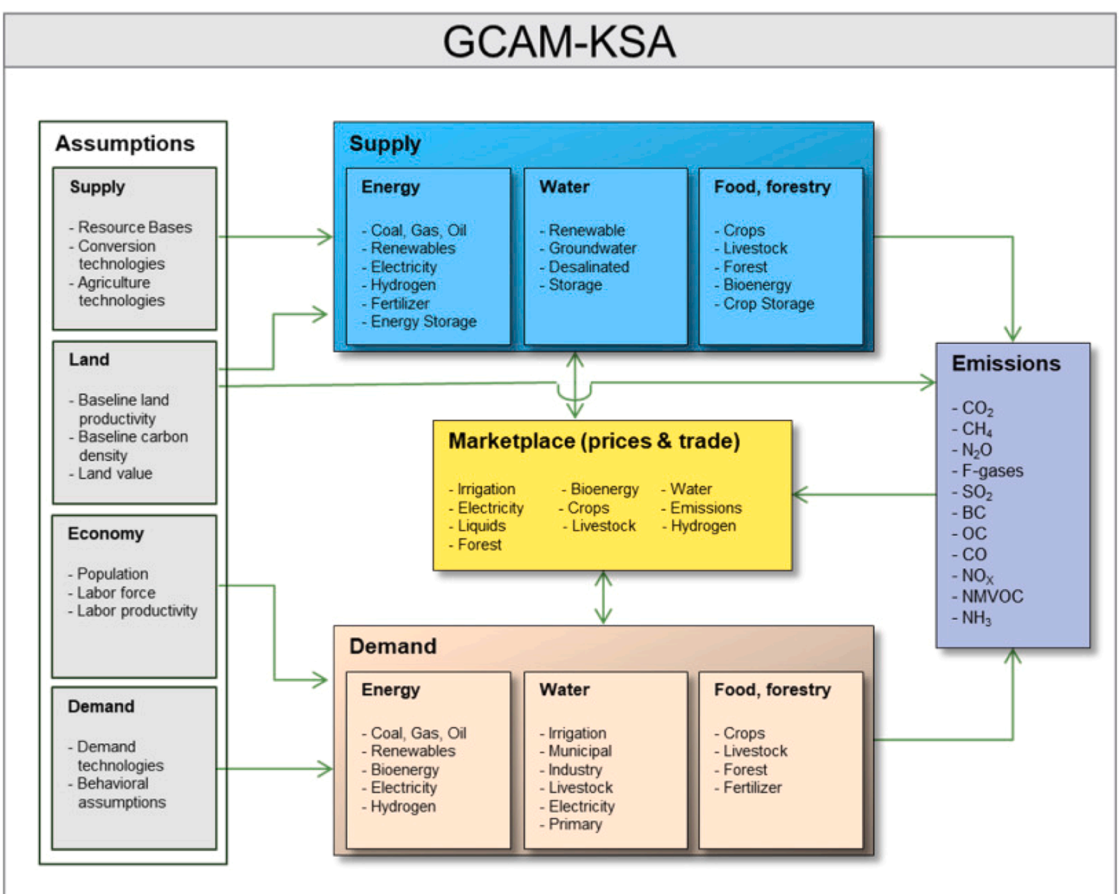

Fig. 1. GCAM-KSA schematic representation of the energy system *(Kamboj, et al. 2023)*.

$$C_T = \int P(E)\ d(E) \quad (1)$$

$$Total\ Policy\ Cost = \sum_{T=2025}^{2060} \frac{C_T}{(1+r)^{T-2025}} \quad (2)$$

2.3. Scenario Design

This study evaluates three distinct energy system scenarios based Saudi Arabia's current and proposed energy transition policies (see Table 3 below). Each scenario is analyzed under both a baseline and a climate policy trajectory, resulting in a total of six scenarios, which are shown in Table 2. This approach enables a comprehensive examination of the long-term impacts of various policies and mitigation strategies on Saudi Arabia's energy system.

Under the baseline trajectory (i.e., Base), we explore the dynamics and outcomes of the energy systems without stringent decarbonization efforts or emissions constraints. These scenarios reflect the natural evolution of the energy system driven by market forces, such as technological costs, consumer behavior, and innovation, without the influence of carbon pricing or explicit climate policies. As a result, carbon prices are set to zero in all baseline scenarios, ensuring they represent a "no climate policy" framework. Conversely, the climate policy pathways (i.e., NZE) incorporate GHG emissions constraints aimed at achieving a reduction of 278 $MtCO_2e$ by 2030, consistent with Saudi Arabia's NDC target, and set a course for a linear decline to net-zero emissions by 2060. These scenarios rely on carbon pricing as a critical driver for technological deployment and emissions reductions. Assumptions for non-KSA regions meeting their NDC targets and net-zero commitments are based on the framework provided by Ou et al., [43].

For the energy system policy assumptions considered, the first scenario, known as the delayed action (i.e. DA) scenario, serves as the basis against which we compare other scenarios. In this scenario, we assume that the KSA has not implemented any energy transition energy system policies. This is achieved by excluding recent energy transition measures, such as energy efficiency enhancements and harmonizing end-use energy prices to represent a trajectory of no price reform. Specifically, no adjustments to energy subsidies or alignment with international benchmarks are included, and traditional hydrocarbons continue to dominate future development without support for low-carbon technologies. To reflect this lack of support, the share weight parameters[1] for low-carbon technologies, such as nuclear and rooftop PV are adjusted. The DA scenario provides the context for evaluating the impact of the other two energy policy scenarios.

The early action energy system assumptions (i.e. EA) incorporates the existing energy system policies currently in effect and announcements made before 2021. Within this scenario, we consider the advantages stemming from various energy efficiency measures initiated under the SEEP (see Table A2 in the appendix about the efficiency). In the building and transportation sectors efficiency improvements are modeled by calibrating the input-output ratio parameters for each end-use sector to reflect various sectoral efficiency targets. Additionally, this scenario reflects the impact of the two rounds of energy price reforms implemented in 2016 and 2018, which gradually aligned energy prices (electricity, gasoline, and diesel) with international benchmarks. Specifically, the model calibrates 2020 fuel prices to reflect Saudi Arabia's actual fuel prices post these reforms. For the power sector, the study models the objective of achieving a balanced power capacity between renewable and gas-based electricity by 2030, while phasing out liquid fuel-based generation.

Lastly, the enhanced Early Action (i.e. EA+) scenario represents an extension of the Early Action scenario. It incorporates additional prospective energy system policies that the Kingdom of Saudi Arabia is considering as part of ongoing efforts to facilitate the Kingdom's energy transition. These enhancements cover various aspects, including industrial energy efficiency [13], electric vehicle (EV) deployment [44], and upscaling of public transportation [45]. See Table A4 for cost assumptions applied to EVs and Table A5 for the adjustment in the public transportation load factor to reflect these policies.

This study applies a consistent set of assumptions regarding socio-economic dynamics across all six scenarios. These assumptions align with the SSP2 (middle-of-the-road) narrative, in this scenario the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns [46]. It should be noted that our modeling exercise accounts for the effects of the COVID-19 pandemic on GDP growth during the period from 2015 to 2020 (see Table A1 in the appendix).

3. Results & Discussions

The results section is organized as follows: Sections 3.1 and 3.2 focus on the baseline scenarios (DA_Base, EA_Base, and EA+_Base). Section 3.1 outlines the energy system trajectories of these baseline scenarios, providing a foundation for understanding how the energy system evolves under existing policies. Section 3.2 delves deeper into the interactions among individual policy instruments, emphasizing both near- and long-term mitigation gaps as well as the energy system inertia that poses challenges to achieving Saudi Arabia's NDC and net-zero targets. Lastly, Section 3.3 examines the trajectories for residual and negative emissions in the DA_NZE, EA_NZE, and EA+_NZE scenarios, evaluating the associated policy costs and their implications for long-term decarbonization strategies.

3.1. Baseline Primary Energy Trajectory

Fig. 2 presents the projected primary energy mix for Saudi Arabia across various baseline scenarios spanning 2015 to 2060. In the DA_Base scenario, robust socio-economic growth leads to a doubling of primary energy demand by 2060 relative to 2015 levels. The energy mix remains heavily dominated by oil and natural gas, which together account for approximately 94% of total consumption throughout the period. In contrast, the EA_Base and EA+_Base scenarios, which incorporate early action policy instruments, significantly reduce reliance on fossil fuels. By 2060, oil demand in these scenarios decreases by 26% and 42%, respectively, compared to the DA_Base scenario. Solar energy expands gradually in the DA_Base scenario, driven by its increasing economic competitiveness, contributing approximately 5% of the total energy mix by 2060. However, renewable energy adoption accelerates relatively more in the EA_Base and EA+_Base scenarios, with non-fossil resources reaching 6% and 7% of the energy mix, respectively, by 2060. Efficiency improvements also play a pivotal role in shaping energy demand trajectories. By 2030, sectoral efficiency measures and energy pricing reform (EPR) policies result in a 15.6% (-1.95 EJ) reduction in primary energy demand under the EA_Base scenario and a 25.3% (-3.14 EJ) reduction under the EA+_Base scenario, relative to DA_Base. These reductions amplify significantly by 2060, with primary energy demand decreasing by 17.7% under EA_Base and 44.5% under EA+_Base. Collectively, the results underscore the critical importance of early action instruments in steering Saudi Arabia towards a more sustainable energy trajectory. These policies not only mitigate growth in fossil fuel consumption but also foster the integration of renewable energy and efficiency improvements, thereby contributing to long-term energy security and climate goals.

3.1.1. Baseline Electricity Trajectory

Saudi Arabia's power sector is projected to undergo significant transformation under the early action scenarios compared to the delayed

[1] Share weight parameter in GCAM represent the relative attractiveness or competitiveness of a technology compared to others within the same sector.

Table 2
Scenario Matrix of Energy system assumptions and emission pathways

KSA Climate Policy Assumptions	KSA Energy Transition Assumptions: Delayed Action	Early Action	Early Action+
Baseline Assumptions: • No Climate-Focused Policies: There are no policies or interventions targeting climate change. • Market-Driven Technology Adoption: Energy system technologies evolve based on market factors like cost, consumer preference, and innovation.	Baseline & Delayed Action **(DA_Base)**	Baseline & Early Action **(EA_Base)**	Baseline & Early Action + **(EA+_Base)**
Net-Zero Assumptions: • Comprehensive Decarbonization by 2060: Strategies are enacted to meet NDC and achieve net-zero GHG emissions by 2060. • Carbon Pricing as a Catalyst: Carbon pricing mechanisms are key drivers of technological advancements in the energy sector.	Net-Zero & Delayed Action **(DA_NZE)**	Net-Zero & Early Action **(EA_NZE)**	Net-Zero & Early Action + **(EA+_NZE)**

Table 3
Energy Transition Scenario Element adapted from Kamboj et al, (2023)

Sectors	Policy Instruments	Delayed Action (DA)	Early Action (EA)	Early Action (EA+)
Power Generation Sector	Retiring all liquid generation by 2030	✗	✓	✓
	Electricity price reforms *	✗	✓	✓
	50 % Gas and 50 % Renewables add capacity from 2025 to 2030	✗	✓	✓
	Availability of Nuclear	✗	✓	✓
Transportation [Domestic Passenger & In-land Freight]	SEEP CAFÉ standards	✗	✓	✓
	Achieving 25% EV market share for new sales in Riyadh by 2030	✗	✗	✓
	Retail price reforms *	✗	✓	✓
	Increase public transport by 30% by 2060	✗	✗	✓
Building [Commercial & Residential]	Minimum energy performance standard for appliance	✗	✓	✓
	Retail price reforms *	✗	✓	✓
	Rooftop PV	✗	✓	✓
Industry	Wholesale price reforms *	✗	✓	✓
	Energy Efficiency Improvement (2%/yr)	✗	✗	✓

Note
1. Red cross mark represents no and green check represents yes
2. EA includes policies implemented or announced before 2021, while EA+ adds prospective policies under consideration for Saudi Arabia's energy transition.
*** calibration of energy and fuel prices in 2020 to represent Saudi Arabia's actual prices following the 2016 and 2018 energy price reforms.**

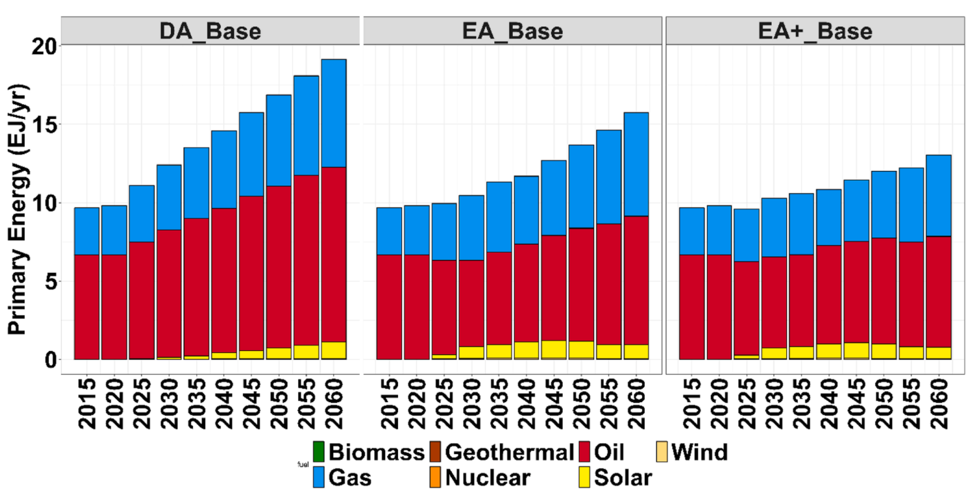

Fig. 2. Primary energy trajectory for DA_Base, EA_Base and EA+_Base scenario under the baseline assumptions.

action scenario, driven by the policy mandate of 50% renewable power capacity and 50% gas-based electricity generation (see Fig. 3). Liquid fuels are entirely phased out by 2030, while natural gas becomes the dominant source of electricity generation, accounting for approximately 74.7% and 78.2% of the generation mix in the EA_Base and EA+_Base scenarios, respectively. The higher share of natural gas generation, despite the 50% renewable capacity policy, is primarily due to its significantly higher capacity factor compared to renewables, allowing gas plants to operate consistently as baseload or dispatchable sources. Renewables, including solar and wind, see substantial growth,

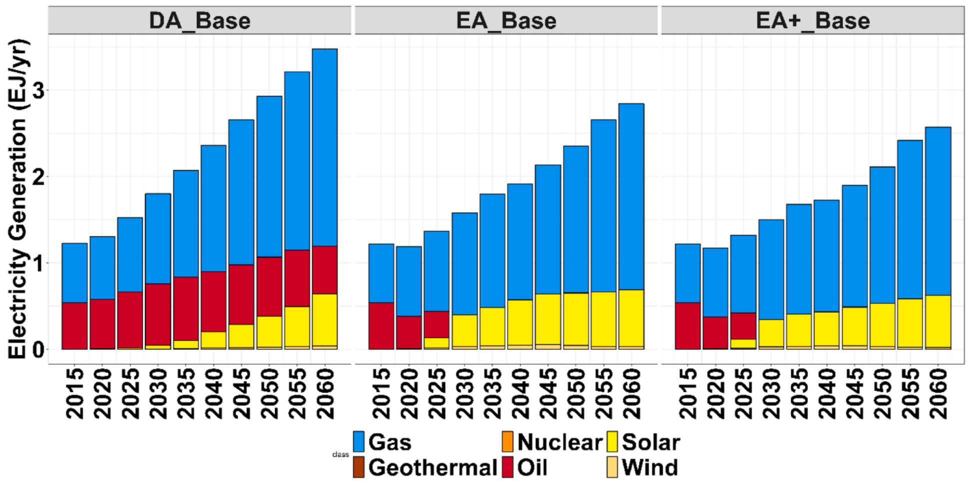

Fig. 3. Electricity generation trajectory for DA_Base, EA_Base and EA+_Base scenario under the baseline assumptions.

contributing 2.5%, 21.3%, and 24.7% of the generation mix in the DA_Base, EA_Base, and EA+_Base scenarios, respectively, with solar playing a dominant role compared to wind. In these baseline modeling projections, solar's dominance reflects its higher resource availability across Saudi Arabia and its cost-effectiveness, which aligns with the assumptions of rapid technological advancements and economies of scale. It is also evident that improvements in energy efficiency, driven by advancements in technical efficiency and the implementation of EPR policies, significantly reduce electricity demand.

3.1.2. Baseline Final Trajectory

Our projections show that final energy consumption across buildings, industry, and transportation sectors varies significantly under the DA_Base, EA_Base, and EA+_Base scenarios (see Fig 4). In the building sector, energy demand is projected to rise to 2.3 EJ by 2060, a 2.4-fold increase compared to 2015 levels. However, the implementation of policies such as minimum energy performance standards for appliances, rooftop PV deployment, and retail price reforms under EA_Base and EA+_Base drives a 16.67% reduction in energy demand by 2030 compared to DA_Base. By 2060, these measures lead to a more pronounced 27.6% reduction. The industrial sector follows a similar trajectory, with energy demand increasing 2.18-fold to 7.23 EJ by 2060 under the DA_Base scenario. Early action policies, including EPR and annual technical efficiency improvements, lead to a 5.2% reduction in energy demand under EA_Base and a significant 23.8% reduction under EA+_Base, with total demand projected at 6.85 EJ and 5.51 EJ, respectively, by 2060. In the transportation sector, energy demand rises from 2.34 EJ in 2015 to 5.51 EJ by 2060 under the DA_Base scenario. However, policies such as SEEP CAFÉ standards, increased public transport utilization, modal shifts, and vehicle electrification deliver substantial energy savings. These measures collectively result in a 20.6% decrease in transportation energy demand by 2060 under the EA+_Base scenario.

3.2. Baseline GHG Emissions Trajectory

Fig. 5 illustrates the baseline GHG emissions trajectory for the energy system assumptions. In the DA_Base scenario, GHG emissions are projected to increase from 722.2 $MtCO_2e$ in 2015 to 1345.6 $MtCO_2e$ by 2060. Comparing the early actions scenarios to the delayed action scenario reveals significant potential for emissions reduction in the Kingdom of Saudi Arabia. In the near term (i.e., 2030), these policies are projected to result in a decrease of 185 $MtCO_2e$ for the EA_Base scenario and 246.0 $MtCO_2e$ for the EA_Base+ scenario. However, these projected

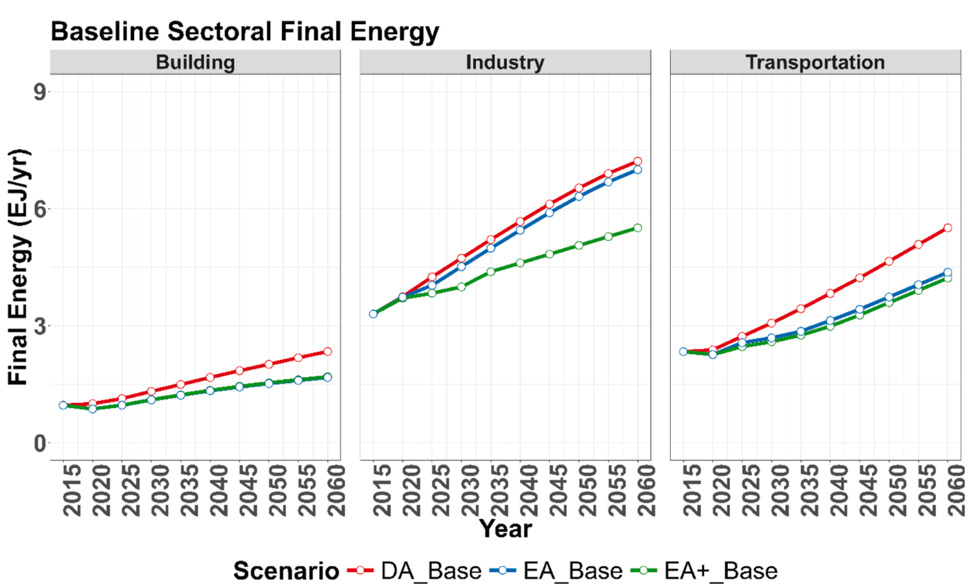

Fig. 4. A. Sectoral final energy trajectory for DA_Base, EA_Base and EA+_Base scenario under the baseline assumptions.

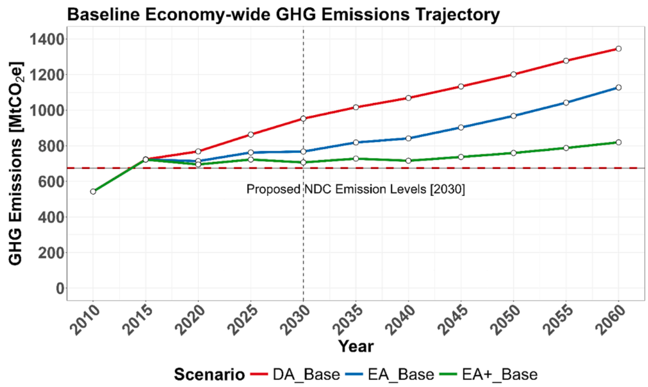

Fig. 5. Baseline economy-wide GHG emissions trajectory for DA_Base, EA_Base and EA+_Base scenarios. Note the red dashed lines represents the 2030 NDC emissions levels of 278GtCO_2 from the DA_Base baseline scenario

short-term reductions do not fully align with the Kingdom's 2030 NDC target. This discrepancy is due to the study's focus solely on the energy system, without considering all the key initiatives proposed in the NDC. In the long term (i.e., 2060), emission reductions become more substantial compared to 2030, with a decrease of approximately 218.2 MtCO_2e for EA_Base and 526.3 MtCO_2e for EA_Base+.

3.2.1. Short-term Emission Implications of Policy Levers

To provide perspective on the NDC gap under early action baseline scenarios, Fig. 6 illustrates the impacts of individual policy instruments and highlights how they interact to achieve economy-wide emission reductions within KSA. Fig. 6A details the individual policies and how they interact in the EA_Base scenario compared to the DA_Base scenario. Fig. 6B provides a similar breakdown for the policy levers in the EA+_Base scenario compared to the EA_Base scenario.

From Fig. 6A, it is evident that the model projections that non-industrial (i.e. building and transportation) efficiency policies are the most effective among the various policy levers. These policies are expected to result in a significant reduction of 97.9MtCO_2e/yr in 2030 compared to the DA_Base scenario. Also, the energy price reform is projected to lead to a reduction of around 67.9 MtCO_2e per annum in 2030. Further, Saudi Arabia's plan of having a 50% renewable power capacity and 50% gas-based power as a standalone policy is projected to yield a reduction of about 59.1 MtCO_2e per annum in 2030. The relatively moderate effect observed in the power sector policies can be attributed to the absence of stringent climate policies that would encourage a more aggressive phase-down of fossil fuels. In this baseline trajectory, the adoption and integration of cleaner technologies are primarily driven by economic competition void of any carbon policy interventions. Consequently, the deployment of gas power occurs without CCS which limits the emission reduction potential of this policy.

The combined interaction effects of the individual policies in the EA_Base scenario resulted in a net increase of 39.8 MtCO_2e per annum in 2030 compared to the summation of their individual impacts. This outcome reveals the intricate interplay and constraints among specific policies. When combined, these policies may unexpectedly introduce limitations and trade-offs that hinder their individual emissions reduction potential. Additionally, in some cases, the combined policies exhibit diminishing marginal returns, where the cumulative impact falls short of the sum of their individual emissions reduction potentials. Nonetheless, it is crucial to emphasize that the combined effect of the policy interactions surpasses the potential of individual policies in isolation. This implies that the Saudi Government's comprehensive energy transition strategy has the potential to yield significant and far-reaching results.

The introduction of public transportation and the scaling up of electric vehicles (EVs) have the potential to reduce emissions by 2 and 3 MtCO_2e per year in 2030, respectively when compared to the EA_Base scenario. These modest estimates are due to conservative assumptions in our scenario design. Strengthening industrial energy efficiency has the potential to lower emissions by 57 MtCO_2e. Interestingly, the interaction effect stemming from these individual policies results in a modest net increase of 1 MtCO_2e. These enhanced policies can help narrow the Kingdom's National Determined Contributions (NDCs) gap but still fall short of reaching the goal.

3.2.2. Mitigation Gap Analysis

Fig. 7 below provides a concise overview of cumulative emissions (i.e., carbon budget) of the three scenarios under baseline trajectory in comparison to an idealized NDC and net-zero decarbonization pathway. This graph aims to illuminate the technological inertia inherent in the early action scenarios, by underscoring the magnitude of the mitigation

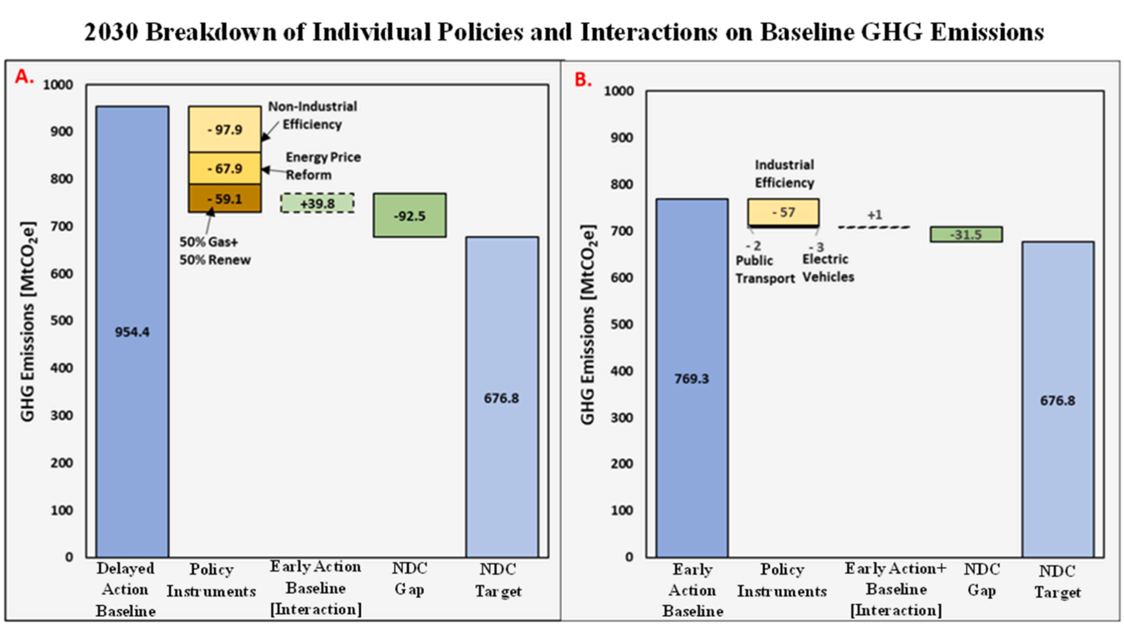

Fig. 6. A. Effect of individual policies and interaction for EA_Base in reference to DA_Base B. Effect of individual policies and interaction for EA+_Base in reference to EA_Base.

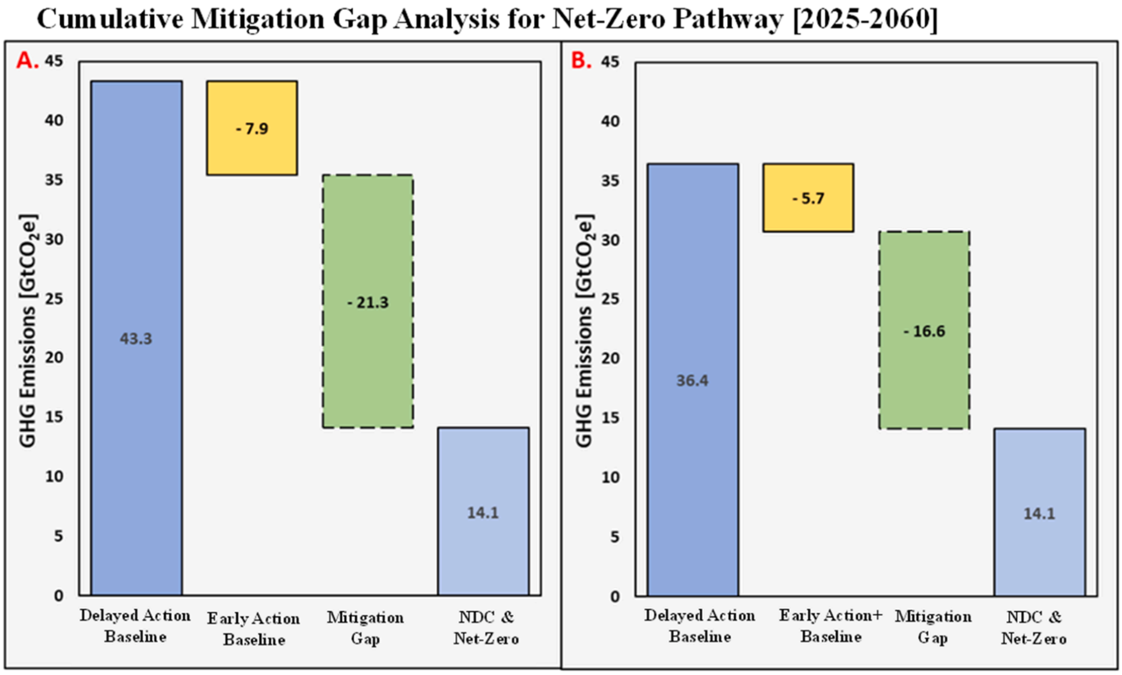

Fig. 7. A. Breakdown of mitigation gap for EA_Base in reference to DA_Base B. Breakdown of mitigation gap for EA+_Base in reference to EA_Base.

effort that is needed for Saudi Arabia to achieve the net-zero pathway.

In the baseline scenario, the cumulative GHG emissions from the DA_Base scenario up to 2060 is projected to add up to 43.3GtCO_2e. This cumulative emission represents the technological inertia within the energy system in the absence of significant energy transition policies in Saudi Arabia. Contrasting this, the achievement of both near-term NDC targets and the long-term net-zero pathway implies that Saudi Arabia must limit its cumulative net emissions to approximately 14.1 GtCO_2e. Bridging the gap between the DA_Base scenario and the net-zero pathway demands substantial mitigation efforts. However, the early action (i.e. EA_Base) policy instruments are expected to decrease the cumulative emissions by 17.9% or 7.9 GtCO_2e compared to the delayed action scenario. Conversely, the enhanced early action scenario (i.e EA+_Base) is projected to achieve a more substantial reduction of about 31.1% compared to DA_Base and 16% compared to EA_Base. The advanced technology efforts in the EA_Base and EA+_Base scenarios result in a significant reduction of the mitigation gap by approximately 21.3 GtCO_2e and 16.6 GtCO_2e, respectively. In essence the early action policy scenarios hold significant potential to reduce the inertia associated with low-carbon technology transition. This, in turn, can play a critical role in supporting Saudi Arabia in its pursuit of NDC and net-zero objectives.

3.3. Residual and Negative Emissions for NDC and Net-Zero

This section aims to shed light on the sectoral emission reductions required to meet Saudi Arabia's NDC goal by 2030 and its ambitious shift towards achieving a net-zero economy by 2060. Fig. 8A illustrates the key emission transformation required to accomplish Saudi Arabia's decarbonization objectives. It focuses on residual emissions and negative emission pathways within the three energy system scenario pathways. Fig. 8 B, offers an overview of sector-specific cumulative residual emissions and carbon removal from 2025 to 2060.

In the near-term period (2025–2030), which coincides with meeting the NDC target, the pathways for the three scenarios show limited divergence in both residual and negative emissions. During this period, the emissions constraint is relatively less stringent, resulting in low demand for negative emissions technologies to offset residual emissions. However, as the net-zero decarbonization pathway begins in 2031, the delayed action (DA_NZE) scenario diverges significantly from the others due to its notably higher residual emissions. This divergence arises from the pronounced technological inertia inherent in the DA_Base scenario, as discussed in Section 3.2.2. The build-up of residual emissions over time in the DA_NZE scenario is a key consequence of delayed mitigation efforts, requiring substantially higher investments in negative emissions technologies to achieve net-zero emissions by 2060. The DA_NZE scenario necessitates a cumulative negative emissions of 9.8 GtCO_2e to offset residual emissions of 23.9 GtCO_2e, underscoring the trade-offs associated with delayed action.

Beyond 2035, a clear divergence is evident between EA_NZE and EA+_NZE. The enhanced policy scenario (EA+_NZE) achieves a significantly higher reduction in residual emissions compared to EA_NZE, driven by improvements in industrial efficiency and transportation. These improvements are particularly important in reducing emissions in hard-to-abate sectors such as heavy industry and transportation. Consequently, the EA+_NZE scenario reduces reliance on Carbon Dioxide Removal (CDR) solutions compared to both EA_NZE and DA_NZE scenarios.

At a sectoral level the transportation sector contributes the highest cumulative residual emissions in the DA_NZE scenario due to slower advancements in transportation efficiency and electrification. The EA_NZE and EA+_NZE scenarios, benefiting from more rapid technological progress, achieve reductions in cumulative residual emissions of approximately 40.8% and 38.7%, respectively, relative to DA_NZE. Reaching Saudi Arabia's 2060 net-zero greenhouse gas emissions goal hinges on significantly reducing emissions from hydrocarbon-dependent industrial sectors (Kamboj et al., 2023). The model suggests that cumulative residual emissions from fossil fuel and industrial (FFI) activities range from 3.9 to 6.1 GtCO_2 across scenarios. While deep decarbonization in FFI sectors poses challenges, enhancing industrial energy efficiency can achieve significant reductions in residual emissions, amounting to 32.4%.

3.4. Policy Cost Implications

Insights from the previous section highlighted that KSA's policy-driven strategies have the potential to steer emissions trajectories differently, as exemplified by the variations in residual and negative

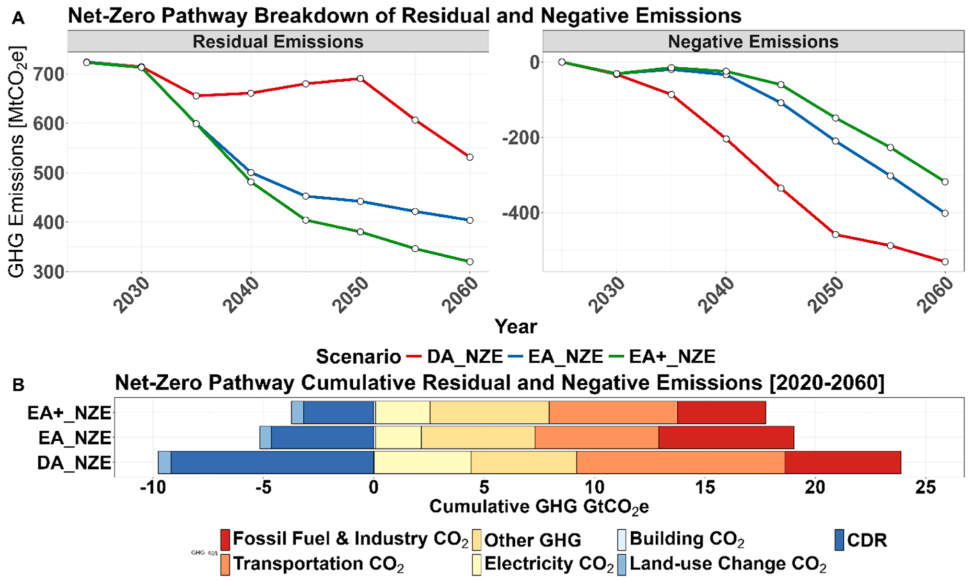

Fig. 8. A. Residual and negative emission trajectory B. Cumulative residual and negative emissions trajectory by sector. Please note CDR in this graph represents direct air capture with CCS technologies[2].

[2] Please note that in this version of GCAM-KSA, BECCS, which is part of the native GCAM-Core, is disabled due to limited biomass resources in Saudi Arabia's arid climate, making it a less viable option.

emission pathways. These findings shed light on the cost implications associated with the mitigation of GHG emissions.

Fig. 9A presents the carbon price for each of the three scenarios across the mitigation periods. It is imperative to emphasize that the carbon prices showcased in Fig. 9A are entirely independent and reflect diverse assumptions about Saudi Arabia's energy system discussed in section 2. The observed differences across the cost signify varying levels of cost-effectiveness associated with both sector-specific and economy-wide emissions reduction strategies. The delayed action scenario (DA_NZE) incurs the highest carbon price among all scenarios across all the time periods, primarily due to the scenario's elevated technological inertia associated with mitigating GHG emissions. However, the early action policy interventions induce a pivotal shift in the cost dynamics. As shown, the carbon price is lower for both EA_NZE and EA+_NZE compared to the DA_NZE scenario.

Fig. 9B illustrates the cumulative policy cost for the scenario spanning from 2025 to 2060. Without the early energy-system policy actions, achieving long-term net-zero emissions in the DA_NZE scenario would require a total policy expenditure of about \$2.27 trillion. Nevertheless, the early action interventions in the form of current and planned policies, is projected to reduce the cumulative policy costs to approximately \$1.39 trillion for the EA_NZE scenario, and even further to around \$0.64 trillion for the EA+_NZE scenario. This corresponds to a reduction of 38.8% compared to the DA_NZE scenario in the case of the EA_NZE scenario, and a substantial 71.8 reduction in the EA+_NZE scenario.

The significance of these cost reductions becomes apparent when assessed in the context of average share of policy cost as a percentage of GDP from 2025 to 2060 (Fig. 10). The comparison highlights that on average the EA_NZE scenario can potentially reduce the economic burden by 5.14 percentage points per year compared to the DA_NZE scenario. Furthermore, for the EA+_NZE scenario, the deployment of advanced low-carbon technologies and strategies has the potential to cut the economic loss by a substantial 10.31 percentage points per year. The

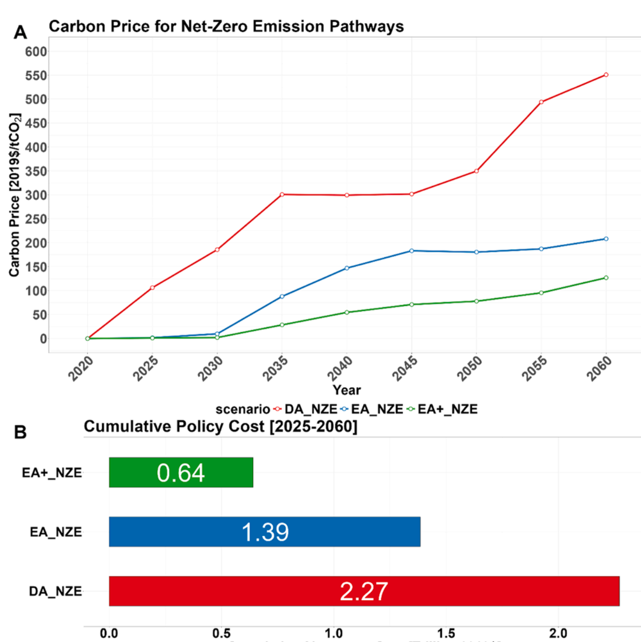

Fig. 9. A. Carbon Price for the Policy Scenarios B. Cumulative Policy Cost [2025-2060]. Note: policy costs are in B are discounted at 5% from the year 2020

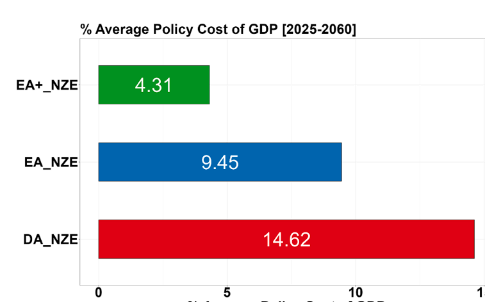

Fig. 10. Average annual policy cost expressed as a percentage of GDP [2025-2060].

marginal abatement curves shown in Fig. 1B (in the appendix) further sheds light on cost-effectiveness associated with the respective scenarios. It is important to highlight that the annualized average policy cost, expressed as a percentage of GDP for the early actions scenario, falls within the range of cost estimates found in the net-zero emission literature. However, the estimate for delayed actions is an outlier, which is expected given that this scenario represents a future of minimal actions towards a low-carbon future.

4. Policy Implications and Conclusion

Saudi Arabia's ambitious aim to achieve net-zero GHG emissions across its economy by 2060 presents a complex challenge, primarily due to its substantial dependence on fossil fuel exports and substantial domestic demand for fossil fuels. Nevertheless, it also presents a unique opportunity to diversify the kingdom's economy away from fossil fuels while promoting long-term economic resilience and sustainability. This study offers valuable insights into the feasibility of this ambitious goal by examining the associated mitigation policy costs for both current and proposed energy transition policies in Saudi Arabia. The findings reveal that these policies can make significant strides in lowering both emissions and primary energy consumption. Sustaining and amplifying the momentum of these policies into the future is crucial to reduce the low-carbon technological inertia associated with Saudi Arabia's net-zero ambitions. Nevertheless, the analysis of the current trajectory of these energy transition policies reveals a potential shortfall in meeting the Nationally Determined Contributions (NDC) goals. Ratcheting up these policies and including other non-energy sector policies will be imperative to bridge and ensure that KSA can achieve the stated emission reductions targets.

Our study reveal that Saudi Arabia's comprehensive energy transition strategy collectively has far-reaching outcomes compared to the outcome of the policies in isolation. Moreover, the analysis of individual policy instruments reveals that non-industrial and industrial sectoral efficiency policies are the most effective policies in reducing Saudi's emissions. Enhancing energy efficiency holds many opportunities for Saudi's deep decarbonization aspiration. First, reducing energy demand improves the flexibility of decarbonizing hard-to-abate sectors. Industrial energy efficiency can play pivotal role in decarbonizing the country's economy. This is especially significant given the industrial sector is currently responsible for approximately 48% of the country's primary energy consumption. In addition improving energy efficiency can also help mitigate the risks associated with the large-scale deployment of CDR technologies. These results illustrate the dual benefit of energy efficiency measures in Saudi Arabia's transition toward a lower-carbon future.

Saudi Arabia's path to net-zero emissions relies on a comprehensive strategy, including a 50% gas and 50% renewable capacity deployment in the power sector. The decarbonization of the power sector will not only contribute to emissions reductions in this sector but can also create substantial opportunities for decarbonization in pivotal end-use sectors, such as transportation and industry. Currently, the decarbonization of Saudi Arabia's power and transport sectors would eliminate about 60% of emissions. The results of the study indicate that current electric vehicle targets and the expansion of public transportation modes will lead to small emissions reductions in the short term. A more ambitious and comprehensive will be required to fully harness the decarbonization potential of the transportation sector. In addition to electrification, future studies could explore the roles of alternative fuels such as hydrogen, biofuels, ammonia, and methanol in reducing emissions from heavy transportation modes like land freight, aviation, and shipping.

To achieve its net-zero target, Saudi Arabia will require further energy price rationalization using policy instruments that accurately reflect the true costs of different energy sources, including their environmental and social externality. This study reaffirms the critical role of Saudi Arabia's energy price reform in reducing primary energy consumption and GHG. Furthermore, implementing a carbon pricing mechanism can encourage businesses and individuals to invest in sustainable and low-carbon solutions, while driving innovation in clean technologies. Although we do not model it explicitly, revenue generated from carbon pricing can be reinvested in renewable energy infrastructure, climate adaptation measures, and support for vulnerable communities affected by climate change.

Transiting from a fossil fuel-based economy to a carbon-neutral economy comes with significant cost implications. Importantly, this study uncovers that Saudi Arabia's early action in the form of current and planned energy transition policies have the potential to significantly ameliorate the long-term financial burdens associated with the net-zero economy transition. While these policies can lead to significant reductions in long-term policy costs, it's important to emphasize that the relative costs associated with the energy transition policies remain substantial. A plausible reason for the significant policy cost estimates can be attributed to the study's limited scope, as it exclusively evaluates specific energy systems policies. Another plausible reason for the high policy cost can be linked to the fact that we assume mitigation action solely takes place within the Kingdom and do not allow the transfer of carbon credits from other regions. While this focused analysis offers valuable insights into the challenges and opportunities of decarbonizing Saudi Arabia's economy, future studies could take a more comprehensive approach by considering a broader spectrum of cross-sectoral policies and the transfer of carbon credits. Such future research endeavours can complement this study by providing insights into how to efficiently allocate resources, thereby potentially minimizing the overall cost burden.

CRediT authorship contribution statement

Raphael Apeaning: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Puneet Kamboj:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Mohamad Hejazi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Yang Qiu:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. **Page Kyle:** Writing – review & editing, Writing – original draft, Software, Methodology. **Gokul Iyer:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100184.

Appendix

Fig. 1A, Fig. 1B, Table A1, Table A2, Table A3, Table A4, Table A5, Table A6 and Table A7.

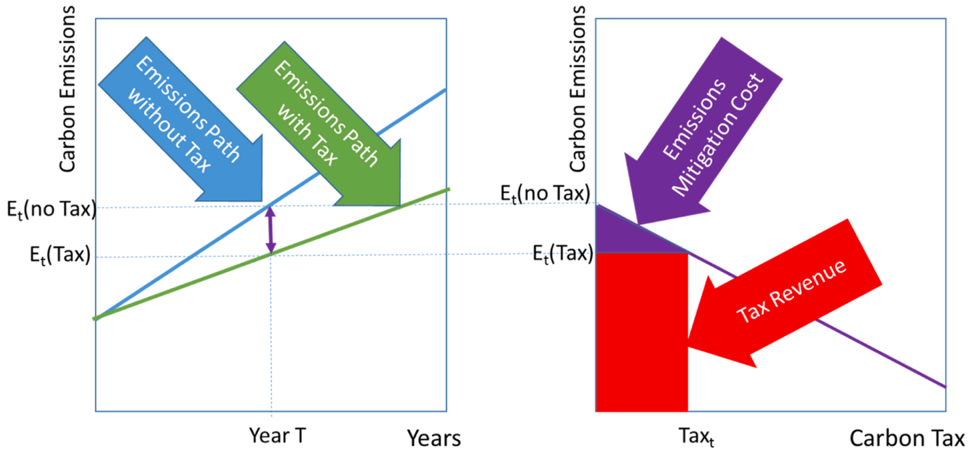

Fig. 1A. Schematic Representation of Emissions Policy Costs.

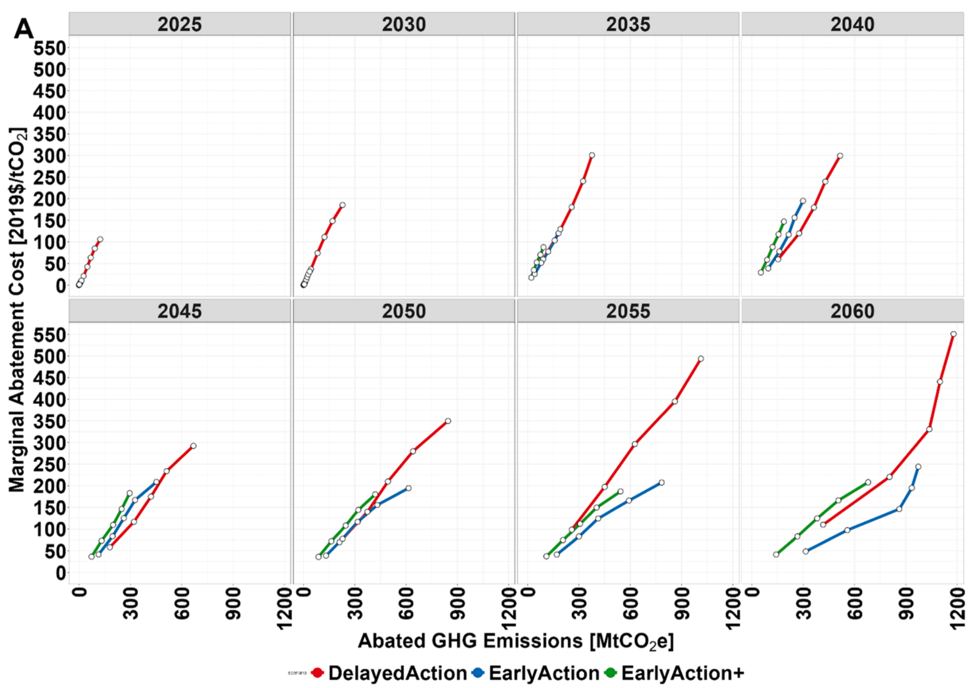

Fig. 1B. Marginal Abatement Cost Curve for the Scenarios.

Table A1
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 A2
Assumption for energy efficiency improvements for key consumer sectors for the EA and EA+ scenarios

			CAGR [2015-2030]			CAGR [2030-2060]		
Sector	End-Use	Technology	DA	EA	EA+	DA	EA	EA+
Buildings	Residential	Cooling	0.29%	0.80%	0.80%	0.25%	0.76%	0.76%
	Commercial	Cooling	0.28%	0.80%	0.80%	0.25%	0.78%	0.78%
	Residential	Other	0.03%	0.49%	0.49%	0.03%	0.45%	0.45%
	Commercial	Other	0.03%	0.49%	0.49%	0.03%	0.45%	0.45%
Transportation	Four-Wheelers	ICE	0.50%	1.60%	1.60%	0.50%	1.5%	1.5%
	Four-Wheelers	Hybrid Vehicles	0.50%	1.50%	1.50%	0.50%	1.4%	1.4%
	Four-Wheelers	CNG	0.60%	1.60%	1.60%	0.60%	1.5%	1.5%
	Four-Wheelers	BEV	0.50%	1.20%	1.20%	0.50%	1.1%	1.1%
	Four-Wheelers	FCEV	0.60%	1.40%	1.40%	0.60%	1.3%	1.3%
Industry	Aggregated Improvement		1.00%	1.00%	2.00%	1.00%	1.00%	2.00%
			CAGR [2015-2030]			CAGR [2030-2060]		
Sector	End-Use	Technology	DA	EA	EA+	DA	EA	EA+
Buildings	Residential	Cooling	0.29%	0.80%	0.80%	0.25%	0.76%	0.76%
	Commericial	Cooling	0.28%	0.80%	0.80%	0.25%	0.78%	0.78%
	Residential	Other	0.03%	0.49%	0.49%	0.03%	0.45%	0.45%
	Commericial	Other	0.03%	0.49%	0.49%	0.03%	0.45%	0.45%
Transportation	Four-Wheelers	ICE	0.50%	1.60%	1.60%	0.50%	1.5%	1.5%
	Four-Wheelers	Hybrid Vehicles	0.50%	1.50%	1.50%	0.50%	1.4%	1.4%
	Four-Wheelers	CNG	0.60%	1.60%	1.60%	0.60%	1.5%	1.5%
	Four-Wheelers	BEV	0.50%	1.20%	1.20%	0.50%	1.1%	1.1%
	Four-Wheelers	FCEV	0.60%	1.40%	1.40%	0.60%	1.3%	1.3%
Industry	Aggregated Improvement		1.00%	1.00%	2.00%	1.00%	1.00%	2.00%

Table A3
Assumption of public transportation load factor for the EA+ scenario.

End-Use	Technology	2015	2030	2060
Bus	BEV/FCEV/Hybrid Liquids	15	15.6	19.5
Passenger Train	NG/Electric	200	200.8	260

Table A4
Assumption for non-energy cost for fours wheeler technologies

Type	Technology	2015	2030	2060	Units
Car	**BEV**	13307	11065	10416	2020 USD
Car	**FCEV**	15290	12715	11365	2020 USD
Car	**Hybrid Vehicles**	11038	11228	11849	2020 USD
Car	**ICE**	10468	10606	11480	2020 USD
Car	**CNG**	11588	11684	12569	2020 USD
Large Car and Truck	**BEV**	22476	20197	19203	2020 USD
Large Car and Truck	**FCEV**	25824	22502	19920	2020 USD
Large Car and Truck	**Hybrid Vehicles**	20503	20249	20544	2020 USD
Large Car and Truck	**ICE**	19445	19127	19904	2020 USD
Large Car and Truck	**CNG**	21525	21071	21791	2020 USD
Mini Car	**BEV**	6583	4283	4031	2020 USD
Mini Car	**FCEV**	7938	5433	4180	2020 USD
Mini Car	**Hybrid Vehicles**	4579	4523	4588	2020 USD
Mini Car	**ICE**	4343	4272	4445	2020 USD
Mini Car	**CNG**	4808	4706	4867	2020 USD

Table A5
Overnight capital cost of electricity technologies for Saudi Arabia

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 A6
Fixed and variable O&M cost of electricity technologies for Saudi Arabia

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 A7
Capacity factors and lifetime of electricity technologies in Saudi Arabia

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

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