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Discussion Paper

Differentiating Upstream Crude Oil Carbon Intensities in a Net-Zero World

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

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Key Points

- Differentiating crude-oil production by carbon intensity within a net-zero pathway triggers asymmetric shifts in both supply and demand.
- Tightening climate-policy stringency pushes aggregated upstream carbon intensity lower as output pivots toward cleaner barrels.
- In net-zero scenarios, low-CI producers such as Saudi Arabia and Russia gain market share, while high-CI exporters suffer steeper declines and greater stranded-asset risk.

Abstract

Most current decarbonization policy design considers crude oil to be a homogenous commodity that misses the real-world heterogeneity in carbon intensity (CI) across different crude oil types. This study integrates asset-level CI heterogeneity into GCAM-KSA to assess how upstream CI variation affects global crude oil production, competitiveness, and stranded asset risk under different climate policy pathways. Using harmonized, field-derived CI data, we simulate both uniform and differentiated CI treatments across net-zero scenarios. While global production volumes remain similar, policy stringency interacts with CI distribution to reallocate market share and concentrate stranding risk. Producers with upstream carbon intensity below the global average (such as Saudi Arabia and Russia) consolidate residual demand, while exporters with above-average CI (including West Africa, Venezuela, and Canada's oil sands) face sharper declines and earlier asset stranding. Differentiated CI modeling of global net-zero scenarios reveals significantly higher stranded asset volumes in high-CI regions, underscoring the distributional impacts of climate policy. These findings suggest that incorporating carbon intensity into benchmarks constitutes an important prerequisite for developing targeted supply-side climate mitigation. By making asset-level CI disclosure and verification a standard practice, policymakers can better align investment flows and trade patterns with climate objectives, incentivize cleaner production, and reduce the risk of stranded assets in high-intensity regions.

Keywords: Carbon Intensity, Crude Oil, GCAM-KSA, Stranded Assets, Net-Zero Pathways

Introduction

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Producing, transporting, and refining crude oil accounts for roughly 15%-40% of well-to-wheel greenhouse gas (GHG) emissions (Dixit et al. 2023). Because these emissions accrue before fuels reach end users, upstream mitigation is indispensable for aligning the sector with climate objectives. Crucially, crude oil is not homogeneous from a carbon standpoint. Field- and asset-level studies reveal striking heterogeneity in carbon intensity (CI), with global life-cycle assessments reporting values as low as ~3-5 gCO_2e/MJ for some light conventional oils and above 25 gCO_2e/MJ for heavy unconventional sources (Masnadi et al. 2018). Differences arise from geology, extraction methods, and operational practices, especially flaring, venting, and fugitive methane (Oil Climate Index Plus Gas Consortium 2022). Masnadi et al. (2018) shows that flaring is a key driver of high upstream CI and report country-level upstream intensities up to 20.3 gCO_2e/MJ. Even within one country, the spread is striking – in Canada, for instance, Mixed Sweet has a CI of 10.73 gCO_2e/MJ, whereas oil-sands synthetics range between 26.15 gCO_2e/MJ and 27.89 gCO_2e/MJ (California Air Resources Board 2024). This heterogeneity highlights the limitations of treating crude oil as a uniform commodity in climate policy. When differences in CI are ignored or averaged out, regulators and investors risk overlooking significant emissions disparities (Hauman, Fattouh, and Terazawa 2024).

Crucially, this variability in crude oil CI complicates regulatory benchmarking and the financial valuation of oil assets (Gordon et al. 2015). Higher carbon-intensive operations impose greater climate damage per barrel, which challenges the use of uniform performance standards and average emission factors (Coffin 2021). Consequently, accurately assessing carbon-related financial and regulatory risks necessitates high-resolution, asset-level emissions data that captures heterogeneity in crude oil production pathways. Under more stringent climate policies, high-CI assets can be exposed to higher risk through carbon pricing, compliance mandates, and penalties, while lower-CI assets can gain cost and market advantages. In fact, integrated assessment modelling indicates that substantial fractions of global oil reserves must remain unextracted to limit warming to 1.5°C to 2°C, with sizable potential stranded-asset losses for upstream equity owners (Welsby et al. 2021; McGlade and Ekins 2015). Essentially, failing to differentiate between cleaner and dirtier sources could risk mispricing assets and misjudging which are most at risk in the climate policy regime.

Existing and emerging policy frameworks have recognized CI as an important climate policy lever. For instance, California's Low Carbon Fuel Standard (LCFS) proposed a volume-weighted crude-average baseline for petroleum, which provides a lever to assess compliance through credits/deficits against a baseline for finished fuels (California Air Resources Board 2024). In addition, Canada's Clean Fuel Regulations (CFR) proposed a goal for gasoline and diesel suppliers to cut lifecycle CI by 14 gCO_2e/MJ by 2030 (vs. 2016) (Dyck et al. 2022; Government of Canada 2022). Further, in the EU, the Fuel Quality Directive relies on weighted-average default CI lifecycle values for petroleum fuels (European Commission 2021). To date, the Lower Carbon Aviation Fuel (LCAF) program under The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the only mechanism that explicitly credits crude oils with upstream flaring intensities below the global average (International Civil Aviation Organization 2023). These policies illustrate a broader regulatory shift away from one-size-fits-all approaches toward transparent CI disclosure and differentiated incentives (Coren 2022). By explicitly integrating CI into crude pricing, regulators can stimulate competition among producers, encouraging decarbonization strategies that both lower emissions and create financial value (Coulomb, Henriet, and Reitzmann 2025; Shapovalova 2023). Further incorporating asset-specific CI data into corporate financial decisions can further strengthen these incentives, guiding capital toward cost-effective mitigation measures (Prest et al. 2024).

The financial stakes of upstream crude oil are high as climate policies tighten, and high-CI oil assets are most exposed to stranding premature devaluation or economic non-viability (Pye et al. 2020; Welsby et al. 2021). Emerging instruments – low-carbon fuel standards and mandatory disclosures – amplify this risk by pushing investors and lenders to differentiate portfolios by emissions intensity (Kefford et al. 2018; Fay et al. 2015). Consequently, high-CI operators face rising financing costs and divestment pressure, while low-CI producers can gain preferential access to capital. However, prevailing financial models and regulatory stress-tests still lean on industry-average emissions factors and rarely incorporate asset-level CI variability, obscuring true asset-specific risk and complicating efforts to identify which assets are most likely to strand.

Empirical evidence linking CI and asset-stranding risk remains limited and highly context-specific. Yet, understanding this relationship is increasingly important, as the viability of oil assets in a 2°C or 1.5°C world will depend not only on cost competitiveness but also on their emissions profile. Despite the growing relevance of CI, most large-scale energy-economic models and scenario analyses treat oil resources in broad categories (conventional vs. unconventional, by region or cost) without explicitly modeling carbon intensity as a differentiating parameter. This represents a critical knowledge gap. Some influential studies have highlighted the concept of "unburnable" fossil fuels – for instance, that a substantial share of known oil reserves would remain unused to meet a 2°C carbon budget (Mercure et al. 2018; Pye et al. 2020). However, to date, there has been no integrated, quantitative assessment of how upstream CI differences might translate into differential stranding outcomes for oil assets over time.

This study addresses that gap by treating carbon intensity not as a secondary descriptor but as a primary determinant of stranded asset risk in the oil sector. We explicitly incorporate regional upstream CI heterogeneity into GCAM-KSA – an extension of the Global Change Analysis Model (GCAM v7.0) tailored to Saudi Arabia – by integrating field-level carbon intensity data. By incorporating harmonized data on upstream GHG intensities of oil production, we are able to simulate how oils of varying CI compete or decline under climate policy constraints. This allows us to ask: How does upstream carbon intensity affect the economic viability and competitive standing of oil production assets under climate policy scenarios? We examine, in a forward-looking manner, how differences in carbon intensity influence oil production trajectories, asset profitability, and exposure to carbon pricing or "carbon credit" markets. By linking upstream emissions intensity to field-level economic outcomes, our study enables a more detailed assessment of how climate policies may affect the competitiveness of different oil resources. Ultimately, we argue that robust carbon intensity benchmarking and differentiated policy strategies can guide more effective decarbonization pathways for the global oil industry. By linking emissions performance to market access and investment decisions, such approaches help policymakers and investors navigate the dual challenges of climate mitigation and economic transition.

Methodology

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2.1. GCAM-KSA

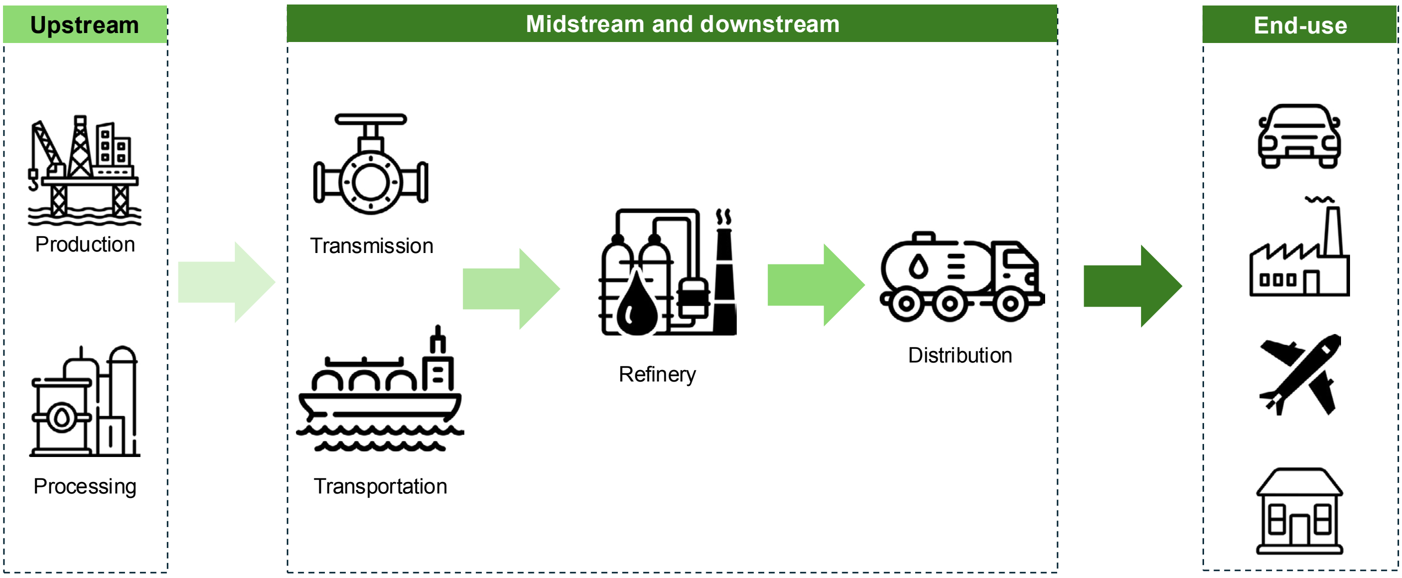
This analysis employs GCAM-KSA (Kamboj et al. 2024). GCAM-KSA treats Saudi Arabia as its own region within GCAM's 32-region global framework and retains GCAM-Core's five-year time step, iterating market and price equilibria at each interval (Calvin et al. 2019). While GCAM-Core integrates energy, water, agriculture, land, and macroeconomic modules, our implementation in GCAM-KSA centers on Saudi Arabia's energy system and GHG emissions. Technology adoption follows a logit choice formulation, allocating market share based on levelized cost differences and calibrated non-cost preferences (Clarke and Edmonds 1993). GCAM-KSA represents resource production (oil, gas, uranium, renewables), transformation processes (electricity generation, refining, gas processing, hydrogen production), and end-use sectors (buildings, industry, transport), with detailed emissions accounting (Muratori et al. 2017; Apeaning et al. 2025). The model tracks 24 gases and pollutants, including CO_2, CH_4, N_2O, fluorinated gases, short-lived climate pollutants, and ozone precursors, across the energy supply chain.

Aligned with this study's objectives, we focus exclusively on upstream Scope 1 (direct) emissions from exploration, extraction, production, and initial processing (Figure 1). This isolates the contributions of specific extraction and processing methods to CI, enabling clear attribution of upstream CI and a transparent assessment of associated financial risks under alternative decarbonization pathways.

By isolating Scope 1 upstream emissions, we assign CI values to specific extraction and processing methods and quantify their contributions to the oil sector footprint and asset risk across decarbonization pathways. GCAM-KSA captures upstream crude oil region-specific variation in resource quality, technology, and operations. GCAM's baseline CI and emissions factors are harmonized to the Intergovernmental Panel on Climate Change Emission Factor Database (IPCC EFDB), the International Energy Agency (IEA), and the Community Emissions Data System (CEDS). To enhance granularity, we replace the model's default upstream carbon intensity values with production-weighted, region-level estimates developed using the Oil Production

Greenhouse Gas Emissions Estimator (OPGEE), which is a high-resolution, engineering-based life cycle assessment tool that accounts for key operational factors such as energy use, venting, and flaring (Dixit et al. 2023). We aggregate field-level CI to region-technology coefficients and map them into GCAM-KSA, calibrating to preserve the global average in the calibration period (see Section A2 in the Appendix for more details). This hybrid calibration yields a cleaner attribution of upstream CI in the model and more realistic, asset-relevant contrasts for policy and finance analysis.

Figure 1. Crude oil value chain: from upstream through midstream and downstream to end use.



Note: This study focuses exclusively on the upstream segment.

Source: Authors.

2.2 Scenario Design

Our scenario framework incorporates two critical analytical dimensions: (i) policy-driven emission stringency to explore the effectiveness and implications of climate policy ambition, and (ii) variability in upstream CI to analyze the impact of regional and operational heterogeneity. Jointly, this integrated framework allows comprehensive exploration of crude oil production trajectories and their associated emissions profiles, providing nuanced insights into the implications for climate policy, economic outcomes, and asset risk.

2.2.1 Emission Pathways

We define three distinct emission pathways to illustrate varying levels of climate policy ambition and technology deployment scenarios (see Table 1) – a baseline scenario and two net-zero GHG pathways. The baseline scenario represents minimal climate mitigation efforts, characterized by limited investment in low-carbon technologies, and no defined peak in emissions. Between 2025 and 2060, this scenario results in global cumulative emissions of approximately 2,432.48 $GtCO_2e$, maintaining relatively stable or slightly declining crude oil production trajectories.

Despite differing levels of stringency, both climate pathways are projected to achieve net-zero GHG emissions by 2060 and are designed to reach net-zero CO_2 between 2050 and 2055, aligning with trajectories that limit warming to well below 2°C (Rogelj et al. 2015). The NetZero_Delayed scenario embodies moderate climate ambition, with moderate but delayed deployment of low-carbon technologies. Under this pathway, emissions peak around 2040, with cumulative emissions from 2025 to 2060 totaling approximately 1,538.2 $GtCO_2e$. For the NetZero_Delayed scenario, the incremental tightening of policy measures leads to a moderate, consistent decline in crude oil production compared to a sharper decline. In stark contrast, the NetZero_Early scenario, which represents a more stringent ambition, is characterized by immediate and stringent carbon pricing from 2025 and rapid, aggressive deployment of low-carbon technologies. Emissions peak early, around 2025, limiting cumulative emissions from 2025 to 2060 to approximately 972.2 $GtCO_2e$. This ambitious strategy drives rapid and substantial reductions in crude oil production, significantly elevating the risk of stranded assets and increasing economic pressures within the fossil fuel industry.

Table 1. Emission scenario assumptions and definitions.

Scenario	Climate policy ambition	Emission peak year (cumulative emissions)	Deployment of low-carbon	Implications for crude oil production
Baseline	None	None (2,432.48 $GtCO_2e$)	Minimal	Stable or slight decline
NetZero_Delayed	Moderate	2040 (1,538.2 $GtCO_2e$)	Moderate and delayed deployment	Moderate initial decline and moderate risk of stranding
NetZero_Early	High	2025 (972.2 $GtCO_2e$)	Rapid and aggressive deployment	Rapid initial decline and higher risk of stranding

Source: Author.

2.2.2 Upstream Carbon Intensity

To complement the emission pathways, our analysis incorporates detailed regional- and county-level upstream CI data, calibrated using comprehensive, peer-reviewed assessments from Dixit et al. (2023). Each emission pathway is evaluated under two distinct CI scenarios:

- Homogeneous CI Scenario: This scenario applies a single global-average carbon intensity value as a standardized benchmark. Such an approach is both practical and policy-relevant, providing a clear reference point for systematic comparison. From a policy perspective, it simulates a world where upstream carbon intensities are uniformly regulated, overlooking regional variations in regulations and operational practices. Practically, it offers a simplified yet robust basis for assessing and benchmarking upstream CI reduction strategies on a global scale.

- Heterogeneous CI Scenario: This scenario accounts for realistic, region-specific variations in CI, shaped by differences in geology, extraction technology, methane leakage, and operational efficiency. By capturing these nuances, this scenario provides a more accurate reflection of the true carbon footprint across regions. It enables deeper insights into how location-specific factors shape emission profiles, economic vulnerabilities, and asset risk, informing more targeted and region-sensitive policy and investment decisions.

Both CI scenarios are modeled such that the global average upstream carbon intensity is held constant across scenarios in the calibration period, which starts from after 2015. Specifically, the sum of regionally weighted CIs in the heterogeneous scenario is set equal to the single benchmark value used in the homogeneous scenario. This calibration ensures that any observed differences in emissions trajectories or economic impacts arise solely from the distribution of carbon intensity across regions, rather than differences in the global average CI. By holding the global CI constant in the calibration period,[1] we can directly isolate and quantify the distinct influence of regional heterogeneity on upstream emissions and associated policy outcomes.

[1] During the modeling period, the global average CI can increase or decrease depending on how production shifts geographically.

2.2.3 Rationale for Scenario Integration

Integrating emission pathways with detailed CI assumptions significantly enhances the analytical scope, enabling an exploration of the interplay between policy-driven emission reductions and regional CI variations. While emission pathways frame the broader policy landscape, the inclusion of detailed, region-specific CI data provides the granularity necessary to precisely evaluate emission reduction potentials and differential economic impacts across varying geographies and operational practices. Ultimately, this integrated scenario framework serves policymakers, industry stakeholders, and investors by yielding actionable insights to inform strategic decisions. It highlights opportunities for targeted interventions and identifies economically resilient decarbonization pathways, thereby supporting equitable and effective climate actions. All scenarios adopt socioeconomic assumptions aligned with the Shared Socioeconomic Pathway 2 (SSP2), reflecting moderate global mitigation and adaptation challenges. This uniform socioeconomic baseline ensures robust analytical comparability and balanced interpretation across diverse policy and technological contexts.

Results

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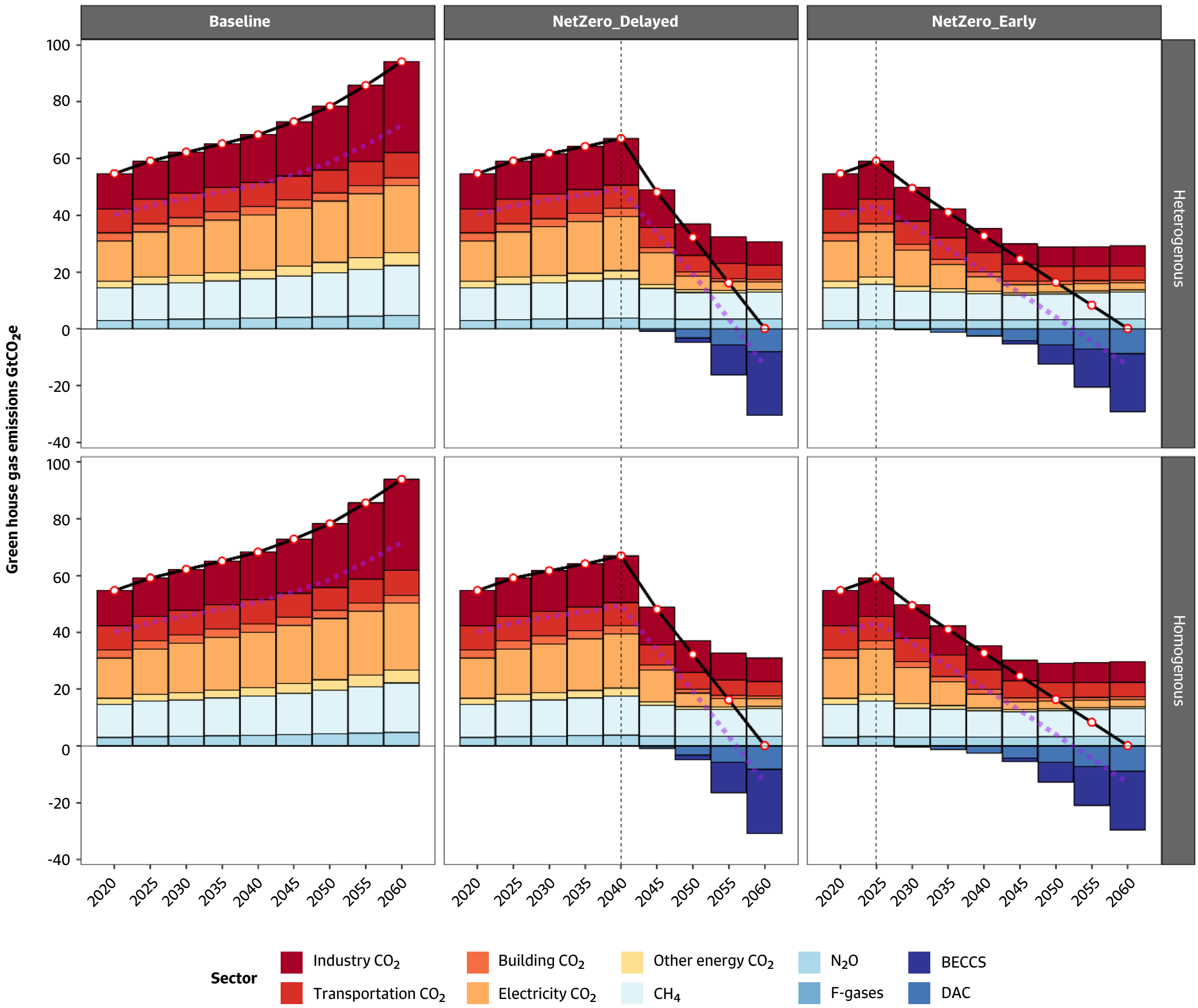
3.1 Overview of Global and Sectoral Emissions Profiles

Figure 2 illustrates the trajectories of global GHG emissions under various climate policy scenarios from 2020 to 2060, emphasizing sectoral contributions and corresponding policy implications. Under the baseline scenario, global emissions follow a pronounced upward trend, steadily increasing from approximately 54.5 $GtCO_2e$/yr in 2020 to around 90.4 $GtCO_2e$/yr by 2060. Key drivers of this growth include population expansion, economic development, intensified industrial activities, and rising energy demands, all highlighting continued dependence on fossil fuel-intensive pathways. This emission trajectory remains consistent under both uniform and non-uniform CI scenarios.

In contrast, the two net-zero scenarios demonstrate substantial emissions reductions compared to the baseline, reflecting different levels of policy ambition and technological advancement. Under the NetZero_Delayed scenario, characterized by incremental and moderate policy tightening, emissions peak at approximately 67.9 $GtCO_2e$ by 2040. Conversely, the NetZero_Early scenario, defined by immediate and rigorous policy measures, results in a considerably steeper decline, reaching significantly lower emissions of around 32.7 $GtCO_2e$ by 2040. Net-zero CO_2 emissions targets are projected to be met by 2050 under the NetZero_Early scenario, whereas the NetZero_Delayed scenario aims for 2055. Extending these pathways beyond 2060 by maintaining both gross and net emissions levels aligns the NetZero_Delayed scenario with a 2°C target, while the NetZero_Early one aligns with the more ambitious high overshoot 1.5°C target.

A key distinction between the two net-zero pathways lies in the onset and scale of negative emissions. Under the stringent NetZero_Early scenario, carbon dioxide removal (CDR) technologies are deployed earlier, resulting in negative emissions beginning as early as 2035. In contrast, substantial CDR deployment in the NetZero_Delayed scenario only emerges after 2040. Nevertheless, residual emissions persist in both of the net-zero scenarios, primarily from hard-to-abate sectors such as industry and transportation, which maintain significant reliance on fossil fuels, including crude oil and natural gas. Importantly, large-scale reductions in gross industrial and energy sector emissions are made possible by the widespread adoption of carbon capture and storage (CCS) technologies, which are integral to achieving deep decarbonization in these sectors.

Figure 2. Global and sectoral GHG emissions pathways.



Note: Short-dashed vertical black lines mark the start of climate policy year, and short-dashed purple lines represent the net CO_2 emissions.
Source: Authors.

3.2 Structural Changes in Global and Sectoral Emissions Profiles.

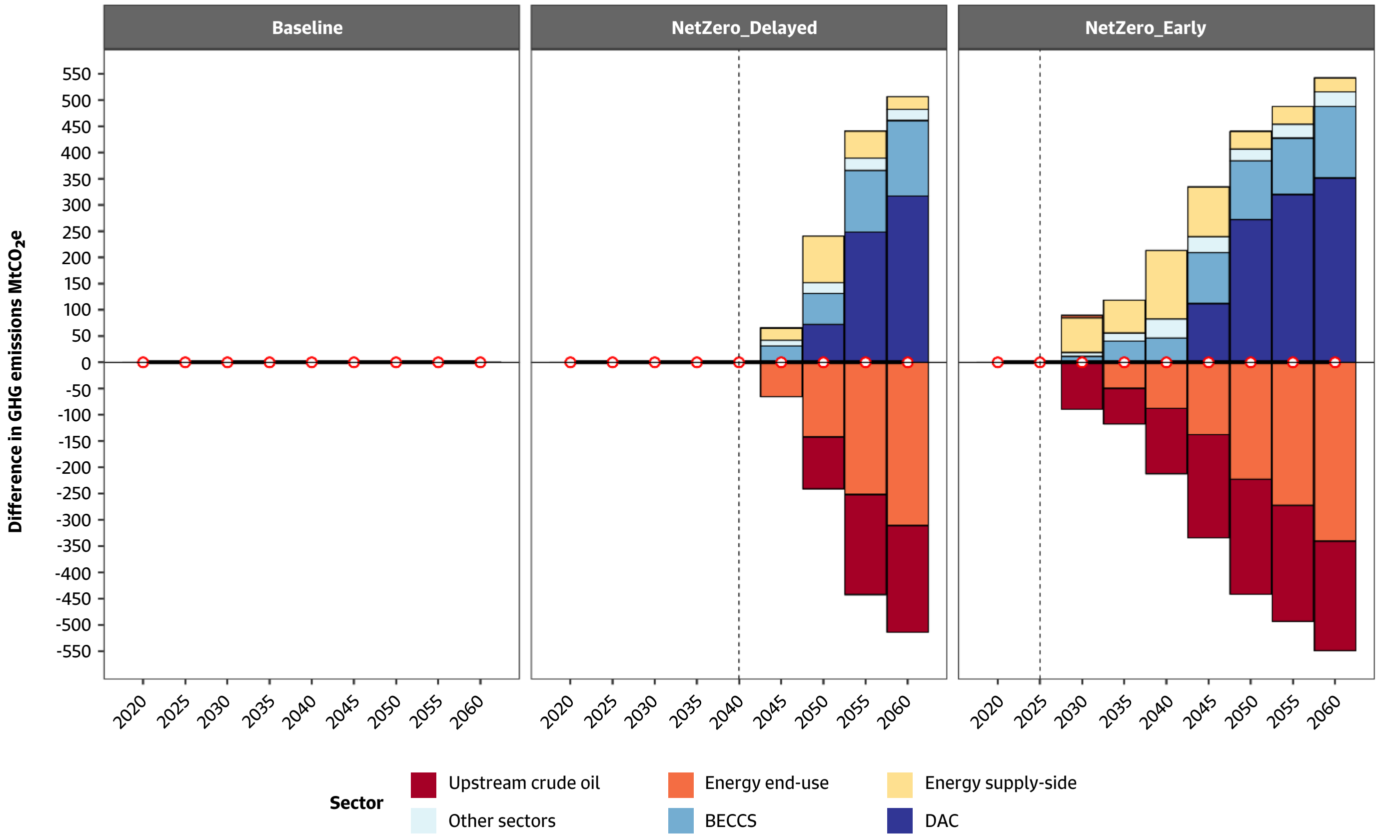
The aggregated emission profiles presented in Figure 2 mask important dynamics arising from regional variations in upstream crude oil CI. Figure 3 explicitly illustrates the emission differences between heterogeneous and homogeneous CI scenarios, with positive bars denoting higher emissions and negative bars representing reductions under heterogeneous assumptions. Between 2020 and 2025, total emissions remain nearly identical across both scenarios, reflecting minimal short-term divergence in upstream production patterns.

In the baseline scenario, the net emission difference between the heterogeneous and homogeneous scenarios are effectively zero with no notable structural shifts occurring. This pattern arises because under the baseline scenario, there is no binding policy constraint or incentive mechanism that would alter upstream technology adoption or operational efficiency, allowing the system to evolve along existing trajectories.

Similarly, under the two net-zero scenarios, the net difference in emissions between heterogeneous and homogeneous assumptions also approaches zero. Nevertheless, unlike the baseline scenario, the heterogeneous assumptions result in a net reduction in both upstream crude oil emissions. This outcome is driven by policy mechanisms that disproportionately penalize high-carbon intensity producers, thereby incentivizing output reductions in high intensity regions or shifting production toward lower-intensity regions. This underscores the effectiveness of targeted policy incentives in promoting cleaner production practices.

Additionally, structural changes extend beyond the crude oil sector in the net-zero pathways. In sectors such as energy supply and end-use experience, net emission increases under the heterogeneous scenario, primarily due to compensatory dynamics. Specifically, reductions in upstream crude oil emissions are partly offset by increased emissions from greater reliance on alternative fossil fuels, notably natural gas infrastructure. Furthermore, the heterogeneous scenario exhibits a pronounced increase in carbon dioxide removal CDR technology deployment relative to the homogeneous one, driven by heightened demand for offsetting emissions associated with higher-intensity crude production regions.

Figure 3. Differences in GHG emissions by sector and scenarios with respect to homogenous CI assumptions.

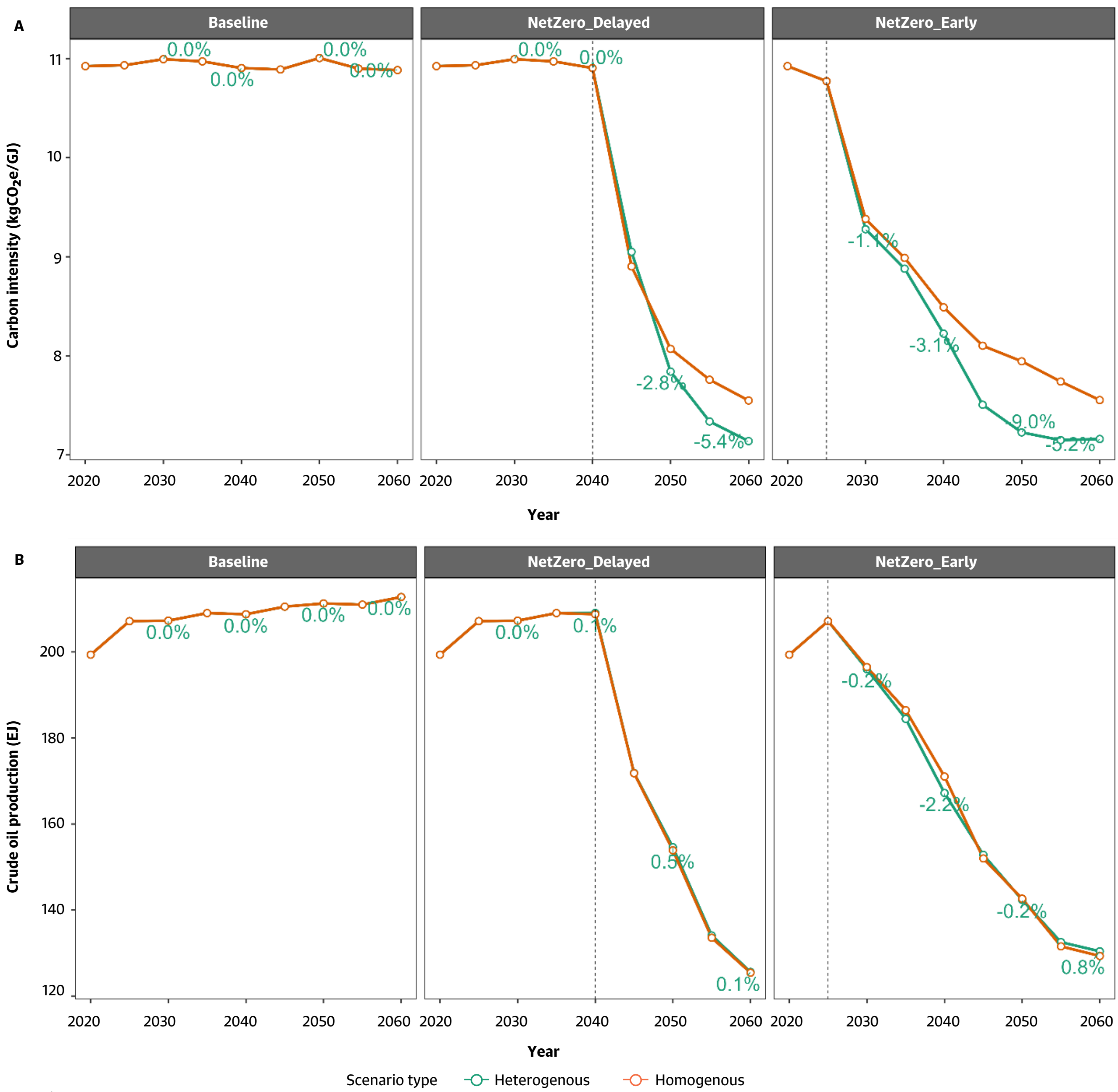


Source: Author.

3.3 Evolution of Upstream Carbon Intensity and Crude Oil Production

The evolution of aggregate upstream CI, depicted in Figure 4A, reveals critical insights into structural transformations driven by climate policy interventions. Under the baseline scenario, aggregate CI for the homogeneous and heterogeneous scenarios remains indistinguishable, stabilizing at around 10.8-11.0 gCO_2e/MJ through 2060, closely aligning with the calibration benchmark. Correspondingly, Figure 4B illustrates consistent crude oil production trajectories under baseline conditions, highlighting that without explicit carbon constraints, global crude oil production remains unchanged. In contrast, significant divergence emerges under the NetZero_Delayed and NetZero_Early scenarios once carbon budgets become binding. By 2050, aggregated CI is distinctly lower in the heterogeneous scenarios compared to the homogeneous ones – approximately 2.8% lower under NetZero_Delayed and, notably, 9.0% lower under NetZero_Early. The difference between these scenarios surpasses 5% in both by 2060. Crude oil production simultaneously declines substantially under net-zero policies, demonstrating the significant impact of policy instruments such as carbon pricing, stringent regulatory standards, and targeted abatement investments. Despite overall similarities in aggregate production declines between the heterogeneous and homogeneous scenarios, differentiated CI pathways reveal profound implications at asset and regional scales (see Section 3.4).

Figure 4. Carbon intensity and crude oil production pathways (heterogeneous vs. homogeneous).



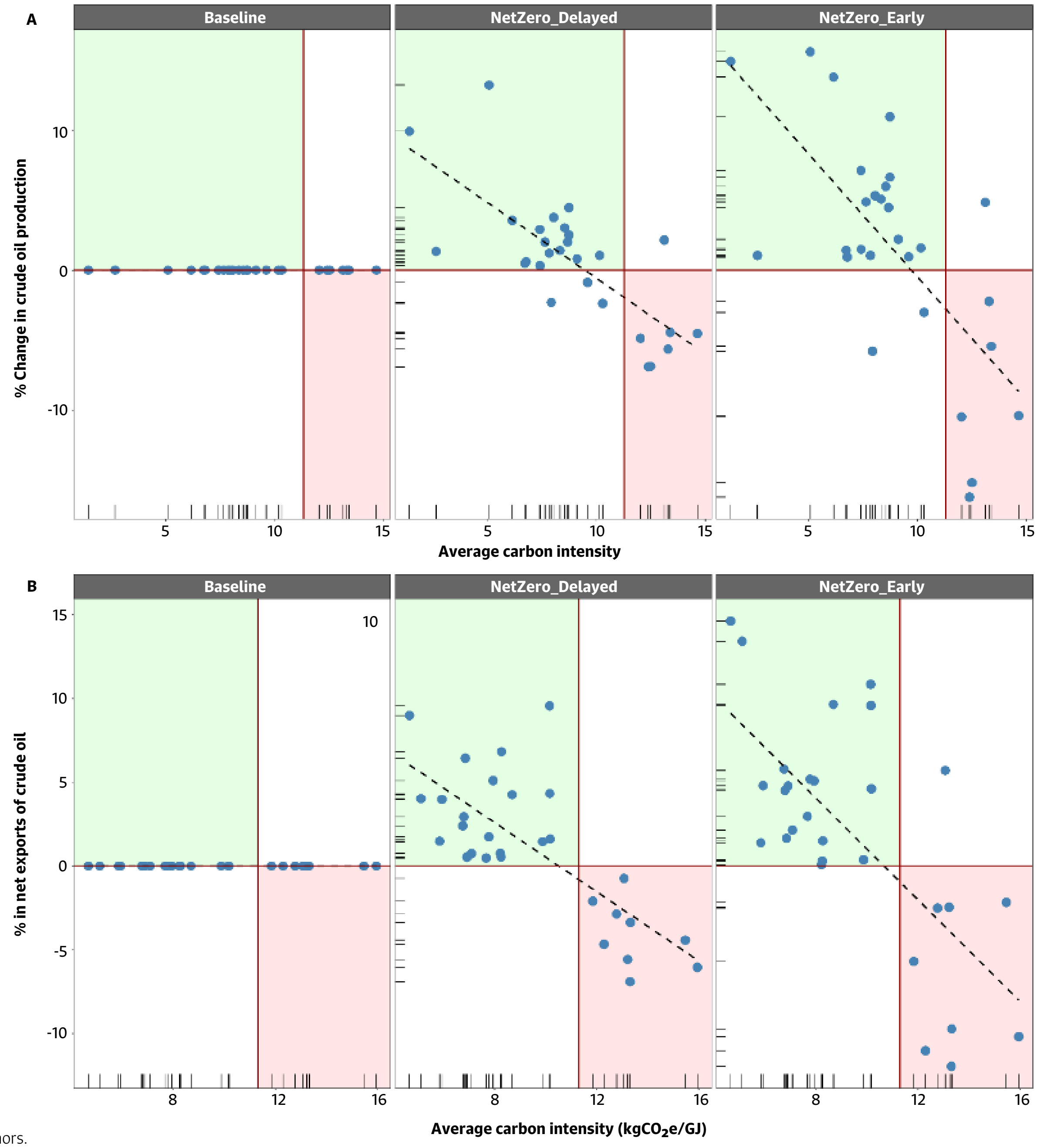
Source: Author.

3.4 Regional Implications of Heterogeneous Upstream Crude Oil

Within GCAM-KSA, upstream CI spans a wide range, from roughly 1.4 gCO_2e/MJ in Saudi Arabia to above 14 gCO_2e/MJ in the North of South America, and this variation signals markedly different levels of exposure to tightening climate policy.

Figure 5 illustrates how these differences in carbon intensity shape production and trade outcomes across the three policy pathways. It shows percentage changes in cumulative crude oil production in Panel A and net exports in Panel B, plotted against regional carbon intensity. In the baseline scenario, changes in production and exports cluster around zero, and they show little sensitivity to carbon intensity, reflecting the absence of binding climate constraints. By contrast, under the NetZero_Delayed scenario and more so under the NetZero_Early one, a negative relationship emerges. Regions with lower-than-average carbon intensity tend to maintain or slightly increase production and exports, while those with higher carbon intensity experience progressively larger declines. This pattern reflects a reallocation of market share toward lower-emission producers as climate policy becomes more stringent.

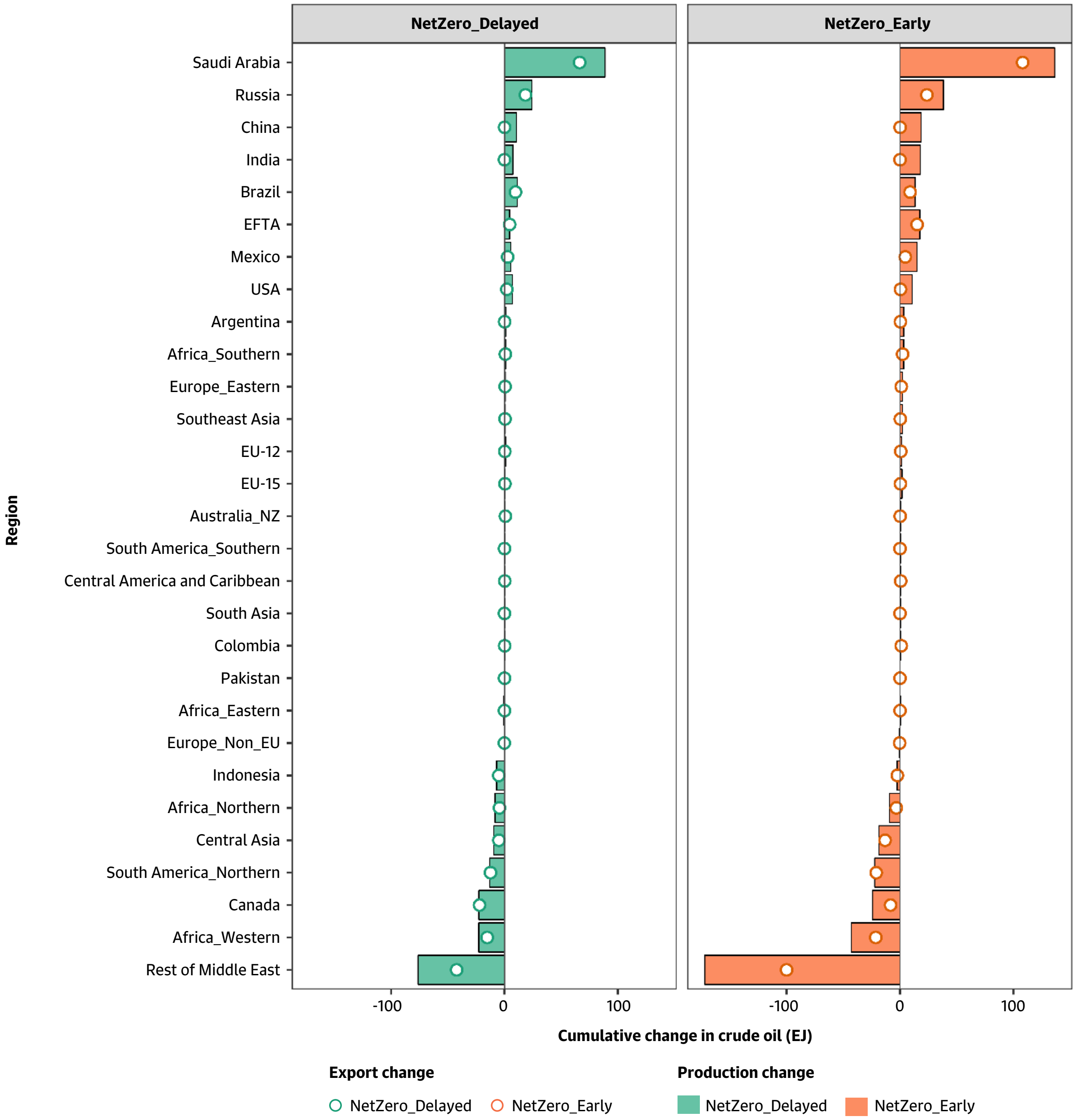
Figure 5. Impact of heterogenous carbon intensity crude oil production and net exports.



Source: Authors.

The magnitude of these reallocations is shown in Figure 6. High-CI regions, particularly the Rest of Middle East (i.e., 12.5 gCO_2e/MJ), Africa_Western (i.e. 12.3 gCO_2e/MJ), and Canada (i.e., 13.3 gCO_2e/MJ), experience substantial production declines under the NetZero_Delayed scenario, with about -76.2 exajoules (EJ), -21.5 EJ, and -23.1 EJ, respectively. This decline even intensifies under NetZero_Early. In contrast, low-CI producers gain share and production resilience, where Saudi Arabia (1.4 gCO_2e/MJ) increases cumulative production between 2025 and 2060 by ~89.1 EJ in NetZero_Delayed and ~138.4 EJ in NetZero_Early, while Russia (i.e., 7.9 gCO_2e/MJ) expands by ~36.1 EJ and ~41.3 EJ, respectively. These shifts imply a growing market premium for low-emission barrels, with clear implications for geopolitical positioning, trade patterns, and capital allocation as climate policy tightens.

Figure 6. Regional cumulative crude oil production and export change for the heterogenous scenario with respect to the homogenous one.



Source: Authors.

Not all regions, however, convert CI advantage directly into export gains. China and India expand domestic production substantially approximately 11.2 EJ and 6.9 EJ under NetZero_Delayed and 17.3 EJ and 16.9 EJ under NetZero_Early, yet these increments primarily satisfy internal demand rather than boosting exports. This divergence underscores that market outcomes can be mediated by energy-security priorities, domestic demand elasticity, and national policy design, in addition to CI. Taken together, the results show that CI heterogeneity does more than shift aggregate emissions; it reorders who can compete as decarbonization accelerates. Low-CI regions emerge as the marginal suppliers in shrinking markets, while high-CI producers face earlier and sharper contractions.

Discussion

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Increasing the stringency of net-zero policies reshapes both the volume and regional distribution of crude oil production. This shift directly affects where and how asset stranding occurs. Under the two net-zero scenarios, between 14.9% and 25.1% of modeled reserves remain unproduced compared to the baseline scenario (see Figure A1 in the Appendix). When climate action is delayed, stranding is relatively limited, ranging from 14.9% to 17.4%. In contrast, earlier and more ambitious action leads to greater impacts, with stranded volumes rising to between 21.9% and 25.1%.

These aggregate outcomes reveal more than just the scale of stranding – they uncover the structural factors that shape regional vulnerability under tightening climate policy. To explore these dynamics, we conducted standardized regression analyses examining how upstream carbon intensity, reserve size, and oil price differentials influence shifts in production and exports when comparing heterogeneous and homogeneous CI assumptions (see Section A4 in the Appendix for more detail). The results show that upstream carbon intensity is the most consistent and influential predictor. Regions with higher CI values tend to lose production and export share under differentiated scenarios, even when controlling reserves and prices. This effect is especially pronounced under the Net-Zero_Early pathway, where tighter carbon constraints amplify the competitive advantage of low-CI producers. Reserve endowments also play a meaningful role, particularly under stringent policy conditions, as larger resource bases help sustain output. In contrast, oil price differences between the scenarios show limited explanatory power, suggesting that emissions intensity and resource scale are more decisive in shaping regional outcomes under climate constraints.

Figure A2 in the Appendix illustrates how upstream carbon intensity influences the distribution of stranded assets across major producers. Regions with lower carbon intensity consistently gain market share, while those with higher intensity face increased exposure to stranding, particularly under the Net-Zero_Early scenario. Saudi Arabia stands out, reducing stranded assets by 12.2 percentage points in the early scenario and 5.7 points in the delayed case, reflecting its advantage of low emissions and large reserves. Russia and Mexico also benefit, with reductions of 9.4 and 10.4 percentage points, respectively, in stranded asset exposure under early action, though the gains are more modest when policy ambition is delayed. In contrast, producers with higher upstream carbon intensity experience growing vulnerability. The Rest of the Middle East sees stranded asset exposure rise by nearly 30 percentage points under early action and by 14.6 points under delayed action. West Africa and Canada follow similar trajectories, with stranding increasing by 24.3 and 8.6 percentage points, respectively. These shifts underscore how carbon intensity functions as a structural disadvantage in carbon-constrained markets, where emissions performance increasingly shapes competitiveness.

While carbon intensity emerges as the dominant factor, reserve size also plays a meaningful role in shaping regional outcomes. Countries like Saudi Arabia and Russia benefit not only from lower emissions but also from large, low-cost reserves that help sustain output even as global demand contracts. In contrast, high-intensity producers with smaller or less flexible reserves – such as Indonesia, Central Asia, and parts of North Africa – are more exposed to early declines in market share, especially under stringent climate policies. Ultimately, the interaction between upstream carbon intensity and reserve scale determines how regions reposition within the global oil supply hierarchy. Where both factors align, producers are better positioned to maintain resilience in a shrinking market. Where they diverge, the risk of asset stranding accelerates. These findings reinforce the strategic importance of early upstream decarbonization, not only to reduce emissions but also to preserve long-term viability in an increasingly carbon-sensitive global energy landscape.

Conclusion and Policy Implications

05

Carbon intensity has shifted from a technical metric to a policy lever that now shapes procurement rules, import regimes, disclosure standards, and, increasingly, credit and insurance. In that context, our results show that in a net-zero world, the allocation of crude oil production is largely shaped by heterogeneity in upstream CI. This asymmetry functions as a filter in which cleaner barrels meet buyer standards and policy screens, whereas carbon heavy supply is progressively priced out or redirected. As market share tilts toward low CI producers, system-wide upstream intensity declines, and the burden of stranding accumulates in portfolios dominated by high CI assets. Our study provides proof of concept that differentiating crude by upstream CI, such as through carbon pricing and CI indexed benchmarks, can reshape the market dynamics of fossil fuel in a climate pathway. In addition, this study addresses a persistent gap in modelling and risk practice, where crude is often treated as homogeneous. It also highlights that once asset level CI is made visible, stranding becomes more concentrated and more sensitive to policy timing, and becomes more clearly mediated by each producer's capacity to deliver credible reductions in CI.

Our analysis also shows that winners and losers are not symmetrical. Saudi Arabia and Russia gain share in both of the net-zero pathways, whereas West Africa, the rest of the Middle East, Venezuela, and Canada experience earlier and deeper stranding. Other low-CI regions expand production, chiefly to satisfy domestic demand rather than to export, which underscores how CI interacts with energy security priorities and national policy design. Taken together, these patterns underline the policy relevance of differentiating CI across the fossil fuel value chain. Such differentiation can be used to incentivize credible upstream decarbonization, steer capital and offtake toward lower CI supply, and guide a more orderly transition.

The practical implications of this study underscore the need to make upstream carbon intensity both transparent and enforceable through asset-level measurement, reporting, and verification. Implementing CI-differentiated benchmarks can drive large-scale supply-side abatement without relying solely on demand reduction. It signals to high-CI producers the imperative to upgrade operations or exit the market, thereby reducing the risk of disruptive late-stage adjustments. Public and private finance should be channeled toward credible decarbonizers through preferential lending terms, expedited permitting for electrified and CCS-enabled fields, and performance-based contracts that reward independently verified CI reductions.

The financial community has a pivotal role in enabling this shift. Treating crude oil as a homogeneous commodity misprices transition risk, as exposures diverge sharply when CI differences are accounted for. Banks, insurers, and sovereign risk managers that continue to price on asset averages risk over-allocating capital to high-liability assets while missing the upside potential of verifiable low-CI portfolios. Integrating asset-level CI diagnostics and satellite-validated methane measurements into core prudential tools – alongside reserve-based lending criteria and bond covenants tied to CI trajectories rather than volumes and costs alone – can align capital allocation with a lower-carbon supply future.

The geopolitical and equity dimensions will strongly influence how these dynamics unfold. CI-aware policy ultimately determines who produces the "last barrel." Countries with structurally high CI will face steeper and more urgent adjustments, whereas those with structurally low CI – if supported by robust finance and governance – can position themselves as anchors of residual demand. Measures such as eliminating routine flaring, electrifying production sites, enhancing leak detection, and deploying CCS can drive emissions down while preserving macroeconomic stability in both producing and importing economies.

While our analysis provides important insights, it also opens opportunities for further research. The version of GCAM applied here does not yet endogenize certain late-stage upstream abatement options (such as full-field electrification, blue hydrogen power islands, or carbon-negative enhanced oil recovery) and abstracts from potential frictions in capital and technology flows. Expanding GCAM's capability by coupling it with field-scale techno-economic modules and integrating high-resolution measurement data could improve representation of both technological and spatial heterogeneity.

Future work could also explore linking GCAM-KSA with a computable general equilibrium framework to capture economy-wide feedback from CI-differentiated trade policies, fiscal impacts, and labor market adjustments. This would enable stress-testing of CI-based trade rules under demand or finance shocks, and would allow examination of sequencing strategies that minimize stranded-asset cascades while maintaining fiscal stability.

Ultimately, in a net-zero world, carbon-efficient producers will strengthen their position, while high-CI suppliers face a shrinking window for adaptation. What remains uncertain is the pace and credibility of policy action, and, with it, the degree to which the transition unfolds in an orderly or disruptive manner.

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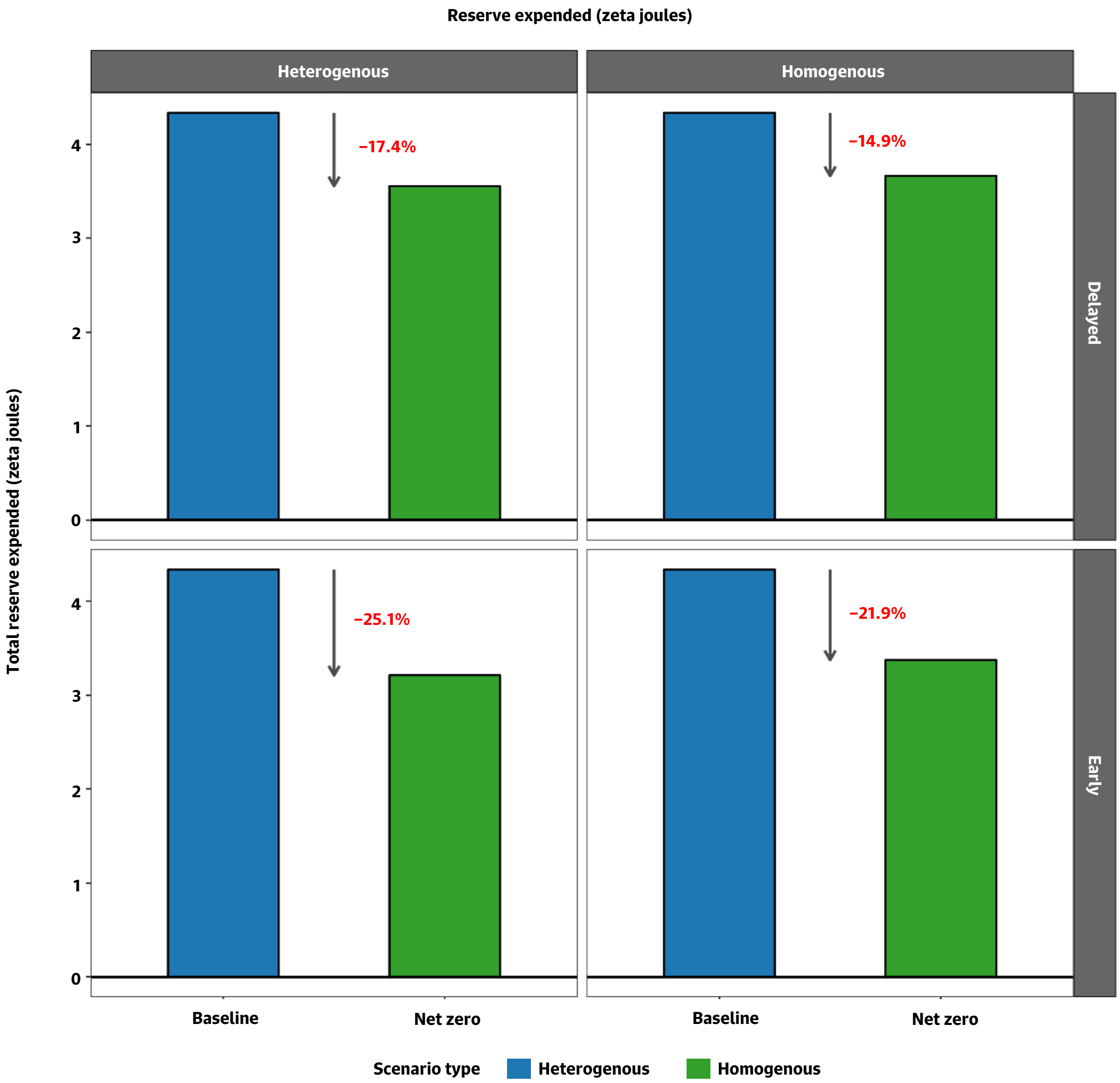
Appendix

A1. Regional and Global Stranded Crude Oil Assets

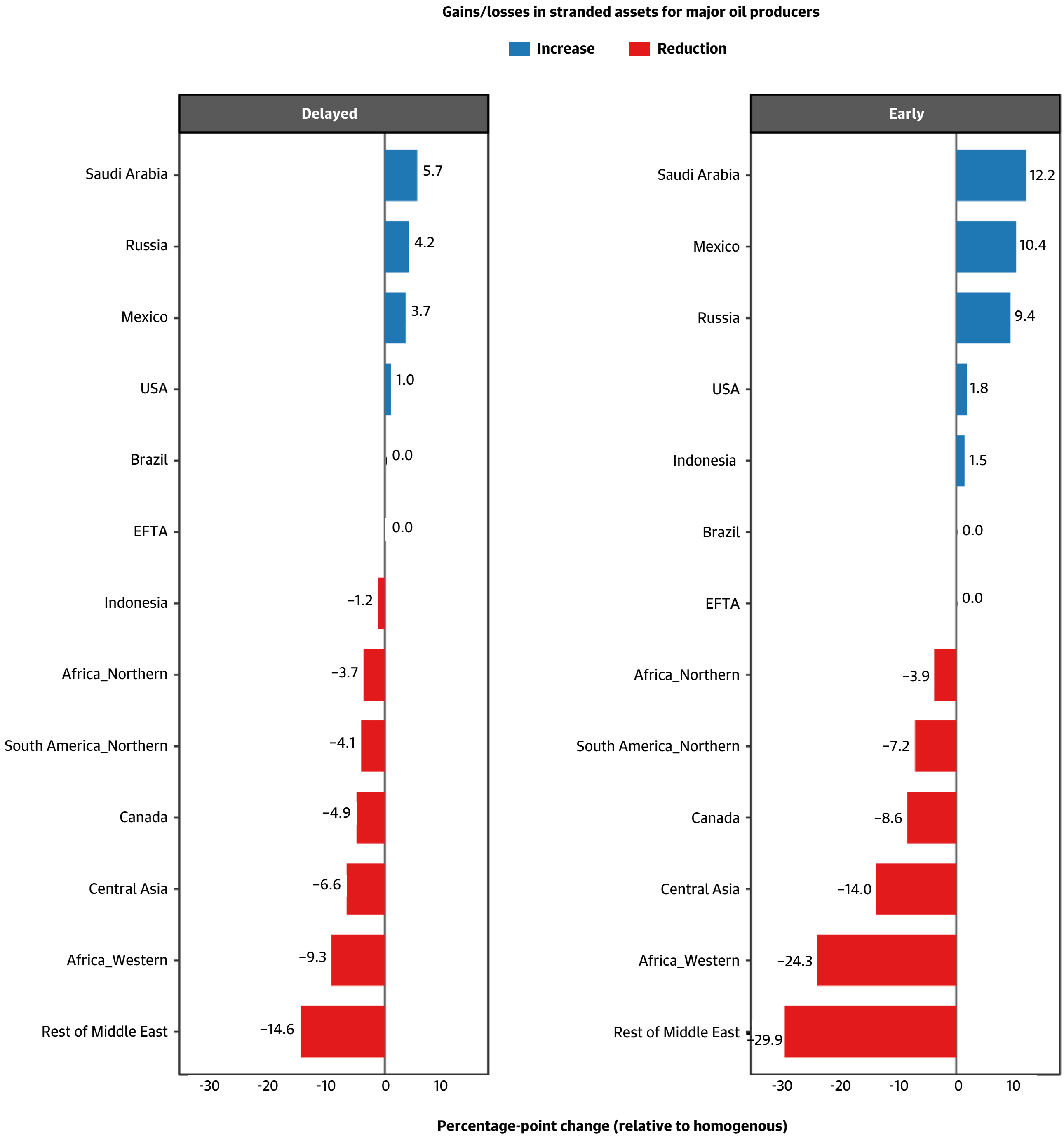
This section presents the results on the magnitude and regional distribution of crude oil reserves expended and the incidence of stranded assets under varying net-zero pathways. For stranded asset estimation, we employ a simple accounting framework, as described in Section A3, which compares economically viable oil reserves under baseline and net-zero scenarios. This method enables transparent attribution of gains and losses in stranded asset shares across major oil-producing regions, highlighting the distributive consequences of alternative transition designs.

Figure A1. Total reserves expended (zettajoules, ZJ) by scenario.



Notes: Panels combine net-zero stringency and CI allocation assumption. Bars compare baseline (blue) with net-zero (green) while red labels report the percent change of net-zero scenarios relative to the baseline one. Baseline reserves expended remain constant at 4.3 ZJ across all of the cases. Net-zero scenarios show consistent reductions in reserve usage, which range from -4.9% to -25.1%, with the largest savings observed under early-heterogeneous transitions.
Source: Authors.

Figure A2. Gains and losses in stranded crude oil assets for major oil producers under heterogeneous burden-sharing, relative to a homogeneous reference.



Notes: Bars show the percentage-point change in stranded asset shares across regions for the delayed (left) and early (right) transitions. Blue bars indicate increases (gains), while red bars indicate decreases (losses) in stranded asset shares compared to a homogeneous allocation.
Source: Authors.

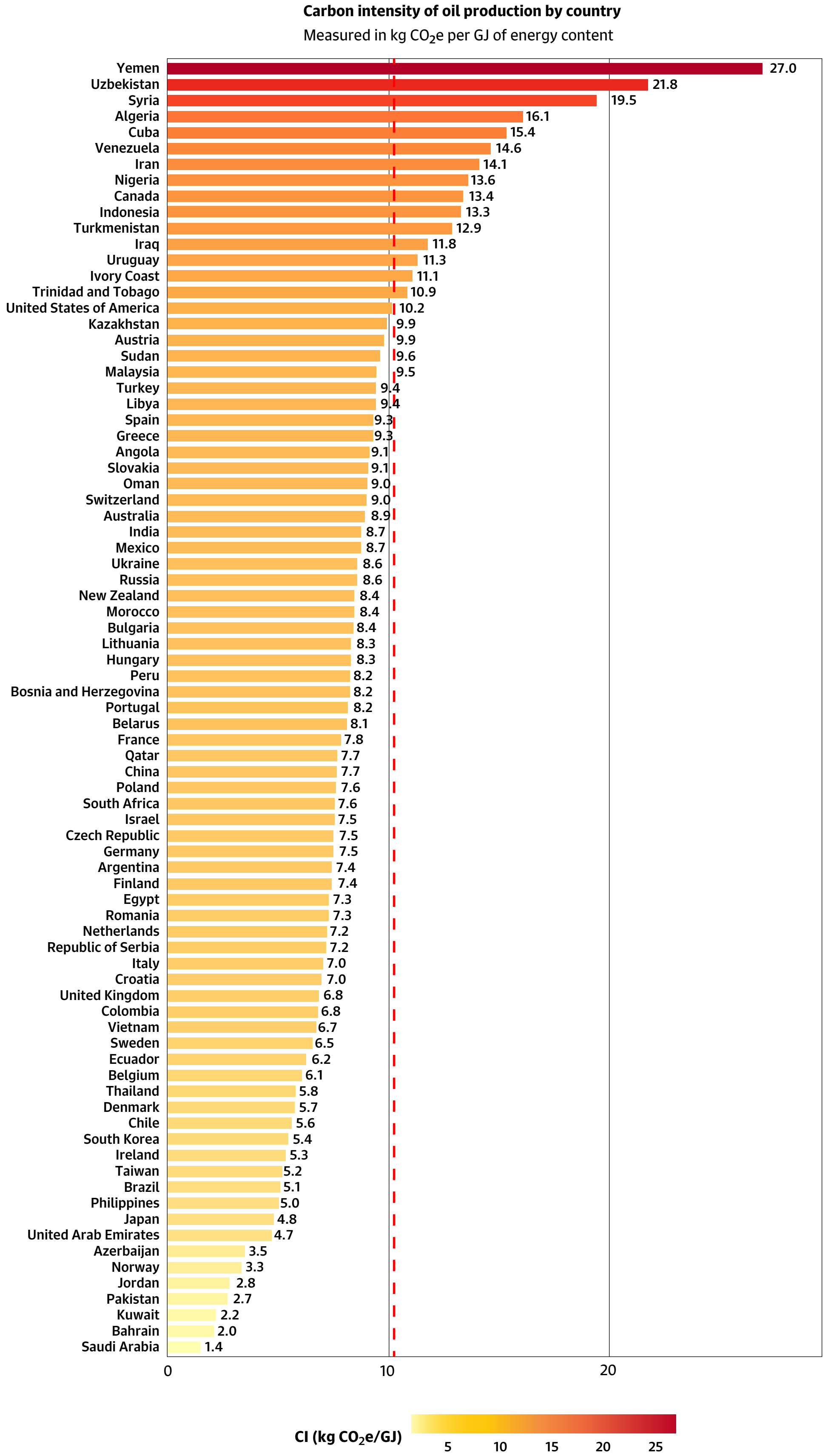
A2. Upstream Carbon Intensity Model Calibration in GCAM

The upstream crude oil carbon intensities in GCAM were calibrated through an iterative three-stage protocol consisting of data assembly and vetting, harmonization to GCAM's regional structure, and final model validation. We began by sourcing country-level upstream carbon intensity values from multiple datasets, including Jing et al. (2020), Masnadi et al. (2018), and Dixit et al. (2023). For this study, we selected Dixit et al. (2023) as the foundational dataset, given that it is the most recent and is based on the updated OPGEE Version 3.0c. This version introduces significant methodological improvements over earlier datasets such as Masnadi et al. (2021), which utilized OPGEE v2.0. The improvements include more refined process modeling and better alignment of estimated carbon intensities with operator-reported data. The dataset spans more than 70 countries and accounts for over 90% of global crude oil production, offering broad geographic coverage and higher resolution than previous estimates.

To harmonize this dataset with the GCAM-KSA version of the model, which includes 33 geopolitical regions, we translated country-level carbon intensity values into regionally consistent inputs. Major oil-producing countries such as Saudi Arabia, the United States, and Canada retained their specific national carbon intensity estimates. For broader aggregate regions such as the Rest of the Middle East or Western Africa, we calculated production-weighted average carbon intensities using constituent countries within each GCAM region. This approach allowed us to retain as much heterogeneity as possible, while ensuring complete data coverage for all regions required by the model (see Figure A3 for regional mapping).

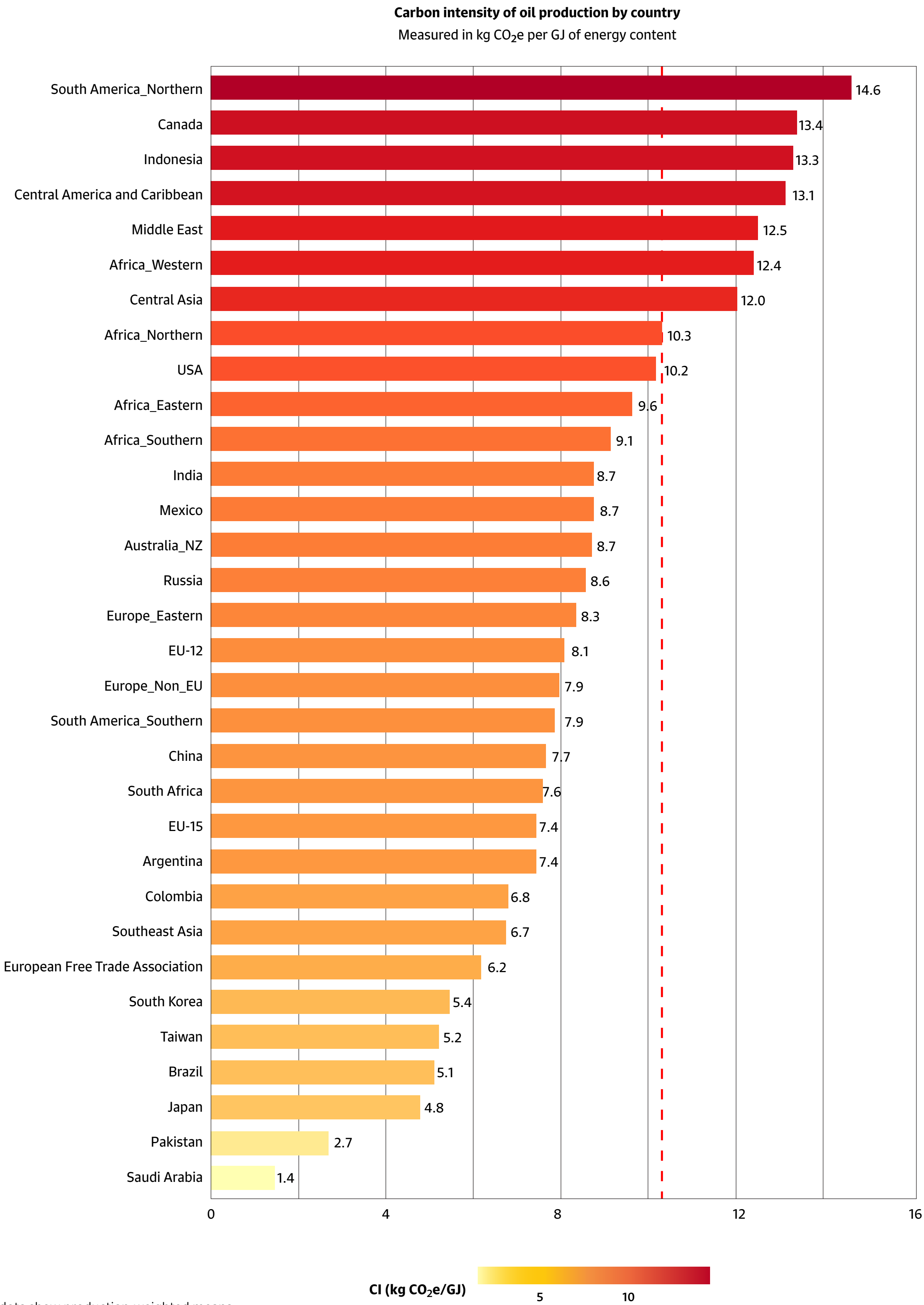
In the final stage, we used these aggregated carbon intensity values to calibrate the model's upstream oil emissions. We then validated the calibration by running historical baseline simulations and comparing the resulting regional and global carbon intensity outputs to established external benchmarks. The differences between model outputs and historical reference values were within a margin of 1% to 6%. These minor deviations primarily stem from the aggregation of country-level data into GCAM's regional definitions, where production-weighting choices and missing field-level reporting can result in small numerical shifts. However, the deviations remained consistent across all regions and were quantitatively small, which reinforces confidence in the robustness of the calibration protocol. In addition, our scenario design – specifically the comparison between homogeneous and heterogeneous upstream carbon intensity assumptions – preserves the internal logic of the model while allowing us to isolate the influence of carbon intensity heterogeneity on system-wide emissions outcomes. This enables a more nuanced understanding of the role upstream variation plays in shaping the mitigation potential and distributional effects of oil sector decarbonization strategies. Altogether, this calibration process ensures alignment between detailed country-level evidence and the regionally aggregated structure of GCAM, thereby improving the accuracy of global upstream oil-sector greenhouse gas emission modeling.

Figure A3. Upstream carbon intensity of crude oil production across countries (kg CO_2e/GJ).



Source: Dixit et al (2023).

Figure A4. Regional level upstream crude-oil carbon intensity (kg CO_2e/GJ).



Note: Black dots show production-weighted means.

Source: Authors.

A3. Computing Stranded Assets in GCAM

Stranded assets refer to oil reserves or coal resources that are technically extractable but remain undeveloped due to changes in market conditions, policy interventions, or declining competitiveness. In climate policy scenarios, such reserves are typically left untapped as a result of emissions constraints, reduced demand, or a shift toward low-carbon alternatives. In this study, stranded fossil reserves are estimated using a cohort-based accounting framework implemented within the Global Change Analysis Model (GCAM). This approach compares extraction trajectories under a Baseline scenario – where no climate policy is imposed and upstream carbon intensity is treated uniformly – with those under a net-zero policy scenario that incorporates carbon heterogeneity and imposes climate targets consistent with a 1.5°C pathway.

In GCAM, fossil fuel extraction is determined endogenously based on region-specific supply curves, demand for energy carriers, and policy constraints. These supply curves are segmented by cost tiers and extracted over discrete time intervals. Each model period – typically decadal in resolution – represents a distinct cohort of fossil reserves. A reserve cohort is defined as the group of fossil resources that are projected to be economically extracted in a specific time period under a given scenario. This temporal segmentation allows for transparent accounting of which cohorts are developed under different policy environments and, conversely, which ones become stranded.

GCAM tracks the cumulative volume of fossil resource extraction for each region and time step, disaggregated by fuel type and scenario. Under the baseline scenario, reserves are extracted according to market forces alone, without any emissions constraints. Under the net-zero policy scenario, extraction is shaped by upstream carbon intensities, carbon prices, and mitigation targets. Stranded assets are identified as the difference between the amount of reserves extracted in the baseline scenario and those extracted under the net-zero policy scenario for each cohort. These represent fossil resources that would have been developed in the absence of climate action but are no longer economically viable or competitively prioritized within a carbon-constrained world. Reasons for stranding include reduced demand, carbon penalties, and substitution by cleaner energy sources.

The total volume of stranded fossil reserves in a given region is computed as the sum of the differences in cohort-level extraction between the baseline and net-zero policy scenarios. The formulation is given by:

$$\text{StrandedReserves}_r = \sum_c (R_{r,c}^{\text{baseline}} - R_{r,c}^{\text{policy}})$$

where $R_{r,c}^{\text{baseline}}$ is the cumulative volume of fossil resources extracted in region r from cohort c under the baseline scenario, and $R_{r,c}^{\text{policy}}$ is the corresponding volume extracted under the net-zero policy scenario. All values are expressed in physical units, such as exajoules (EJ) or megatonnes (Mt), depending on the fuel type and reporting needs. This approach isolates the physical quantity of reserves that become undeveloped due to the policy intervention, offering a consistent and model-transparent metric of stranded assets.

The use of cohorts, rather than vintages, enhances interpretability by linking stranding to the expected time of extraction rather than discovery or project commissioning. It enables analysts and policymakers to identify not only how much is stranded, but also when and where stranding occurs. This is especially valuable in evaluating the distributional impacts of different transition pathways and in assessing the investment risks for producing regions and companies. By avoiding assumptions about future prices, asset valuations, or financial write-downs, the cohort-based method provides a physically grounded and policy-relevant indicator of stranded fossil resources under various climate scenarios.

A4. Evaluating Difference in Crude Oil Production and Net Export Across Scenarios

To assess the influence of regional variation in upstream carbon intensity – alongside other structural factors such as crude oil reserves and regional price dynamics – we estimate a series of standardized linear regression models. This approach allows us to identify the main drivers of regional shifts in oil production and trade outcomes under different net-zero pathways. The dependent variables are defined as the cumulative difference in regional crude oil production and net exports, measured as the difference between outcomes under heterogeneous and homogeneous upstream carbon intensity assumptions:

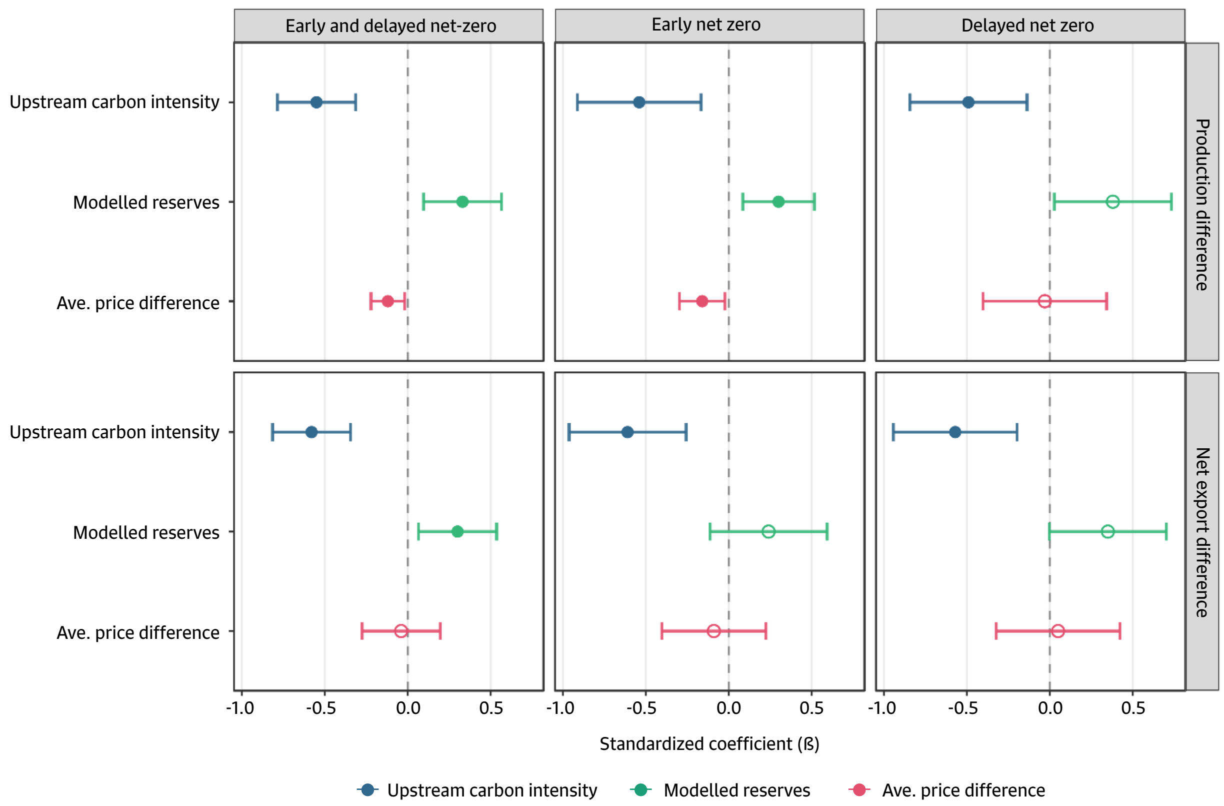
$$\Delta\text{Production}_r = \sum_t \text{Production}_{r,t}^{\text{het}} - \sum_t \text{Production}_{r,t}^{\text{hom}}$$

$$\Delta\text{NetExports}_r = \sum_t \text{NetExports}_{r,t}^{\text{het}} - \sum_t \text{NetExports}_{r,t}^{\text{hom}}$$

Here, "het" and "hom" denote scenarios with heterogeneous and homogeneous upstream carbon intensities, respectively. We estimate a linear model using three z-standardized predictors: regional upstream CI, modeled crude oil reserves (as a proxy for long-term production potential), and the average difference in oil prices between the two scenarios across the model horizon. Standardization allows us to compare the relative strength of each factor directly. The model specification is as follows:

$$y_r = \beta_0 + \beta_1\,\text{CI}_r + \beta_2\,\text{Reserves}_r + \beta_3\,\Delta P_r + \varepsilon_r$$

Figure A5. Standardized regression coefficients with 95% confidence intervals for each scenario-outcome combination.



Source: Authors.

Figure A5 reports standardized coefficients with 95% confidence intervals for the pooled case that combines Net-Zero_Early and Net-Zero_Delayed, as well as for each scenario separately. Results are presented for production differences and net export differences. Three consistent patterns emerge across the models. Please note that the error bars represent 95% confidence intervals. Coefficients whose confidence intervals do not cross the zero line are considered statistically significant at the 5% level, indicating a robust directional association. Conversely, when the error bar crosses zero, the estimated effect is not statistically distinguishable from zero, implying no significant relationship under that scenario-outcome pairing.

First, upstream carbon intensity is the strongest and most stable predictor. The coefficient is negative and statistically significant in every panel, indicating that regions with higher upstream carbon intensity tend to lose production and net export share when heterogeneity is introduced. This effect is most pronounced under the Net-Zero_Early scenario, where tighter carbon constraints shift competitive advantage toward low-intensity producers.

Second, modeled reserves show a positive and moderately strong association with outcomes. The effect is statistically significant in the pooled regression and also under the Net-Zero_Early scenario for crude oil production differences. This suggests that, when policies are more stringent, the scale of crude oil endowment plays a greater role in sustaining output, particularly for regions operating below the global average carbon intensity.

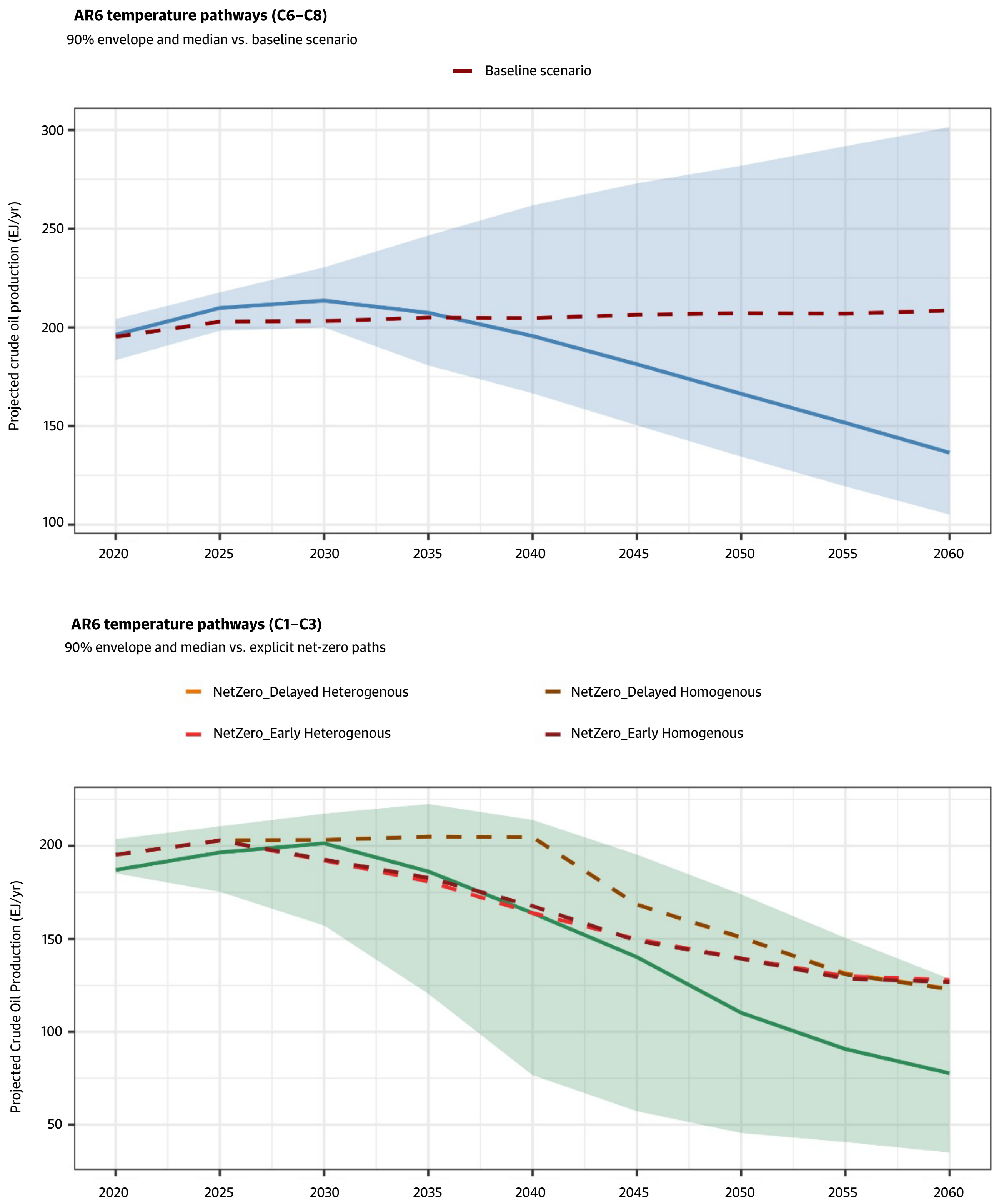
Third, the average price difference between the heterogeneous and homogeneous scenarios exhibits limited explanatory power. The coefficients are small and generally centered near zero. A modest negative association appears in the Net-Zero_Early panels, but this effect is weak when compared to the influence of carbon intensity and reserves. Under the Net-Zero_Delayed scenario, the effect becomes even less pronounced.

Overall, the analysis shows that introducing upstream carbon intensity heterogeneity reshapes the competitive landscape of global oil supply. Low-intensity regions consistently gain market share, while high-intensity producers contract, even when reserves and prices are held constant. Among the three variables, carbon intensity emerges as the primary determinant of regional resilience under net-zero pathways. Reserves remain important, especially in regions with large conventional resource bases, and their influence becomes more pronounced when policy action is delayed. Early alignment with net-zero policy enhances the importance of carbon efficiency and diminishes the role of price-based competition. These findings reinforce the strategic imperative for producers to decarbonize upstream operations early to maintain viability in low-carbon oil markets.

A5. Comparison of Crude Oil Projections with AR6 Emission Pathways

Figure A4 compares our model results for crude oil production trajectories against the AR6 database. In the top panel, the baseline scenario tracks the AR6 median closely through the early decades, remaining well within the 90% envelope. After 2040, the baseline diverges upward from the AR6 median, showing a flatter production profile while still falling within the upper half of the AR6 range. The lower panel compares our two net-zero pathways – Early and Delayed, under heterogeneous and homogeneous upstream carbon intensity assumptions – to the AR6 subset C1, C2, and C3 scenarios. Through 2040, our Net-Zero_Early pathway aligns closely with the AR6 median, while the Net-Zero_Delayed pathway sits slightly above it. After 2045, both pathways remain inside the AR6 uncertainty band, but tend toward its high-oil edge, especially by 2060, when our values are roughly 60% above the AR6 median yet still just under the 90th percentile. Overall, our projections are more oil-permissive than the AR6 medians in the long term – reflecting slower assumed demand reductions, greater reliance on CCS/CDR to offset residual emissions, and the absence of stringent early supply-side constraints – while remaining fully consistent with the broader AR6 scenario envelope.

Figure A6. Global crude oil production trajectories (EJ yr^{-1}), 2020-2060.



Notes: Top: AR6 C6-C8 pathways – median (blue) with 90% envelope (blue shading) – compared with the baseline scenario (red dashed). Bottom: AR6 C1-C3 pathways – median (green) with 90% envelope (green shading) – overlaid with explicit NetZero_Early and NetZero_Delayed scenarios under homogeneous and heterogeneous carbon-intensity assumptions (colors per legend). Shaded bands denote the 5th-95th percentile range; lines show medians or scenario trajectories.
Source: Authors.

About the Authors

Raphael Apeaning

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

Puneet Kamboj

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

Diego Moya

Diego Moya holds a Ph.D. in Energy Economics, Transitions, and Policy from Imperial College London. He has served as an Honorary Academic Visitor at Imperial since September 2022 and is a former Visiting Scholar at Griffith University, Australia. He joined Saudi Aramco as an Energy Sustainability Scientist in December 2022. His research focuses on global energy transitions, applying GeoAI, big-data analytics, geospatial modeling, agent-based modeling, and life-cycle assessment to energy systems, supply chains, and emissions. He is an appointed Lead Author for IPCC AR7 (WGIII, Chapter 9: Energy Systems) and previously served as a Reviewer for IPCC AR6.

Yang Qiu

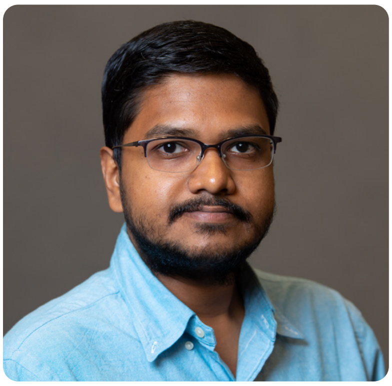
Yang is a postdoctoral researcher at the Pacific Northwest National Laboratory (PNNL). Yang has a Ph.D. in Environmental Science and Management from the University of California, Santa Barbara, two M.S. degrees – first in Applied Statistics from the Syracuse University, and second in Environment Science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

Neal Graham

Neal Graham is an Earth scientist at the Joint Global Change Research Institute in College Park, MD. His research interests include human–water system interactions and short- and long-term multisectoral impacts on the human–Earth system. Neal holds a BS in meteorology from Rutgers University and an MS and PhD in atmospheric and oceanic sciences from the University of Maryland.

Kyle Page

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



Gokul Iyer

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

Mohamad Hejazi

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

About the Project

This study is part of the Climate Adaptation and Mitigation Partnership (CAMP) project. The CAMP project is both timely and crucial for Saudi Arabia, given the mounting risks associated with climate change impacts, the urgency of advancing toward a low-carbon future while maintaining national economic growth, and the potential economic ramifications of global mitigation efforts on the Saudi energy sector and economy. Against this backdrop, the project investigates (1) the climate conditions in Saudi Arabia, (2) the sectoral impacts and the role of adaptation measures, and (3) the pathways for the Saudi economy to achieve a low-carbon future or climate neutrality by midcentury. The study will also adopt the circular carbon economy concept in characterizing the Saudi government's efforts to decarbonize the economy while supporting continued growth.

kapsarc.org
info@kapsarc.org
/kapsarc