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Discussion Paper

Key Drivers of Decarbonizing Hard-to-Abate Energy-System Sectors by Midcentury

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Abstract

To limit global warming to 1.5°C or 2°C, achieving a net-zero or near-zero greenhouse gas emission energy system by midcentury is essential. This ambitious target requires the decarbonization of hard-to-abate sectors, particularly transportation and heavy industry. This study employs an integrated energy-economic-climate assessment model to explore decarbonization pathways aligned with these temperature goals. The results show that by 2050, residual emissions from key industrial sectors – such as chemicals, fertilizers, iron and steel, aluminum, and cement – are projected to range from 30.2% to 82.5% of baseline levels under climate policy scenarios. In transportation, emissions from aviation and shipping are expected to remain between 70.2% and 91.2% of baseline levels. The analysis of decarbonization drivers reveals that demand-side strategies – such as improving energy efficiency and optimizing activity levels – are the main levers for decarbonizing aviation and shipping. On the supply side, technologies such as carbon capture and storage (CCS) are crucial for reducing emissions in heavy industries, whereas electrification is key for decarbonizing aluminum. This study provides actionable insights into the strategies needed to achieve a near-zero or net-zero energy system by mid-century, emphasizing the importance of integrating technological innovation with strong policy support.

Keywords: Hard-to-Abate Sector, Decarbonization, Energy Transition, Net-Zero Energy Systems

1. Introduction

The need to address climate change and reduce greenhouse gas emissions has placed the decarbonization of global energy systems at the forefront of international policy discussions (UNEP 2023). This effort aligns with the 2015 Paris Agreement's ambitious goal of keeping the temperature increase below 2°C and pursue efforts to keep the increase as low as 1.5°C (Gambhir et al. 2019). However, this task is fraught with challenges, including the path dependence of fossil fuels and overcoming regulatory and market barriers that obstruct the transition toward cleaner energy solutions (Paltsev et al. 2022; Sharmina et al. 2021; Yang et al. 2022). These hurdles are particularly pronounced in hard-to-abate sectors such as aviation, shipping, road freight, and heavy industry. The decarbonization challenges of these sectors include their highly energy-intensive operations, the absence of easily scalable low-carbon technologies, and the global economic frameworks that support these industries (Åhman 2020; de Pee et al. 2018). To meet the Paris Agreement's climate objectives, a transformation to a near-zero or net-zero-carbon energy system by midcentury is vital (Davis et al. 2018; DeAngelo et al. 2021; Kuramochi et al. 2018). This transformation demands a concerted effort to reduce emissions across every sector of the energy landscape. However, many scenario studies suggest that by midcentury the implementation of carbon removal technologies will be essential to counterbalance the residual emissions from hard-to-abate sectors (Luderer 2018). Moreover, these sectors are expected to experience a significant increase in emissions by midcentury despite anticipated improvements in efficiency and technology (Sharmina et al. 2021).

The complexity associated with decarbonizing hard-to-abate sectors calls for innovative approaches and technologies. Advancements in clean energy technologies, such as green hydrogen, advanced biofuels, and carbon capture and storage (CCS), offer promising avenues for emission reduction in heavy industries and transportation sectors (Bergero et al. 2023; Sharmina et al. 2021; Van Vuuren et al. 2018). Additionally, electrifying transportation, supported by the growth of renewable energy sources and clean energy solutions, offers another strategy for reducing emissions (Davis et al. 2018; DeAngelo et al. 2021). However, the feasibility and challenges of integrating these clean energy solutions vary significantly across various hard-to-abate sectors. For example, while the adoption of clean hydrogen in the transportation and industrial sectors faces common challenges such as high production costs and the need for extensive infrastructure, each sector also encounters unique obstacles. In transportation, the focus is on improving hydrogen fuel cell technology for better efficiency and durability, alongside developing a comprehensive refueling network to support widespread vehicle adoption (Bergero et al. 2023; Burandt et al. 2019). In contrast, the industrial sector must overcome the significant hurdle of retrofitting existing processes for hydrogen use, particularly in high-temperature applications (Kumar, Tiwari, Milani 2024; van Sluisveld et al. 2021).

Numerous research endeavors have independently explored the impacts of technological advancements on sectors that pose challenges for decarbonization. These efforts generally fall into the following two main categories:

1. **Scenario and modeling studies**: These studies utilize models to identify potential technological pathways for decarbonizing these sectors. Notable modeling studies include those by Bergero et al. (2023), Fiorini et al. (2023), Franz et al. (2022), Nakano, Sano, and Akimoto (2022), Paltsev et al. (2022), Yang et al. (2022), and Sharmina et al. (2021). Sharmina et al. (2021) explored decarbonization strategies for critical sectors such as aviation, shipping, road freight, and industry to limit global warming to 1.5 to 2°C . Additionally, Paltsev et al. (2022) and Yang et al. (2022) investigated the economic implications of decarbonization efforts in India and China, respectively. Bergero et al. (2023), Fiorini et al. (2023) and Nakano et al. (2023) focused on the impact of decarbonization on air transport. Furthermore, Franz et al. (2022) explored the requirements for maritime transition in line with the Paris Agreement.

2. **Feasibility assessments studies**: These studies evaluate the practicality and viability of implementing new technologies within hard-to-abate sectors. Feasibility studies typically take a more grounded approach, concentrating on the technical and operational aspects of technology deployment. For example, Superchi et al. (2022) analyzed the substitution of gray hydrogen with green hydrogen in hard-to-abate industries. Azadnia et al. (2023) identified and analyzed the risks associated with establishing a green hydrogen supply chain in Europe's challenging sectors. Furthermore, Busby and Shidore (2017) examined the political, organizational, and technoeconomic feasibility of decarbonization efforts in India's hard-to-abate sectors.

Both approaches in the literature complement each other by offering insights into the solution space and challenges associated with the decarbonization of hard-to-abate sectors. By building on the abovementioned literature, this study aims to explore the pathways for decarbonizing the critical hard-to-abate end-use sector of energy systems by midcentury. Through the use of a technology-rich integrated assessment model called the global change assessment model (GCAM), this study aims to uncover the primary technological drivers and constraints hindering the decarbonization of these sectors. This study focuses on two distinct illustrative midcentury climate pathways, one aligned with limiting global warming to 1.5°C and the other, which is less stringent, aligned with a 2°C temperature rise. These illustrative projections provide a framework for assessing feasibility and strategies for effectively achieving substantial emission reductions across various sectors. This study bridges the two areas of literature discussed earlier by exploring potential solutions and examining the feasibility of decarbonizing these sectors from the perspective of technological drivers. To achieve this goal, this study applies a decomposition analysis to examine the direct and indirect energy system drivers for decarbonizing the hard-to-abate transportation and industry sectors. This work then explores the potential demand- and supply-side strategies for aligning these sectors with pathways that are compatible with the Paris Agreement. Overall, this study aims to contribute and provide actionable insights that can support global efforts toward achieving a near-zero[1] or net-zero energy system by midcentury.

The remainder of this study is structured as follows. In Section 2, an overview of the GCAM, scenario design, and decomposition framework is provided. Section 3 delves into the energy transformation and emission profiles, with a specific focus on the implications of decarbonization in the hard-to-abate sector. Finally, Sections 4 and 5 summarize the key insights and conclusions, respectively.

2. Methodology

2.1 Global Change Assessment Model (GCAM)

The GCAM is a dynamic-recursive model with a technology-rich representation of the economy, energy, land use, and water linked to a climate model (Calvin et al. 2019). The model consists of 32 geopolitical regions, runs in five-year time steps from 1990 to 2100 and simulates future emission paths for 24 greenhouse gases and short-lived species, including CO_2 (from fossil fuel combustion and land use change), CH_4, N_2O, NOx, SO_2, BC, OC, CO and NMVOC (McJeon et al. 2011).

The GCAM's energy system consists of resource production (e.g., oil, coal, and natural gas), energy transformation (e.g., power generation and refining), and end-use (e.g., building, industrial, and transport) sectors. The demand for energy services in end-use sectors is determined by the equilibrium prices and quantities for each market. For each period, these dynamics are driven by exogenous assumptions of population growth and labor productivity, as well as the prescribed representation of resources, technology, and policy constraints. Technology choice in the GCAM is endogenously determined by market competition, represented by a logit model mimicking decision-making among competing technology options. The logit formulation allocates market share to technologies on the basis of their levelized costs, which are mediated by the influence of noncost factors such as societal preferences, existing infrastructure, and noncost barriers to market entry. Furthermore, the logit model is calibrated to avoid a "winner-takes-all" response. The GCAM's building end-use sector consists of residential and commercial sectors and models floorspace and three aggregate services (heating, cooling, and other). The GCAM's industrial end-use sector is represented by nine subsectors, which include six manufacturing subsectors (iron and steel, chemicals, aluminum, cement, fertilizer, and other industry). Importantly, the "other industry" category comprises a diverse array of sectors involved in energy transformation, manufacturing, and nonmanufacturing activities2. The GCAM transportation sector is disaggregated into passenger (road, rail, and domestic aviation), freight (road and rail), international aviation, and international shipping transportation. See the Appendix for schematic representations of the GCAM transportation and industrial subsectors.

2.2 Scenario Design

This study explores a reference scenario and two midcentury decarbonization pathways (see Table 1). The reference scenarios serve as a counterfactual for the decarbonization scenarios (i.e., nationally determined contribution (NDC) and NDC+), which assume that no climate policies are in place, thereby representing a counterfactual baseline trajectory against which the impacts of the NDC and NDC+ pathways can be compared. The decarbonization scenarios are modeled with varying assumptions regarding the progression of commitments over the short and medium terms. Importantly, the assumptions used in constructing the scenarios are based on Iyer et al. (2023). In the short term (2020-2030), the NDC scenario assumes that regions will fulfill their declared NDC targets, setting the foundation for further climate action. In the second scenario, the NDC+ scenario, regions classified as "critically insufficient" and "highly insufficient" by the Climate Action Tracker (CAT) are required to reduce emissions by 30% below their current NDC levels. This proactive approach aims to significantly curtail emissions from the outset. For the medium term (2031-2050), both scenarios project that countries and regions with official long-term strategies (LTSs) or net-zero commitments will adhere to these plans. The NDC scenario assumes a minimum annual decarbonization rate of 2% for regions without LTSs, which aligns with a 2°C temperature increase target. In the case of the NDC+ scenario, regions without LTSs adopt a more ambitious 5% annual decarbonization target, aiming for compatibility with the stringent 1.5°C target. Together, the NDC and NDC+ scenarios illustrate differentiated pathways toward energy system decarbonization by mid-century. Furthermore, this study applies socioeconomic assumptions related to shared socioeconomic pathway 2 (SSP2), which represents a "middle-of-the-road" scenario that assumes no significant departures from historical growth patterns. This situation provides a balanced view of future challenges and feasibility in achieving decarbonization in hard-to-abate energy system sectors. This study employs the base model technology assumption from the GCAM to reflect a future scenario where energy technologies evolve according to current trends and policies. Using the GCAM's base assumption for sectorial technology representation affords the study an effective way in which to capture the essential dynamics of global energy systems and inherent challenges associated with hard-to-abate sectors.

2.3 Decomposition Analysis

This study aims to explore the primary drivers of decarbonization in hard-to-abate sectors, particularly transportation and industry. This work divides the decarbonization drivers into three main categories, namely, direct CO_2 emissions, indirect CO_2 emissions, and non-CO_2 emissions, as detailed in Equation (1). Indirect CO_2 emissions include reductions achieved through strategies such as electrification, hydrogen utilization, and CCS. In contrast, direct CO_2 emissions focus on emissions released directly from processes within these sectors, often referred to as point-source emissions. To provide a deeper understanding, this study applies a simplified variant of the Kaya identity, dissecting direct CO_2 emissions into the following more granular drivers: activity, energy intensity, and carbon intensity. The activity driver is a key metric that quantifies the emission reductions achieved through behavioral changes and demand avoidance, measured in terms of sectoral output. In the transportation sector, this is reflected by the distance traveled (in million passenger kilometers or million ton kilometers), whereas in the industrial sector, it is represented by the quantity of industrial output (in megatons or exajoules). The energy intensity metric evaluates the energy efficiency of the processes within these sectors, denoting the amount of energy required per unit of output. Improvements in this area can lead to substantial emission reductions, particularly in industries and transport modes with high energy demands. Finally, the carbon intensity metric assesses the CO_2 emitted per unit of energy consumed, providing an indicator of the carbon footprint associated with the energy use of each sector. By focusing on these components, this study provides a structured framework through which to assess the technological and operational challenges inherent in decarbonizing the transportation and industrial sectors.

Table 1. Assumptions of emission trajectories for scenarios (2020 to 2050).

Scenario	Short term (2020-2030)	Medium term (2031-2050)
Reference	• No emission constraints and emissions driven by socioeconomic dynamics	
NDC	• Regional NDC targets achieved	• Regional LTSs and net-zero targets achieved • Minimum 2% annual GHG intensity reduction
NDC+	• Emissions in critical regions reduced by 30% below current NDC levels	• Regional LTSs and net-zero targets achieved • Minimum 5% annual GHG intensity reduction

$$\mathbf{GHG} = \mathbf{Direct\ CO_2} + \mathbf{Indirect\ CO_2} + \mathbf{Non\text{-}CO_2}$$

Equation (1)

$$\mathbf{Direct\ CO_2} = \underset{\substack{\uparrow \\ \textit{Activity}\ (\Delta \mathrm{Act})}}{\mathbf{Activity}} \times \underset{\substack{\uparrow \\ \textit{Energy Intensity} \\ (\Delta \mathrm{EI})}}{\frac{\mathbf{Final\ Energy}}{\mathbf{Activity}}} \times \underset{\substack{\uparrow \\ \textit{Carbon Intensity} \\ (\Delta \mathrm{CI})}}{\frac{\mathbf{Direct\ CO_2}}{\mathbf{Final\ Energy}}}$$

Equation (2)

$$\mathbf{Indirect\ CO_2} = \mathbf{Electrification\ CO_2}\ (\Delta \mathrm{Elec}) + \mathbf{Hydrogen\ CO_2}\ (\Delta \mathrm{H_2}) + \textit{CCS}\ (\Delta \mathrm{CCS})$$

Equation (3)

$$\Delta \mathrm{GHG} = \overbrace{\underbrace{\Delta \mathrm{Act} + \Delta \mathrm{EI} +}_{\substack{\text{Demand-Side} \\ \text{Strategies}}} \underbrace{\Delta\ \mathrm{CI}}}^{\text{Direct } CO_2 \text{ Emissions}} \underbrace{\overbrace{+ \Delta\ \mathrm{Elec} \quad \Delta \mathrm{H_2} \quad + \Delta \mathrm{CCS}}^{\text{Indirect } CO_2 \text{ Emissions}}}_{\substack{\text{Supply-Side} \\ \text{Strategies}}} \overbrace{+ \Delta \mathrm{Non\text{-}CO_2}}^{\text{Non-}CO_2 \text{ Emissions}}$$

Equation (4)

3. Results: Scenario Analysis

3.1 Primary Energy Transformation

Our modeling results indicate that under the reference scenario, the global primary energy supply increases from 564.7 EJ in 2015 to 919.3 EJ in 2050 (see Figure 1), representing a growth of 63%. Fossil fuels, including oil, natural gas, and coal, continue to grow, collectively accounting for approximately 73.4% of the total primary energy mix in 2050. Notably, natural gas demand rises significantly from 127 EJ in 2015 to 218 EJ in 2050. Furthermore, solar and wind resources are projected to surge to approximately 69.69 EJ by 2050, representing a 17-fold increase relative to 2015 levels.

Advancements in energy efficiency and behavioral shifts significantly lower total primary energy consumption across the two decarbonization pathways. In 2050, the demand reduction for the NDC scenario corresponds to 15.9% of that of the reference scenario, whereas the reduction for the NDC+ scenario corresponds to a greater decrease of 21.9%. In addition to demand reduction, the primary energy outlook for the decarbonization pathways involves structural transformation. As illustrated in Figure 1, this transformation is marked by a shift from traditional fossil fuels toward renewables, nuclear energy and the integration of CCS technologies with fossil energy.

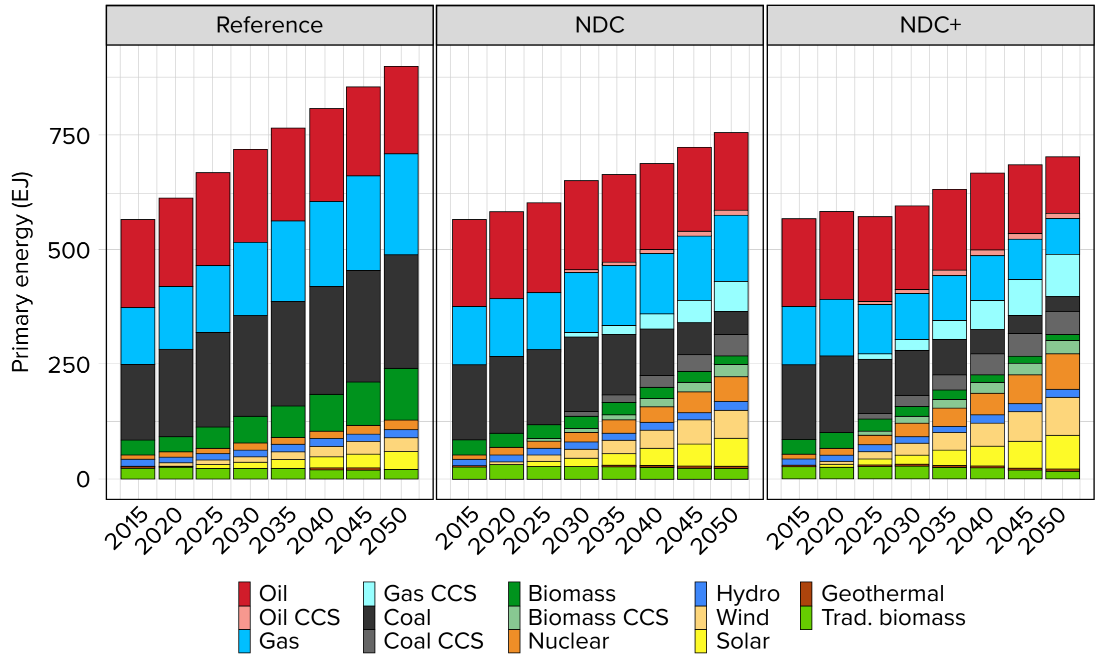
The 2050 projections for the decarbonization pathways show a substantial increase in solar and wind energy installations compared with the reference scenario. The results indicate a net increase of 57.3 EJ for the NDC scenario and 89.1 EJ for the NDC+ scenario. As a type of critical transitional fuel, natural gas technologies integrated with CCS are projected to play an important role in midcentury decarbonization strategies, accounting for approximately 8.7% and 13.3% of the energy supply in the NDC and NDC+ scenarios by 2050, respectively.

3.2 Final Energy Transformation

Electricity demand is forecasted to significantly increase by 2.63 times from the 2015 level of 74.6 EJ, reaching 196.8 EJ by 2050 for the reference scenario. This considerable surge in electricity demand in the reference scenario stems from increased end-use demand in both developed and developing nations and mirrors the current potential of electrification advancements across sectors such as transportation and new applications in buildings. However, the projection of hydrogen as an end-use energy service is moderate, reaching approximately 12.4 EJ by 2050.[3]

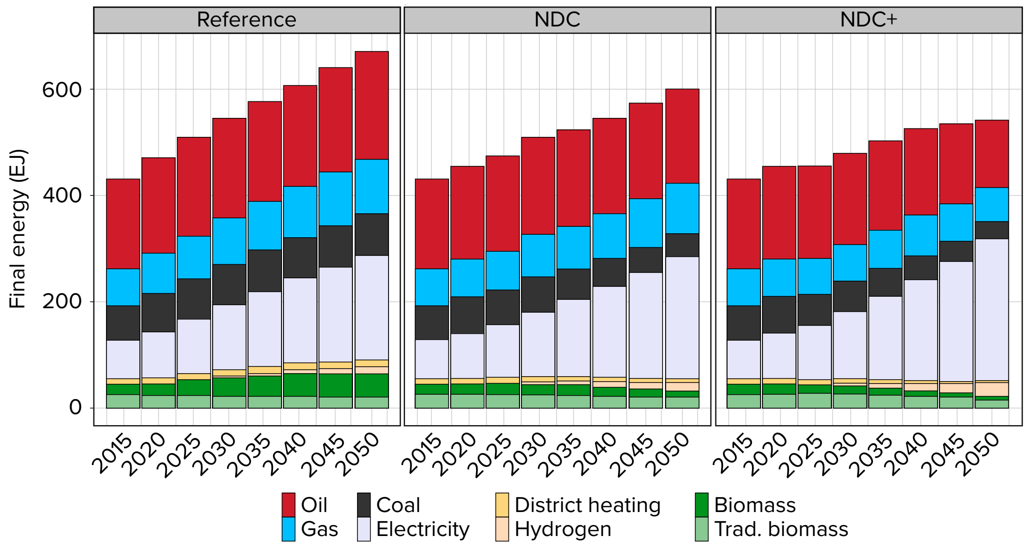
The results for the decarbonization pathways indicate a notable increase in both hydrogen and electricity compared with the reference outlook (refer to Figure 2). Specifically, within these pathways, the net end-use demand for hydrogen is projected to increase by 4.7 EJ for the NDC scenario and 14.9 EJ for the NDC+ scenario

Figure 1. Primary energy trajectories of the reference and decarbonization scenarios.



Source: Authors.

Figure 2. Final energy trajectories of the reference and decarbonization scenarios.



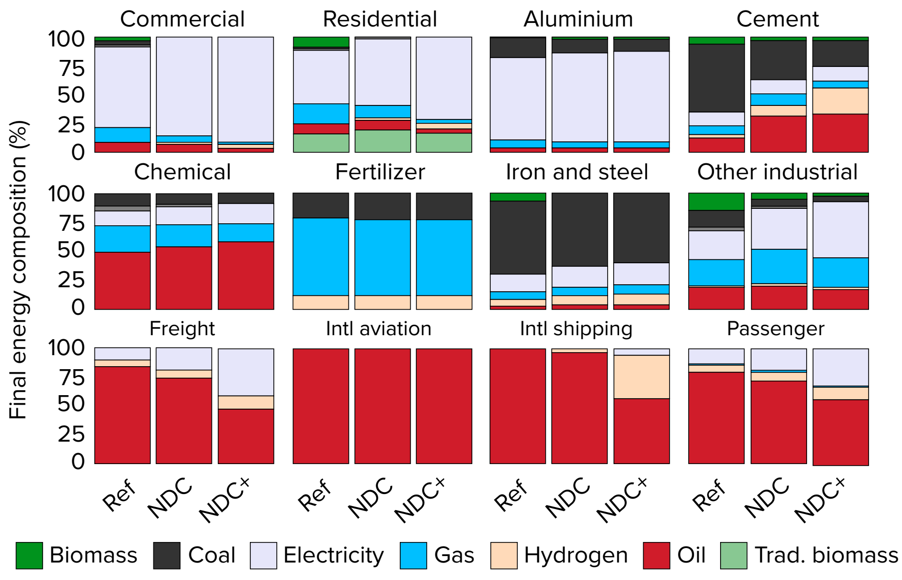
Source: Authors.

by 2050 (which corresponds to 39.2% and 312.4% increases, respectively, compared with the reference). In contrast, the mitigation constraints lead to a substantially greater increase in electricity demand, with net increases of 32.9 EJ and 69.9 EJ for the NDC and NDC+ scenarios, respectively, by 2050. This disparity can be attributed to several factors. First, electricity has broader and more extensive application across various sectors, such as transportation, industry, and residential consumption, than does hydrogen. Second, rapid advancements in electrification technologies, coupled with cost reductions for mature technologies such as wind and solar, significantly contribute to the projected growth in electricity demand relative to hydrogen demand.

3.3 End-Use Energy Consumption

Figure 3 shows the energy service composition for 2050 across the following three scenarios: the reference scenario and two decarbonization scenarios (NDC and NDC+). This figure shows the structural differences in energy end-use services between the mitigation scenarios and the reference scenario. The final energy compositions vary significantly across sectors such as building, industry, and transportation. These distinctions across scenarios are particularly evident in the adoption of electrification and hydrogen technologies. For the mitigation scenarios, there is a pronounced tilt toward electrification in critical sectors such as passenger cars and freight transportation, where electricity makes up approximately 6.3 to 16.2% of total end use by 2050. Furthermore, owing to its versatility, electricity still has a sizable share in the building sector, especially in commercial buildings, where it is projected to make up approximately 84.5% to 90.1% of total end use by 2050 for the mitigation pathways. Compared with that in the reference scenario, the role of hydrogen as an end-use energy carrier is significantly greater in the mitigation scenario. In the NDC+ scenario, hydrogen emerges as a significant energy source within the cement sector, comprising 22.4% of its energy mix, equivalent to 2.1 EJ. This finding indicates a substantial increase from the reference scenario, where hydrogen accounts for only

Figure 3. Sectoral final end-use composition of the reference and decarbonization scenarios for 2050.



Source: Authors.

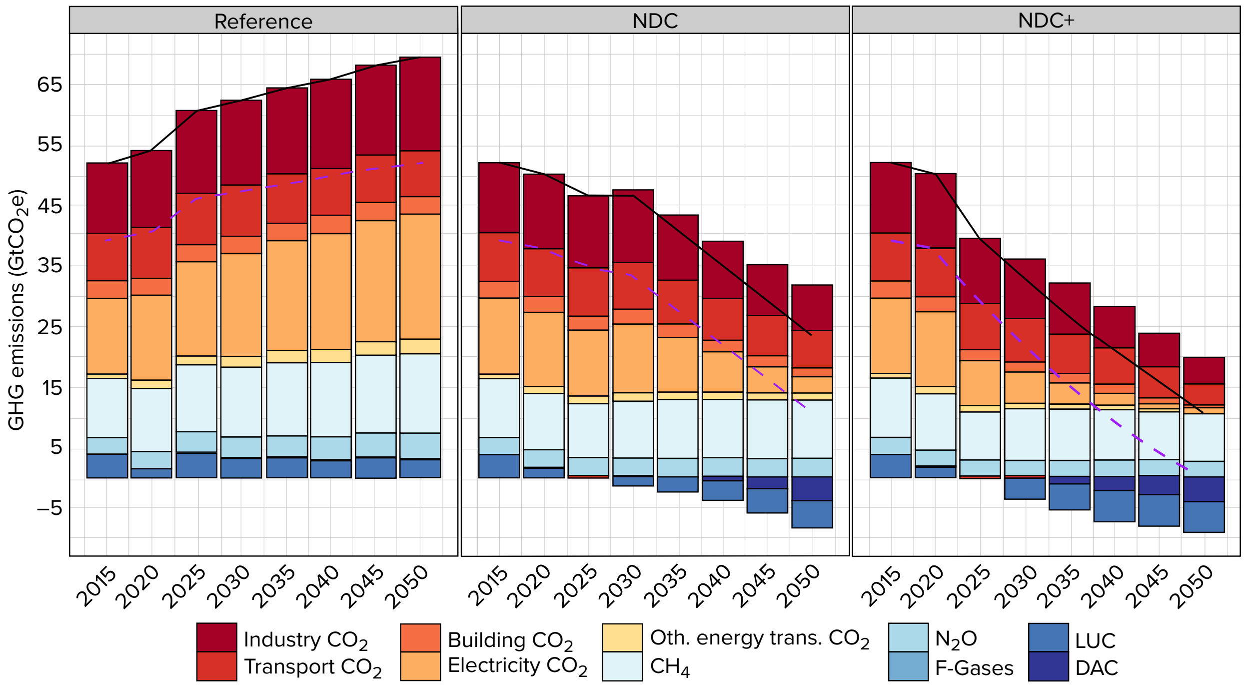
2.96% (i.e., 0.47 EJ) of the sector's energy consumption. Similarly, the iron and steel sector has a heightened hydrogen utilization rate of 9.95% (i.e., 0.1 EJ) in the NDC+ scenario, whereas it is 6.82% (0.03 EJ) in the reference scenario.

3.4. Economy-Wide and Sectoral GHG Emission Profiles

Figure 4 depicts the trajectory of sectoral CO_2 and GHG emissions across both the reference and decarbonization pathways. Variations in emission profiles are driven by the abovementioned technology trajectory, which results in notable differences in sectoral residual emission outcomes. In the reference scenario, GHG emissions are projected to increase to 66.8 $GtCO_2e$ by 2050, representing a 1.4-fold increase compared with 2015 levels. Within the reference scenario, the electricity sector's CO_2 emissions increase continuously, positioning it as a dominant emitter by 2050. Specifically, the projection indicates that emissions from this sector will reach 20.6 $GtCO_2e$ by 2050, accounting for approximately 30.8% of the total projected GHG emissions.

In contrast with the reference scenario, projections for 2050 under the NDC and NDC+ scenarios illustrate a starkly different future for the electricity sector. The residual emissions are projected to plummet to near zero, with forecasts of approximately 1.9 $GtCO_2e$ for the NDC scenario and a further reduction of 0.79 $GtCO_2e$ for the more ambitious NDC+ scenario in 2050. In addition, the projection of negative emissions also varies across mitigation scenarios. The negative emissions generated from land use strategies such as reforestation or afforestation account for approximately 4.6 $GtCO_2$ and 5.1 $GtCO_2$ by 2050 for the NDC and NDC+ scenarios, respectively. The deployment of direct air capture accounts for approximately 3.7 GtCO2 and 4.1 $GtCO_2$ emissions by 2050 for the NDC and NDC+ scenarios, respectively.

Figure 4. Greenhouse gas emission trajectories for the reference and decarbonization scenarios.



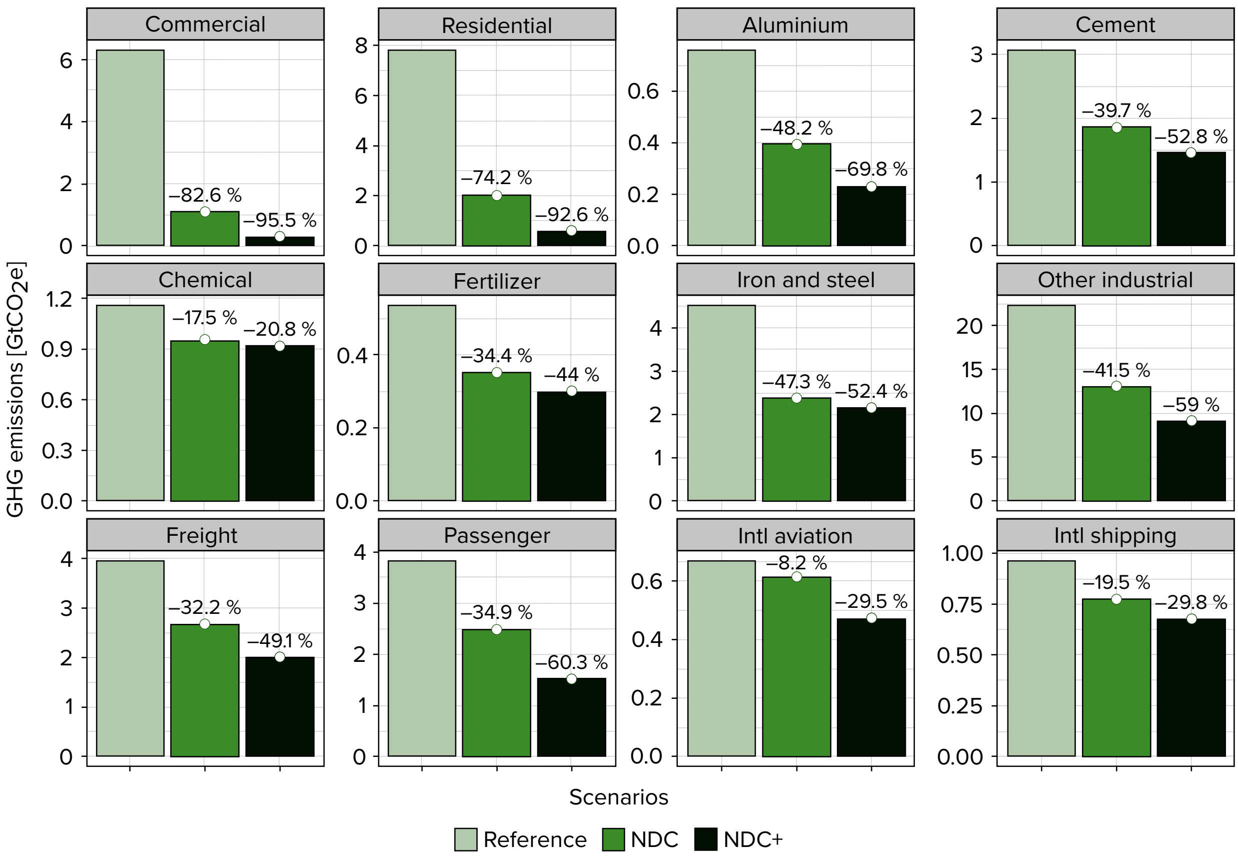
Source: Authors.

Note: The black line represents the net GHG emissions, and the purple dashed line represents the net CO_2 emissions.

Figure 5 provides a detailed view of sector-specific residual emissions under the reference scenario and two mitigation scenarios, highlighting the feasibility of decarbonization across different sectors. Importantly, these projections account for all greenhouse gas emissions in CO_2-equivalent terms, offering a more comprehensive perspective on the potential for emission reductions. The building sector, which includes residential and commercial buildings, has significant potential for reduction, with emissions projected to decrease by 74.2–95.5% from the reference levels.[4] In contrast, the chemical sector shows considerable residual emissions, accounting for more than 79% of the emissions in the reference scenario, even under the more stringent NDC+ regime.

International aviation and shipping also face significant challenges in emission reduction, with projections indicating that over 70% of reference-level emissions will persist through 2050. Conversely, the decarbonization of passenger vehicles presents a more optimistic scenario, with emissions anticipated to be approximately 34% and 60% of the reference scenario under the NDC and NDC+ regimes, respectively (i.e., NDC+: 917.2 $MtCO_2$, NDC: 954.7 $MtCO_2$, and reference: 1157.4 $MtCO_2$). The "other industry"[5] category is expected to experience a moderate reduction, with emissions projected to be 51.4% to 56.9% of the 2050 reference levels. In the case of iron and steel and cement production, more than 47% of residual emissions are expected to remain unabated by 2050.

Figure 5. Sectoral greenhouse emission projection for 2050.



Source: Authors.

4. Decomposition Analysis of Key Drivers

This section aims to explore the key drivers involved in decarbonizing the hard-to-abate transportation and industry sectors. Table 2 provides a heatmap that highlights the relative contributions of various direct and indirect mitigation drivers by 2050. ΔGHG represents the change in greenhouse gas emissions (measured in $GtCO_2e$) compared with the reference scenario shown in Figure 5. Other drivers – ΔAct (activity), ΔEI (energy intensity), ΔCI (carbon intensity), ΔElec (electrification), ΔH2 (hydrogen), ΔCCS (CCS), and ΔNon-CO_2 (non-CO_2 GHG emissions) – are expressed as percentages of ΔGHG, indicating their respective contributions to overall mitigation efforts (Equation (4)). The discussion is structured around two sectors (transportation and industry) and two categories (demand-side and supply-side strategies). Demand-side strategies focus on ΔAct and ΔEI, whereas supply-side strategies include direct decarbonization levers (i.e., ΔCI) and indirect levers such as ΔH2, ΔCCS and ΔNon-CO_2.

4.1 Decarbonization Drivers for Transportation

Our modeling results provide a nuanced perspective on the potential effectiveness of supply-side strategies considering the current trajectories and anticipated technological advancements. The results in Table 2 indicate that the combined contribution of electrification and hydrogen deployment in the aviation sector is minimal, accounting for less than 1% of the emission reduction due to the current limitations of these technologies. Similarly, hydrogen contributes only marginally to the decarbonization of the shipping sector, with contributions of approximately 2.2% in the NDC+ scenario and 3.6% in the NDC scenario. Furthermore, owing to the limited availability of viable decarbonization solutions in the aviation and shipping sectors, carbon intensity – which serves as a structural indicator of the carbon efficiency of energy use – also plays a marginal role, contributing less than 1% to overall decarbonization efforts. However, the outlook is more optimistic for freight and passenger transportation modes. In the freight sector, carbon intensity is projected to be a key driver of decarbonization, contributing 36% in the NDC scenario and 37% in the NDC+ scenario. The structural shift in carbon intensity for freight transportation is further supported by the adoption of electrification, which contributes approximately 27%, and hydrogen,

Table 2. Overview of sectoral decarbonization drivers for 2050.

		Demand-side strategies		Supply-side strategies					
	Δ GHG ($GtCO_2e$)	Δ ACT	Δ EI	Δ CI	Δ Elec	Δ H2	Δ CCS	Δ Non-CO2	
Commercial	-5.2	0.1%	9.6%	2.2%	88.2%	0.1%	-	0.3%	NDC
Residential	-5.8	-	10.6%	3.2%	84.6%	0.1%	-	1.5%	NDC
Aluminum	-0.4	0.5%	18.3%	0.3%	79.1%	0.0%	1.6%	0.1%	NDC
Cement	-1.2	16.7%	29.8%	18.8%	7.2%	2.7%	24.6%	0.2%	NDC
Chemical	-0.2	5.4%	19.2%	14.4%	16.9%	0.0%	44.0%	0.1%	NDC
Fertilizer	-0.2	10.9%	28.1%	6.7%	-	8.1%	46.5%	0.0%	NDC
Iron and steel	-2.2	8.8%	33.4%	4.8%	12.0%	2.6%	39.0%	0.1%	NDC
Other industry	-9.3	2.0%	19.0%	6.6%	32.9%	0.5%	23.1%	15.9%	NDC
Freight	-1.3	6.9%	36.6%	17.4%	28.7%	9.5%	-	0.8%	NDC
Intl aviation	-0.1	11.4%	84.9%	0.6%	0.2%	0.8%	-	1.6%	NDC
Intl shipping	-0.2	35.0%	60.2%	0.5%	-	3.6%	-	1.3%	NDC
Passenger	-1.3	9.8%	38.6%	6.1%	33.7%	10.7%	-	0.3%	NDC
Commercial	-6.0	0.1%	10.9%	2.3%	85.8%	0.2%	-	0.3%	NDC+
Residential	-7.2	-	12.5%	6.7%	78.3%	0.4%	-	2.0%	NDC+
Aluminum	-0.5	0.6%	18.0%	0.4%	79.4%	0.0%	1.6%	0.1%	NDC+
Cement	-1.6	17.4%	28.8%	18.5%	8.8%	3.0%	23.3%	0.2%	NDC+
Chemical	-0.3	6.4%	18.7%	15.4%	17.3%	0.0%	42.1%	0.1%	NDC+
Fertilizer	-0.2	13.2%	30.3%	1.6%	-	8.8%	46.3%	0.0%	NDC+
Iron and steel	-2.6	11.9%	27.7%	3.2%	12.6%	5.5%	39.0%	0.3%	NDC+
Other industry	-13.1	2.9%	20.3%	7.3%	30.3%	0.6%	21.7%	16.8%	NDC+
Freight	-2.0	7.7%	37.3%	18.5%	27.9%	8.0%	-	0.8%	NDC+
Intl aviation	-0.2	13.0%	83.6%	0.3%	0.1%	0.9%	-	1.9%	NDC+
Intl shipping	-0.3	37.9%	59.4%	0.4%	-	2.2%	-	0.9%	NDC+
Passenger	-2.3	10.4%	39.0%	2.1%	38.6%	9.9%	-	0.5%	NDC+

Note: The red bars represent the magnitude of mitigation (ΔGHG) measured in $GtCO_2e$ compared with the reference scenario.

which contributes approximately 8%. In the passenger transportation sector, electrification and improvements in carbon intensity are the major drivers of decarbonization, each contributing more than 30%. Additionally, hydrogen deployment plays a significant role, contributing more than 9% to emission reductions in both scenarios.

Given the limited availability of viable supply-side solutions in shipping and aviation, our modeling results suggest that demand-side strategies focused on reducing energy intensity and activity levels are the most effective drivers of decarbonization. For example, energy intensity improvements contribute to more than 80% of emission reductions in the aviation sector and approximately 60% in the shipping sector across both scenarios. Additionally, our findings indicate that demand-side strategies in the passenger car sector, such as energy conservation behaviors (ΔAct) and the adoption of more efficient vehicles (ΔEI), are projected to achieve significant emission reductions, ranging from 48.4% to 49.4%, in both scenarios. In the freight sector, emission reductions are driven primarily by energy efficiency improvements (ΔEI), which account for 36% of the reductions in both scenarios. In contrast, the activity-level driver plays a minor role in freight sector decarbonization, contributing approximately 6.9% and 7.7% in the NDC and NDC+ scenarios, respectively.

4.2 Decarbonization Drivers for Industry

The strategic integration of CCS is essential for reducing point-source emissions across various industrial sectors. Our modeling results highlight that CCS plays a pivotal role in decarbonizing industries, particularly in chemicals, fertilizers, and iron and steel, where it is projected to contribute over 39% of the total emissions reductions. CCS also has a significant effect on the cement and other industry sectors, accounting for more than 20% of emissions reductions. However, its role in the aluminum industry is relatively minor, as approximately 70% of emissions from aluminum production are attributed to electricity consumption during smelting. In this context, clean electrification emerges as the primary driver of emission reduction in the aluminum sector, accounting for approximately 79% of the potential reduction. Electrification also contributes moderately to emission reductions in other heavy industrial sectors, including chemicals, other industry, cement, and iron and steel, with contributions ranging from 7.2% to 32.9%. The adoption of hydrogen, although slower than electrification, has a more moderate impact, with contributions as low as 2% in sectors such as cement and iron and steel under the NDC scenario and up to 8% in the fertilizer sector. Finally, the structural change in direct carbon intensity (ΔCI) is moderate, ranging from 1.6% to 4.8% in fertilizers and iron and steel at the lower bound and from 14.4% to 18.8% in cement and chemicals at the upper bound.

Demand-side strategies for decarbonization in heavy industries can be achieved through the adoption of energy-efficient processes and equipment, as well as by redesigning industrial processes to increase resource efficiency and promote circularity (Allwood et al. 2017). The results suggest that improvements in energy intensity can contribute between 18% and 30% of total emissions reductions. These significant gains in energy efficiency stem from the cost-effectiveness of efficiency improvements compared with supply-side decarbonization strategies in heavy industrial sectors. In addition, the contribution of activity-level drivers to decarbonization – such as optimizing production volumes or shifting to less carbon-intensive products – is relatively moderate. Owing to the structural nature and complexity involved in achieving activity-level decarbonization, the model projects contributions as low as 0.5% in the aluminum sector and as high as 17.4% in the cement sector.

5. Opportunities and Challenges for Decarbonizing Hard-to-Abate Sectors

To offer a practical interpretation of the modeling results, this section aims to discuss the potential solutions and challenges associated with each driver. The discussion of the results is structured around demand- and supply-side strategies for each of the two hard-to-abate sectors. The demand-side strategies include interventions aimed at reducing emissions through behavior changes or the adoption of efficient technologies. The supply side encompasses strategies associated with direct and indirect fuel switching to low-carbon alternatives and capture technologies.

5.1 Demand-Side Decarbonization Opportunities and Challenges for Transportation

Demand-side strategies present substantial opportunities to reduce emissions in the transportation sector, particularly in aviation, maritime, and passenger vehicles. Our model highlights that improvements in energy efficiency and activity levels are key drivers of decarbonization in the aviation and maritime sectors. For aviation, the widespread adoption of lightweight composite materials in aircraft structures and components can lead to significant emission savings (Nagaraju et al. 2023; Ranasinghe et al. 2019). Additionally, improvements in engine designs and aerodynamic refinements can increase fuel efficiency by 7% to 30%, contributing significantly to emission reduction (Bravo-Mosquera, Cerón-Muñoz, and Catalano 2022; McDonald et al. 2022; Owen, Lee, and Lim 2010). Similarly, the maritime sector can achieve up to a 19% reduction in CO_2 emissions through slow steaming (Wang et al. 2022), with additional fuel savings of 10% to 15% from hull optimization and propulsion efficiency upgrades (Balcombe et al. 2019). Wind-assisted propulsion technologies offer another 5% to 20% reduction in fuel consumption (Smith et al. 2013), whereas waste heat recovery systems can enhance energy efficiency by 5% to 7% (Bouman et al. 2017).

On the activity side, advanced logistical planning and optimized routing have the potential to further reduce fuel consumption and emissions in both aviation and maritime transport. In aviation, optimized flight planning based on real-time conditions can save up to 7% of fuel per flight, significantly reducing CO_2 emissions (Rosenow, Lindner, and Scheiderer 2021; Xu et al. 2014). In maritime transport, applying advanced operational strategies to optimize vessel speed and routing can lead to a 5% to 10% reduction in fuel consumption (Bouman et al. 2017). Additionally, changes in supply chain management, such as enhancing local production and distribution networks, can minimize the need for long-haul transportation, particularly for nonurgent or perishable goods, thereby reducing emissions (Cuenot et al. 2012).

For passenger vehicles, demand-side strategies such as adopting fuel-efficient vehicles, expanding public transit options, promoting carpooling, encouraging remote work, and developing walkable cities have the potential to reduce emissions by approximately 48.4% to 49.4% (Li et al. 2022). Eco-driving behavior, which can improve fuel efficiency by 4% to 10%, further supports this reduction (An, Earley, and Green-Weiskel 2011; Jeffreys, Graves, and Roth 2018). The regulatory push for stricter fuel efficiency standards in the U.S. and Europe has already demonstrated a measurable decrease in new car emissions (Fontaras, Zacharof, and Ciuffo 2017). Moreover, technological advancements, including the adoption of advanced powertrains and lightweight materials, can reduce vehicle emissions by up to 30% by 2030 (Luk et al. 2017).

Despite promising opportunities for decarbonization, several challenges can hinder the implementation of demand-side strategies. In the aviation and maritime sectors, the high infrastructural and transactional costs associated with developing and certifying new technologies, such as lightweight composite materials, present significant barriers (Camacho, Jurburg, and Tanco 2022; Zhang and Xu 2022). Operational disruptions during upgrades, geopolitical constraints, and resistance to changing established behaviors – such as optimizing flight routes – further complicate efficiency improvements (Rosenow, Lindner, and Scheiderer 2021). The maritime industry faces similar obstacles, including high costs and technological limitations in implementing slow steaming, wind-assisted propulsion, and hull optimization (Bouman et al. 2017). Furthermore, many technological improvements identified for the aviation and maritime sectors are not yet commercially viable, delaying their widespread adoption (Fadiga et al. 2024).

For passenger vehicles, transitioning to more efficient modes of transportation is challenged by resistance to behavioral changes, especially in regions with strong car cultures (Bachmann et al. 2018). Public transit expansion requires substantial investment and faces resistance in areas where car usage dominates, whereas carpooling and ridesharing initiatives often struggle without strong incentives (Si et al. 2023). Stricter fuel economy standards can lead to higher manufacturing costs, potentially increasing vehicle prices and reducing their market adoption (An, Earley, and Green-Weiskel 2011). In the freight sector, the widespread use of older, less efficient vehicles, along with the high costs of lightweight materials and technological constraints, further limits the effectiveness of energy efficiency initiatives (Camacho, Jurburg, and Tanco 2022; Meyer 2020). Regional regulations and local supply chain complexities also pose significant challenges. Efforts to increase efficiency through optimized routing and better load management frequently encounter resistance due to concerns over potential operational disruptions and financial burdens (Meyer 2020; Zhang and Xu 2022).

5.2 Supply-Side Decarbonization Opportunities and Challenges for Transportation

Supply-side decarbonization strategies offer potential avenues for reducing carbon emissions in the transportation sector, although their impact varies across different modes. In the aviation sector, there is significant interest in low-carbon alternatives such as sustainable aviation fuels (SAFs). SAFs, such as biofuels and synthetic fuels, can be blended with conventional jet fuel and used in current aircraft without extensive modifications, providing a feasible path to reduce carbon intensity (Bergero et al. 2023; Fiorini et al. 2023). In the maritime sector, fuel switching to low-carbon alternatives such as liquefied natural gas (LNG), biofuels, and methanol is being actively explored as a means to reduce emissions compared with traditional heavy fuel oil (Bouman et al. 2017; Faber et al. 2022). Additionally, ammonia and hydrogen are emerging as promising zero-carbon fuels, with significant potential to transform the shipping industry if challenges related to infrastructure and technology are addressed (Balcombe et al. 2019).

The freight transportation sector, particularly for heavy-duty vehicles such as long-haul trucks, also holds promise for decarbonization through the adoption of clean alternative fuels and electrification. Hydrogen fuel cell vehicles are especially promising in this segment, offering a practical clean energy alternative where battery-electric solutions may fall short (Camacho, Jurburg, and Tanco 2022). For light-duty trucks and delivery vans, electrification is increasingly viable because of shorter ranges and frequent stops, which align well with existing charging infrastructure (Birky et al. 2017; Smith et al. 2019).

Conversely, supply-side decarbonization strategies face significant challenges, particularly in aviation. While promising, electrification and hydrogen technologies are currently limited by technological, economic, and infrastructural barriers. Battery technology for electrification, for example, is constrained by energy density, making it feasible primarily for short-haul flights (Ranasinghe et al. 2019). Hydrogen-powered aviation remains largely experimental and is also hindered by concerns around storage, safety, and energy density (Yusaf et al. 2024). Moreover, the extensive infrastructure needed, including specialized fuel stations and storage facilities, adds further complexity to the deployment of hydrogen in aviation (Manigandan et al. 2023).

While our results indicate that the electrification of passenger cars is a viable solution for decarbonization, this transition faces significant challenges. The key among these is securing sustainable and resilient supply chains for critical minerals such as lithium, cobalt, and nickel, which are essential for battery production but vulnerable to geopolitical risks and environmental concerns. The development of a comprehensive charging infrastructure powered by renewable energy is equally critical to support widespread electric vehicle (EV) adoption (Dou et al. 2023; Paltsev et al. 2022). Additionally, achieving technological parity with conventional vehicles – particularly in terms of range, charging speed, and overall convenience – remains a major hurdle (NASEM 2022).

While transitional fuels such as LNG and biofuels offer a path to lower emissions for maritime transportation, the adoption of these fuels requires substantial investment in new infrastructure and technological adaptation, which presents both financial and operational challenges (Balcombe et al. 2019). The freight sector also faces significant obstacles, particularly the high upfront costs associated with adopting new technologies such as hydrogen fuel cells and the need for widespread charging and refueling networks. Additionally, consumer adoption is a challenge, as it requires both education on the benefits of these technologies and financial incentives to offset the higher initial costs (Rinaldi et al. 2023; Sandaka and Kumar 2023).

5.3 Demand-Side Decarbonization Opportunities and Challenges for Industry

Demand-side decarbonization in heavy industries offers substantial opportunities to reduce emissions through the adoption of energy-efficient processes and equipment and the redesign of industrial operations to increase resource efficiency and promote circularity. Our modeling exercise highlights that activity-level drivers are particularly crucial in sectors such as iron and steel, fertilizer, and cement, where aligning industrial activities with decarbonization goals can significantly lower emissions. For example, minimizing material yield losses and improving the recycling or reuse of materials in the iron and steel and aluminum sectors can lead to considerable reductions in energy use and emissions (Stephenson and Allwood 2023; Walzberg and Carpenter 2024). The Ellen MacArthur Foundation (2019) estimates that the efficient and more circular use of materials in industries such as cement, steel, plastics, and aluminum could reduce emissions by up to 40% by 2050. Additionally, consumer behavior changes aimed at reducing product and service demand can further contribute to emission reductions (Stephenson and Allwood 2023). Technological advancements also play a key role, as the steel industry can increase energy efficiency by recovering waste heat for onsite power generation and recycling furnace gases as fuel (Sun et al. 2022). In the aluminum sector, advanced smelting technologies that reduce energy consumption and greenhouse gas emissions are critical (Gautam, Pandey, and Agrawal 2017). Furthermore, the chemical industry can achieve substantial efficiency improvements through advanced catalysis, process intensification, and raw material recycling (Ramírez-Márquez et al. 2023). Cross-cutting technologies such as high-efficiency boilers, heat integration systems, and advanced automation can also be applied across energy-intensive sectors to increase overall efficiency.

However, significant challenges impede the widespread adoption of demand-side decarbonization strategies in heavy industries. High upfront costs and prolonged payback periods often discourage investment in energy-efficient processes and advanced technologies, making it difficult for industries to justify the transition to more sustainable practices (Allwood et al. 2017; Stephenson and Allwood 2023). Moreover, limited consumer demand for low-carbon products reduces market incentives for adopting greener technologies and practices. Technological constraints also pose substantial hurdles; many efficient technologies and processes, such as electric furnaces, are still in the early stages of development and face challenges in terms of scalability and commercial viability (Ramírez-Márquez et al. 2023). Additionally, the complexity of regional regulations and issues within local supply chains further limits the effectiveness of these decarbonization measures (Camacho, Jurburg, and Tanco 2022). Efforts to increase efficiency through optimized routing and better load management are frequently met with resistance due to concerns over potential disruptions to operations and the associated financial burdens (Meyer 2020). Achieving the full potential of demand-side decarbonization in heavy industries requires addressing these challenges through robust policy frameworks, economic incentives, and continued technological innovation.

5.4 Supply-Side Decarbonization Opportunities and Challenges for Industry

The integration of CCS is pivotal for reducing point-source emissions across various industrial sectors. Our modeling results indicate that CCS can account for approximately 40% of emission reductions in the chemical, iron and steel, and fertilizer industries. For example, in the chemical industry, CCS technologies, including both pre- and postcombustion methods, can capture up to 90% of CO_2 emissions from processes such as steam cracking and ammonia production (Smith, Hill, and Torrente-Murciano 2020). In the iron and steel sector, integrating CCS with blast furnace-basic oxygen furnace (BF-BOF) processes, direct reduced iron (DRI) technology, and electric arc furnaces (EAFs) can capture between 60% and 90% of emissions (Boldrini et al. 2024). The fertilizer industry can also benefit significantly from CCS, capturing over 85% of CO_2 emissions when applied to existing ammonia production facilities. Additionally, CCS in cement plants during clinker production can capture between 50% and 70% of CO_2 emissions (Bui et al. 2018). Furthermore, innovative fuel strategies, such as electrification, hydrogen utilization, and low-carbon feedstocks, offer further decarbonization potential for critical sectors, including aluminum, cement, chemical, fertilizer, and iron and steel. In the aluminum sector, the electrification of the Hall-Héroult process through inert anode technology not only eliminates direct emissions but also improves energy management efficiency (Ratvik, Mollaabbasi, and Alamdari 2022). The cement industry can reduce emissions by 30% to 40% with alternative fuels such as biomass, waste-derived fuels, and hydrogen, alongside advanced clinker substitution methods (Sousa and Bogas 2021; Watari et al. 2022). The chemical industry can reduce emissions by approximately 50% by transitioning from fossil fuels to hydrogen for ammonia and methanol production and by electrifying process heat using renewable energy sources (Teske et al. 2022). The iron and steel industry can achieve a reduction in CO_2 emissions of over 90% by replacing coking coal with hydrogen in the DRI process, particularly when combined with CCS technologies (Rissman et al. 2020; Wesseling et al. 2017). Other heavy industries, such as glass, paper, and ceramics, can achieve up to a 50% reduction in emissions by adopting biofuels, hydrogen, and the electrification of heating processes (Gailani et al. 2024; Thiel and Stark 2021).

However, there are several supply-side decarbonization challenges in industry. Technological scalability is a major issue hindering the decarbonization of heavy industries, as exemplified by the nascent commercial viability of technologies such as inert anodes in aluminum production and hydrogen-based reduction in iron and steel manufacturing (Paltsev et al. 2022; Yang et al. 2022). The technological readiness levels of these innovations are moderate, which implies that their widespread use may be limited. The associated economic challenges are also significant, with high deployment costs being a major barrier. For example, the chemical industry's shift to hydrogen for ammonia production requires substantial initial investment (Rattle, Gailani, and Taylor 2024; Rissman et al. 2020). Moreover, regulatory frameworks often lack robust incentives to drive industrial transitions toward lower-carbon processes, further stalling progress. Supply chain limitations, particularly in terms of raw material availability for large-scale green hydrogen production in the fertilizer sector, are constrained by resource scarcity and underdeveloped market conditions (Zou et al. 2022). Additionally, environmental and social considerations, including public acceptance and potential unintended consequences, must be carefully navigated to ensure the successful deployment of these technologies (Boa Morte et al. 2023; Kim et al. 2024). The absence of strong regulatory frameworks and economic incentives further complicates the adoption of CCS and other innovative technologies, making it difficult to scale these solutions to meet global decarbonization targets (Bui et al. 2018).

6. Conclusion and Policy Implications

This study utilizes the GCAM with its comprehensive technological framework to assess the possibility of decarbonizing traditionally hard-to-abate sectors by the mid-21st century under two different climate pathways. Our findings indicate that subsectors within industries and transportation will face more substantial decarbonization challenges than will sectors such as building. Despite significant shifts in both primary and final energy consumption, along with enhancements in demand-side energy efficiency prompted by decarbonization efforts, our analysis underscores the various technical challenges across these sectors. These challenges stem from differences in technological maturity, economic viability, and infrastructure capabilities, leading to varying levels of residual emissions across subsectors by mid-century.

Our analysis of drivers reveals that demand-side strategies, specifically in activity optimization and energy efficiency improvement, play a critical role in compensating for the lack of supply-side solutions for decarbonization in hard-to-abate sectors. To align with near-zero emission targets by midcentury, activity optimization entails a comprehensive reevaluation and restructuring of energy usage across sectors. For example, in transportation, enhancing logistics efficiency, expanding public transit options, and encouraging nonmotorized transportation are key measures through which to reduce emissions effectively. In industrial sectors, streamlining processes to minimize energy consumption without compromising output can significantly impact decarbonization efforts. Furthermore, integrating energy efficiency with activity optimization can substantially reduce the overall carbon footprint, even in the absence of newer, cleaner technologies that are not yet viable or widely available.

The implications of these findings are profound. First, they underscore the necessity for policy frameworks that not only encourage the adoption of existing technologies but also significantly invest in behavioral change and process improvements. Second, they highlight the need for targeted investment in research and development to overcome the technological hurdles in these sectors. By improving energy efficiency and optimizing activities, sectors can lessen their dependence on breakthrough technological innovations, which often require more time to develop and deploy. This reliance on demand-side strategies offers a viable interim approach to overcoming decarbonization challenges. While the development of global technological solutions has progressed, there is an immediate opportunity to achieve substantial reductions in carbon emissions through the smarter, more efficient use of energy and optimized activities.

The implementation of demand-side strategies for decarbonization presents several challenges. Behavioral resistance requires comprehensive education and incentives to shift long-established habits, such as adopting public transport or modifying industrial processes for better energy efficiency. Economic constraints can deter the initial investments needed for energy-efficient technologies and infrastructure improvements, necessitating financial incentives or innovative financing models. Effective policy support is crucial, as regulatory frameworks must promote energy efficiency and sustainable urban planning. Technological limitations and knowledge gaps also hinder potential reductions in energy usage and emissions, underscoring the need for ongoing research and development, as well as education to bridge information gaps. Additionally, market structures often fail to naturally incentivize energy conservation, suggesting a need for policies that align financial incentives with decarbonization goals, such as carbon pricing. Finally, ensuring that demand-side strategies are inclusive and equitable is essential, as they must not disproportionately burden vulnerable populations, ensuring accessibility and benefits for all societal segments.

In the context of supply-side strategies, our modeling results reveal varying levels of electricity and hydrogen penetration. While certain sectors show promising adoption rates, the overall integration of these energy sources remains uneven across industries. This variability can be attributed to technological readiness, infrastructural developments, and sector-specific challenges. Electricity has exploited the building sector, outpacing the industrial and transportation sectors, owing primarily to the well-established grid infrastructure and the maturity of electrification technologies in this context. Conversely, hydrogen adoption is more nascent, with its impact largely confined to sectors where high-energy-density fuels are critical, such as heavy transportation and certain industrial processes.

The integration of hydrogen and electricity into sectors such as transportation and heavy industries presents complex challenges. These include the necessity for advanced technological development, substantial infrastructure investments, and adaptations to meet the unique technical requirements of these applications. Scaling hydrogen to levels suitable for decarbonization necessitates significant enhancements in production, storage, and distribution capacities. Similarly, electric solutions require refinement to efficiently manage high energy demands. Challenges such as substantial upfront costs, the need for robust regulatory frameworks, and hurdles concerning market readiness and consumer acceptance also play crucial roles.

Our modeling results indicate that the strategic integration of CCS technologies represents a vital component in the decarbonization of heavy hard-to-abate industrial sectors. However, the deployment of CCS faces several hurdles. Technological challenges remain in achieving operational efficiency and reliability at scale, while the high costs of CCS technologies necessitate substantial financial investments. Furthermore, the lack of extensive infrastructure for transporting and storing captured CO_2 adds another layer of complexity. Regulatory and public acceptance issues also pose potential obstacles, as the long-term safety and environmental impact of CO_2 storage continue to raise concerns among some stakeholders.

In addressing the challenges of decarbonization, these hard-to-abate sectors require a nuanced and coordinated policy approach that combines technological advancements, supportive policies, financial incentives, and strategic public-private partnerships. Policymakers and stakeholders need to prioritize the development of specific regulations that encourage the integration of both emerging and existing technologies, acknowledging that a one-size-fits-all strategy is not effective. Increased research and development funding is crucial for overcoming technological barriers and reducing costs, whereas financial incentives such as subsidies and innovative financing models are essential for lowering the initial costs of low-carbon technologies. Engaging local communities is key to gaining public acceptance and ensuring equitable policy implementation. Moreover, regulatory frameworks must be robust and adaptable to support the dynamic nature of technological advancements and ensure that these measures do not disproportionately burden vulnerable populations. Overall, this multifaceted approach is essential for an effective and inclusive transition to a low-carbon economy.

Endnotes

[1] Near-zero emissions refer to a scenario where greenhouse gas emissions are reduced to a very low level, with only a small fraction of emissions remaining.

[2] We aggregate these sectors into one category to allow for a more streamlined analysis and focus on critical hard-to-abate industrial sectors.

[3] The moderate projection of hydrogen uptake in our study can be connected to the caveat that GCAM does not fully account for hydrogen's present commercial uses in industries such as chemicals, refining, and steel production where it's used in a gas mixture. Our focus is specifically on hydrogen when utilized as a final energy carrier or industrial feedstock, with an emphasis on exploring novel production technologies and applications (Wolfram et al. 2022).

[4] Although the study does not specifically focus on the building sector, we highlight the results from this sector to serve as a benchmark for comparing the progress of hard-to-abate sectors.

[5] This category is made up of a collection of diverse energy-intensive and manufacturing processes.

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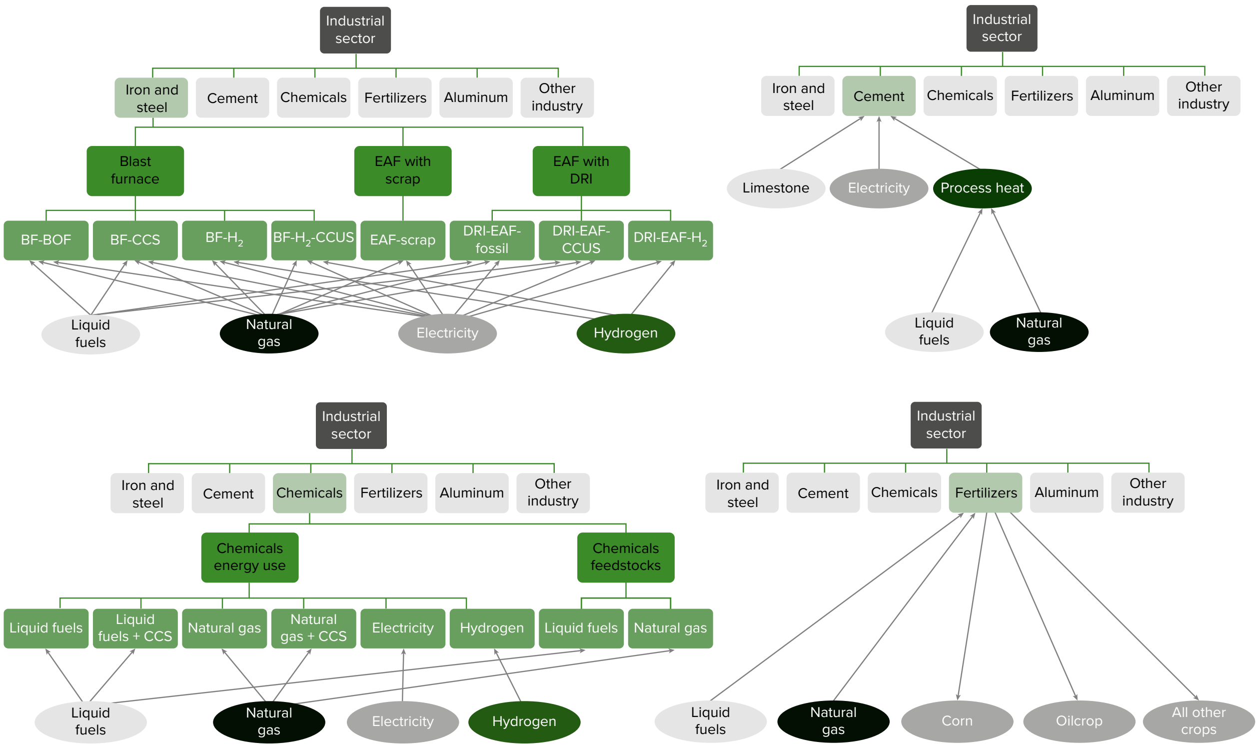
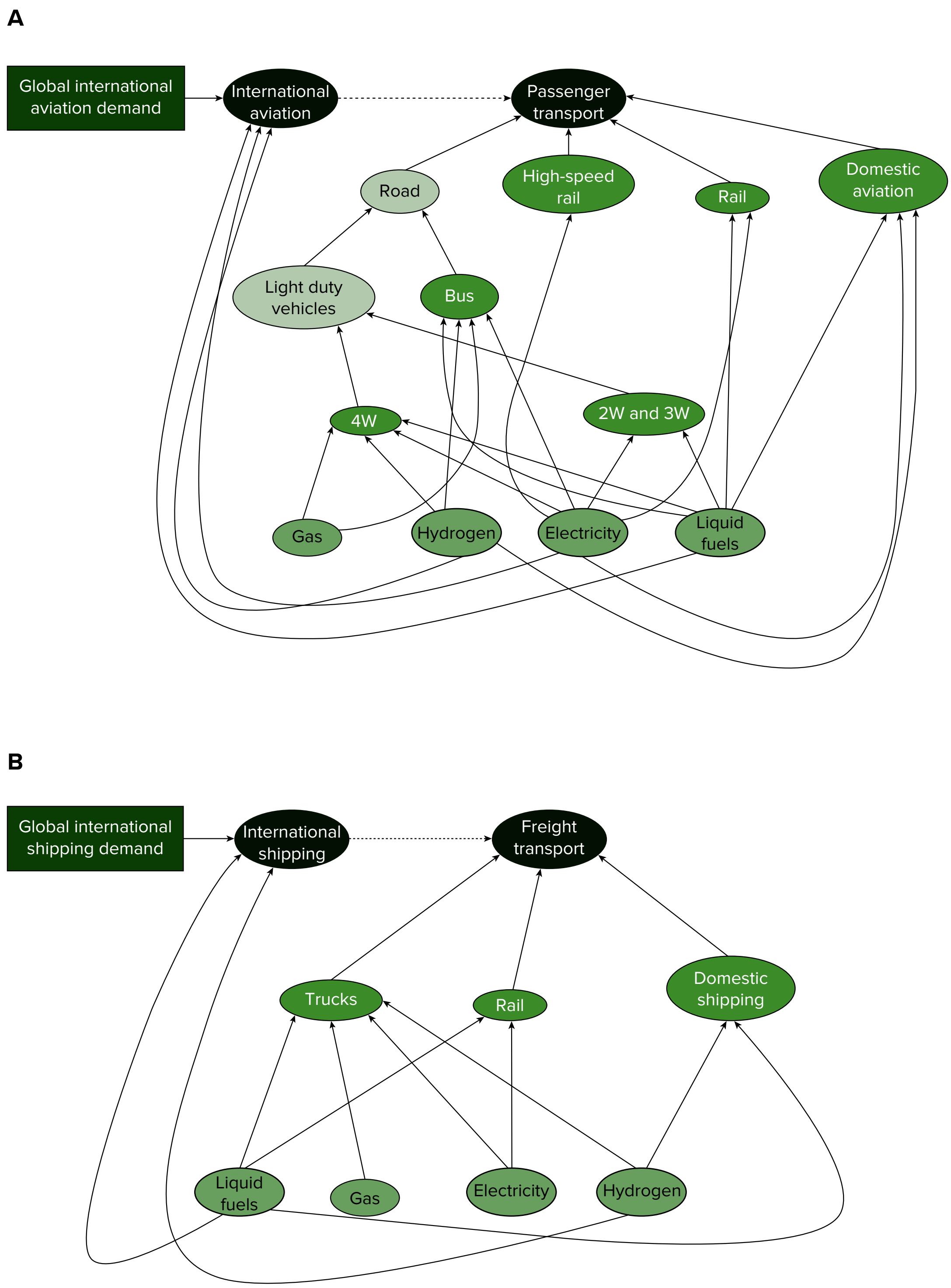
Appendix

Figure A1. GCAM's representation of the industrial sector.



Source: Adapted from Kamboj et al. (2024).

Figure A2. The GCAM's representation of the transportation sector.



Source: Adapted from Kamboj et al. (2024).

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About the Project

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

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