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Highlights

- This paper compares global transportation/energy models in terms of scope, structure and the types of scenarios that have been developed, with particular emphasis on projections of low-carbon fuels like hydrogen, biofuels, e-fuels and electricity in transportation decarbonization scenarios.
- Our review of the models and their scenarios indicates that scenarios with deep CO_2 reduction or globally ambitious climate policies tend to show a large increase in the role of electrification, advanced biofuels and in some cases hydrogen in transport energy by 2050 and/or later years.
- Different transport modes and sectors have different requirements and are projected to adopt different low-carbon fuels. Electricity is projected to play a key role in road and rail, though liquid low-carbon fuels dominate shipping and aviation and are expected to eventually surpass petroleum use.
- Deep CO2 reduction scenarios tend to assume strong policies that drive reductions. Policies such as efficiency standards, technology requirements, achieving technological innovation, and infrastructure investment are typically important drivers for influencing the adoption and scale-up of low-carbon technologies and fuels across regions.

Executive Summary

The global energy and fuels sector is undergoing rapid transformations driven by climate policies, technological advancements, and shifting geopolitical dynamics. Various energy systems and fuel modeling approaches have been developed to assess future energy demand, supply transitions, and policy impacts. This study compares various global energy and fuels models to assess low-carbon fuel adoption and energy demand in the transportation sector. Models like GCAM, MESSAGEix, REMIND-MAgPIE, Shell's WEM and others show significant variations in scenario types, assumptions and projections.

In modest decarbonization scenarios, often aligned with current or stated policy plans, petroleum typically remains the dominant fuel across most transport modes through mid-century, with limited penetration of electricity, hydrogen, and advanced biofuels. In contrast, deep decarbonization scenarios, targeting net-zero emissions by 2050, typically project a transformative shift toward electrification of light-duty vehicles and rail, substantial roles for hydrogen in freight and aviation, and increasing uptake of advanced biofuels and synthetic fuels in sectors less amenable to electrification. Such scenarios also include ambitious climate policies such as carbon pricing, strong regulatory frameworks, and subsidies for clean technologies, that tend to drive this adoption of clean electricity, biofuels, and hydrogen.

The timing and scale of low-carbon transitions are highly sensitive to specific policy instruments and intensity, fuel prices, and infrastructure readiness and investment. Models such as ITEDD and GET emphasize the importance of early investment in refueling and charging infrastructure to enable fuel switching at scale. GCAM includes Policy Scenarios such as carbon pricing and cap-and-trade systems. These simulate GHG pricing mechanisms that influence fuel demand and technology adoption, effectively acting as economic incentives (or disincentives) to switch to low-carbon alternatives. GMM features CO_2 tax scenarios, which represent direct fuel taxation mechanisms. These policies serve to shift technology choices and reduce emissions, illustrating how carbon pricing can steer the energy system toward cleaner fuels.

The comparative findings provide important insights for policymakers, illustrating the contrasting outcomes of incremental versus more ambitious climate strategies and the sector-specific pathways through which low-carbon fuels contribute to transportation decarbonization.

1 Introduction

The transportation sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 25% of total energy-related CO_2 emissions. Decarbonizing transportation is therefore essential for meeting international climate commitments such as the Paris Agreement and achieving net-zero emission targets by mid-century. A critical aspect of this transition is the adoption of low-carbon energy and fuels such as electricity, biofuels, hydrogen, liquid and gaseous "e-fuels" such as methanol, ammonia, drop-in e-gasoline, e-diesel, e-kerosene (jet fuel), and synthetic methane, which are expected to play varying roles in different regions and across different transport modes, including light-duty vehicles, heavy freight, aviation, and maritime transport. However, the pace, scale, and feasibility of transitions to these different fuels are subject to technological advancements, costs, CO_2 reduction potential, policy interventions, infrastructure developments, and economic constraints.

To address these uncertainties, a variety of global energy and fuels models have been developed to project future fuel demand, emissions pathways, and cost trajectories under different scenarios. These models serve as essential tools for policymakers, energy planners, and industry leaders by evaluating the impact of policy incentives, carbon pricing mechanisms, and technological innovation on the energy and transportation sectors. However, significant differences exist in methodological approaches, underlying assumptions, and scenario designs across various models, leading to discrepancies in projected outcomes for low-carbon fuel adoption. A systematic comparative analysis of these models is therefore necessary to enhance their interpretability, credibility, and policy relevance. At the same time, there is growing recognition that demand-side drivers, such as changes in urban form, teleworking, and shared mobility can play a decisive role in shaping transport activity and fuel demand, yet these factors are often underrepresented in global fuel-oriented models (Thomas et al., 2024).

This study differs by focusing specifically on the comparative analysis of global energy and fuels models, with an emphasis on how they represent the adoption of low-carbon fuels across transport modes. Whereas demand-oriented studies highlight behavioral and infrastructural factors influencing transport activity, our analysis concentrates on the supply-side dimension of decarbonization, fuel options, system integration, technology adoption, and policy mechanisms—to better understand the pathways available for large-scale fuel transitions in the transportation sector. The research addresses the following questions:

1. What are the fundamental methodological differences between major global transportation energy and fuels models?
2. How do these models incorporate low-carbon fuel pathways, and what are their respective projections for biofuels, hydrogen, liquid and gaseous "e-fuels"?
3. What policy scenarios are modeled, and how do they influence projections for transportation fuel transitions?
4. What are the key strengths, limitations, and sources of uncertainty in existing modeling frameworks?

5. How can energy and transportation modeling be improved to better inform decarbonization policies and investment decisions?

The paper is organized as follows: section 1 provides an overview of the major global energy and fuels models, categorizing them based on their methodological frameworks, application domains, and projection horizons. Section 2 examines the key scenarios modeled across different frameworks, including baseline (business-as-usual) projections, climate policy pathways, low-carbon fuel transitions, and economic growth scenarios. Section 3 compares global energy and transportation projections to 2050 and beyond, analyzing energy demand by fuel type, transport mode under three types of scenarios across IEA, EIA and different models. Section 4 discusses the implications of these models for global energy and transport policy, analyzing their relevance in climate mitigation strategies, carbon pricing mechanisms, trade policies, and regional energy security concerns. Section 5 explores future challenges and emerging trends in energy and transportation modeling, including AI-driven scenario analysis, open-source modeling approaches, and the integration of socioeconomic factors into fuel transition projections. Section 6 concludes with key findings and policy recommendations, outlining areas for improvement in modeling approaches and providing guidance for energy policymakers, researchers, and industry stakeholders.

2 Overview of Global Energy and Fuels Modeling Approaches

This section provides an overview of twelve major global energy and fuels models, as well as one collaborative platform to compares some of these models (the International Transport Energy Modeling or iTEM Framework), and two fuel "outlook" types of scenarios from energy companies Shell and BP (which clearly are based on models, though little detailed information about these models was available so they are not included in our model comparisons). Thus, we compare the 12 models, and then compare their scenarios along with iTEM, Shell and BP scenario reports.

The twelve global energy and fuels models can be categorized by their methodological framework and primary application areas into a) integrated assessment models (IAMs), b) simulation models, and c) optimization models. These can be characterized as follows:

a) IAMs are interdisciplinary frameworks that integrate components from climate science, economics, energy systems, and land use to evaluate the interactions between human and natural systems, primarily for long-term policy assessment and decision-making in areas such as climate change mitigation.
b) Simulation models are primarily descriptive. They aim to replicate and explore the dynamic behavior of a system over time under varying conditions and assumptions, without seeking to identify an optimal outcome.
c) Optimization models are normative and prescriptive, using mathematical formulations to identify the best possible solutions such as minimizing costs or emissions subject to a set of constraints.

While IAMs may incorporate both simulation and optimization techniques within a single framework, the fundamental distinction lies in their objectives. IAMs focus on integrated policy analysis, simulation models on behavioral exploration, and optimization models on identifying optimal strategies. These three types of models serve as essential tools for energy policymakers, industry stakeholders, and researchers in assessing the implications of fuel transitions, climate mitigation strategies, and economic trade-offs in a rapidly evolving global energy landscape. BP and Shell do not use standard academic or government-developed models (like IAMs or bottom-up tech models). Instead, they use internal proprietary tools to support scenario-based outlooks, focused on narrative exploration and business strategy, rather than optimization or simulation modeling.

The following provides a summary of each of the major models and the two projection outlooks, while Table 1 compares these somewhat systematically, including model type, key features, application areas, developer, updated year, and projection year.

2.1 Integrated Assessment Models

Global Change Assessment Model (GCAM)

The Global Change Assessment Model (GCAM) is an integrated assessment model designed to analyze the interactions between energy, economy, land use, and climate policy. It operates as a partial equilibrium model, capturing economic and policy feedback mechanisms while incorporating land-use change modeling to assess climate mitigation pathways. GCAM is widely used for climate policy analysis, energy system transitions, and greenhouse gas (GHG) emissions projections at global and regional levels. The model is developed and maintained by Pacific Northwest National Laboratory (PNNL), the U.S. Department of Energy (DOE), and the University of Maryland. The most recent update was in 2024, with projections extending to 2100 (Joint Global Change Research Institute (JGCRI), 2023).

Model for Energy Supply Strategy Alternatives and their General Environmental Impact – ix (MESSAGEix)

The MESSAGEix model is an integrated assessment model (IAM) designed to analyze long-term energy system transformations under various economic, environmental, and technological constraints. It provides a comprehensive framework for evaluating sustainable energy pathways, integrating energy system planning, climate policy analysis, and macroeconomic feedback loops. MESSAGEix is widely used for long-term climate mitigation studies and sustainable development scenario assessments. The model is developed and maintained by the International Institute for Applied Systems Analysis (IIASA), with projections extending to 2050, 2070, or even 2100, depending on the study objective (Huppmann et al., 2019).

Regional Model of Investment and Development (REMIND-MAgPIE)

The REMIND-MAgPIE framework links a detailed global energy-economy model (REMIND) with a spatially explicit land-use model (MAgPIE), allowing for a sophisticated analysis of the trade-offs between energy decarbonization, land-based mitigation strategies, and food security Click or tap here to enter text.(Bertram et al., 2018; Dietrich et al., 2019). REMIND operates as an intertemporal optimization model, assuming perfect foresight across regions and sectors, aiming to find the least-cost pathways to meet global climate targets. MAgPIE provides a highly detailed representation of land-use dynamics, agricultural production, and food trade, with a focus on land-based mitigation measures such as afforestation and bioenergy deployment. The REMIND-MAgPIE framework is extensively applied in Model Intercomparison Projects (MIPs), scenario design consistent with the Paris Agreement goals, and interdisciplinary analyses linking energy transitions with land and food systems. The framework is regularly updated, with its latest developments incorporated in 2023, providing projections extending to the year 2100.

Integrated Model to Assess the Global Environment (IMAGE)

The Integrated Model to Assess the Global Environment (IMAGE) is a comprehensive simulation-based integrated assessment framework developed to explore the complex interactions between human activities and the Earth system, with a particular focus on long-term environmental sustainability and climate change mitigation. IMAGE integrates detailed representations of energy systems, land use, agricultural production, natural ecosystems, and atmospheric processes to simulate global and regional developments under varying socio-economic and policy scenarios. It is developed by the IMAGE-team under the authority of PBL Netherlands Environmental Assessment Agency (IMAGE - Integrated Model to Assess the Global Environment | PBL Netherlands Environmental Assessment Agency, 2025). It supports Model Intercomparison Projects (MIPs), international climate assessments, and strategic planning exercises by providing consistent and detailed projections across energy, land, and environmental domains. The IMAGE framework is continually updated, with its latest enhancements introduced in 2021, and it offers projections extending through the end of the 21st century.

World Induced Technical Change Hybrid model (WITCH 5.0)

The World Induced Technical Change Hybrid model (WITCH 5.0) is an advanced integrated assessment modeling framework designed to investigate the interplay between climate policies, technological change, and economic development at the global and regional levels. Developed by the RFF-CMCC European Institute on Economics and the Environment, WITCH 5.0 integrates a dynamic optimization approach with detailed representations of energy systems, innovation processes, and climate impacts Click or tap here to enter text.(*WITCH - World Induced Technical Change Hybrid Model*, 2021). The model emphasizes the endogenous evolution of technological change, allowing for the assessment of how investments in research and development, learning-by-doing, and knowledge diffusion affect mitigation costs and policy outcomes. WITCH 5.0 incorporates a game-theoretic structure that can simulate both cooperative and non-cooperative international climate strategies, providing nuanced insights into policy design and strategic behavior among regions. Continuously updated, with the latest version released in 2023, WITCH 5.0 projects socio-economic, energy, and emissions trajectories through 2100.

Asia-Pacific Integrated Model (AIM)

The Asia-Pacific Integrated Model (AIM) is a comprehensive integrated assessment modeling framework developed to analyze the dynamic interactions among energy systems, land use, economic development, and greenhouse gas emissions, with a particular emphasis on the Asia-Pacific region. Developed by the National Institute for Environmental Studies (NIES) in Japan, in collaboration with Kyoto University and the Mitsubishi Research Institute, AIM comprises a suite of interconnected modules that simulate both global and regional socio-economic pathways Click or tap here to enter text.("Climate Policy Assessment," 2003). The framework includes energy system optimization, land-use change simulation, and macroeconomic modeling to assess climate policy impacts and sustainable development strategies. AIM supports scenario-based assessments aligned with the Shared Socioeconomic Pathways (SSPs) and contributes to international model intercomparison exercises, including those informing the IPCC.

Comprehensive Framework for Energy and the Environment (COFFEE)

The Comprehensive Framework for Energy and the Environment (COFFEE 1.0) is an integrated energy system model designed to evaluate long-term pathways for decarbonization and climate policy, with a particular focus on Latin America and other emerging economies. Developed by the Energy Planning Program (PPE) at the Federal University of Rio de Janeiro (UFRJ), COFFEE extends the MESSAGE modeling architecture by incorporating region-specific energy, land-use, and emissions data. It applies to a cost-optimization approach to simulate the evolution of the energy system under varying policy constraints and technological assumptions, enabling the assessment of national and regional strategies for sustainable development and emissions reduction (*COFFEE – COmputable Framework For Energy and the Environment Model – IAMC*, 2020).

2.2 Simulation Models

International Transportation Energy Determinants (ITEDD) Model

The International Transportation Energy Determinants (ITEDD) Model is designed for forecasting global transportation energy demand by examining energy consumption under different scenarios. It places a strong emphasis on demand for drivers and uncertainties, allowing for an in-depth assessment of the factors influencing fuel demand in the transportation sector. ITEDD is utilized by the U.S. Energy Information Administration (EIA) to inform policy decisions and energy outlook reports (Eia, 2017). The model was last updated in 2023, with projections extending to 2050.

Global Energy and Climate Model (GEC Model)

The Global Energy and Climate (GEC) Model provides comprehensive energy system projections by integrating components of the World Energy Model (WEM) and the Energy Technology Perspectives (ETP) model. The WEM component simulates energy market dynamics, while the ETP component is a technology-rich, bottom-up model that evaluates emerging energy technologies and their deployment potential. The GEC Model is employed to generate sector-specific and regional energy scenarios, offering detailed insights into global energy system transformations. It is developed and maintained by the International Energy Agency (IEA), with the latest update in 2024 and projections extending to 2050 (*Global Energy and Climate Model – Analysis - IEA*, 2024).

Global Trade Analysis Project (GTAP)

The Global Trade Analysis Project (GTAP) is a multi-region, multi-sector economic modeling framework that provides data and policy insights for analyzing international trade, economic policies, and sustainability challenges. The GTAP model simulates market interactions, trade agreements, tariff changes, tax policies, and carbon pricing impacts, making it a widely used tool for analyzing trade policies, climate change implications, energy transitions, and economic sustainability. Developed by Purdue University, the model was last updated in 2017, with projections extending to 2050 or beyond, depending on the scenario(Aguiar et al., 2022).

Global Energy System Model (GET)

The Global Energy System Model (GET) is an energy system optimization model with a particular emphasis on the transportation sector. It employs a least-cost optimization approach to determine the most cost-effective combinations of fuel and vehicle technologies within a decarbonizing global energy system. GET is primarily used for analyzing fuel choices and competition for primary energy resources under different technological and policy scenarios. The model is developed by Chalmers University and was last updated in 2013, with projections extending beyond 2050 and is constantly updated depending on research question. Recent publications focus on the maritime sector (Taljegard et al., 2014; Lehtveer, Brynolf and Grahn, 2019; Kanchiralla et al., 2025)

2.3 Optimization Models

Global Multi-Regional MARKAL (GMM) Model

The Global Multi-Regional MARKAL (GMM) Model is a technology-rich, bottom-up energy system model designed to minimize costs while considering technology learning and adoption rates. The model accounts for biofuels, hydrogen, and long-term transport scenarios, making it highly relevant for transportation and energy planning, as well as scenario analysis up to 2050. The GMM model has been used in collaboration with stakeholders such as Volkswagen and the World Energy Council (WEC). It is maintained by the Paul Scherrer Institute (PSI) and the University of Geneva Click or tap here to enter text.(Gül et al., 2009). The model was last updated in 2011, with projections extending to 2050.

2.4 Others

International Transport Energy Modeling (iTEM) Framework

The International Transport Energy Modeling (iTEM) framework serves as a collaborative platform that integrates insights from various transport energy models to improve the understanding of global transport and energy system interactions Click or tap here to enter text.(Yeh et al., 2017). It features

Model Intercomparison Projects (MIPs), historical transport statistics databases, and policy scenario workshops, making it a valuable tool for informing policy development, advancing research methodologies, and guiding strategic energy planning. The iTEM initiative is continuously updated, with the latest developments in 2024 and long-term projections extending to 2100.

Shell, BP and ExxonMobil Energy Outlooks

Shell, BP, and ExxonMobil, three of the world's leading energy companies, do not employ traditional integrated assessment models (IAMs), simulation models, or energy system optimization models. Instead, they develop internally structured, scenario-based strategic outlooks that integrate proprietary modeling tools and qualitative visioning to explore long-term potential energy transitions under uncertainty. These frameworks are not normative; they are primarily intended to characterize possible futures for strategic planning and communication rather than to achieve societal targets or address policy concerns. For each case, specifically:

- Shell produces scenario outlooks through its dedicated Shell Scenarios Team, which blends systems thinking, macroeconomic trends, policy insights, and energy market analysis to explore multiple long-term futures typically extending to 2100 (*World Energy Model | Shell Global*, 2025). Shell scenarios are narrative-rich and designed to explore plausible pathways in a complex and uncertain world.
- BP develops its Energy Outlook using an internal suite of economic and energy models focused on global energy demand, supply dynamics, and emissions trajectories (*Energy Outlook | Energy Economics | Home*, 2025). BP's scenarios are driven by macroeconomic trends, policy developments, and technology assumptions. BP's modeling is quantitative but strategically oriented, with outputs used to inform investment planning, policy engagement, and risk analysis.
- ExxonMobil develops its Global Outlook as a scenario-based strategic tool grounded in its analysis of long-term market fundamentals, demographic growth, technology adoption, and policy trends (ExxonMobil, 2025). This outlook provides projections for global energy demand, supply, and emissions through 2050, emphasizing the need to balance affordable, reliable energy with emissions reductions. It incorporates assumptions on both existing and anticipated climate-related public policy along with assumptions of technological improvement.

Table 1 Summary of Global Energy and Fuels Modeling Approaches

Model	Type	Key Features	Application Area	Developer	Updated Year	Projection Year
GCAM (Global Change Assessment Model)	Recursive-dynamic IAM	Links energy, water, land, and economy systems; flexible scenario analysis; partial equilibrium modeling	Global climate-energy-land pathways; policy analysis; resource interaction studies	PNNL, DOE & U. of Maryland	2024	2100
GET (Global Energy System Model)	Systems engineering optimization model	Technology substitution for energy system transitions; cost minimization under carbon constraints	Global low-carbon energy pathways; decarbonization strategy evaluation	Chalmers University	2025	2100
GMM (Global Multi-Regional MARKAL Model)	Bottom-up energy system optimization model	Multi-regional energy technology optimization; long-term supply-demand balancing	Regional and global energy policy and technology assessments	PSI & U. of Geneva	2020	2011
ITEDD (International Transportation Energy Determinants Model)	Simulation model	Transport energy demand projections based on socio-economic drivers; limited supply-side integration	Global transport energy demand forecasts; scenario exploration	EIA	2025	2050
GEC (Global Energy and Climate Model)	Simulation model	Future energy market and emissions projections; technology and policy scenario analysis	Energy-climate interaction studies; emissions projections	IEA	2024	2050
GTAP (Global Trade Analysis Project)	Computable general equilibrium simulation (CGE) model	Detailed international trade, energy, and environmental policy analysis	Global trade, energy markets, and emissions policy evaluation	Purdue University	2025	2050 or even 2100
MESSAGEix	Optimization-based IAM	Integrated modeling of energy, land, and climate; flexible scenario design; policy constraints modeling	Global sustainable development pathways; energy-land-climate mitigation strategies	IIASA	2025	2050, 2070, or even 2100

Model	**Type**	**Key Features**	**Application Area**	**Developer**	**Updated Year**	**Projection Year**
REMIND-MAgPIE	Intertemporal optimization IAM (perfect foresight)	Cost-optimal energy-land-climate transitions; spatially explicit land-use modeling	Global decarbonization, land-use change, climate mitigation policy assessments	Potsdam Institute for Climate Impact Research	2025	2100
IMAGE (Integrated Model to Assess the Global Environment)	Recursive-dynamic IAM	Sectoral detail in land use, energy, ecosystems; environmental co-benefit analysis	Sustainable development analysis; biodiversity and land-use projections	PBL Netherlands Environmental Assessment Agency	2021	2100
WITCH 5.0 (World Induced Technical Change Hybrid model)	Intertemporal optimization IAM with game theory	Endogenous technological change; strategic international cooperation; adaptation modeling	Climate policy strategy, innovation pathways, cost-benefit analysis of mitigation	European Institute on Economics and the Environment	2023	2100
AIM (Asia-Pacific Integrated Model)	Hybrid IAM (optimization and simulation modules)	Regional energy, land-use, and socio-economic development modeling; detailed Asia-Pacific representation	Regional sustainable development pathways; mitigation scenarios; climate policy impact studies	National Institute for Environmental Studies (NIES), Japan	2023	2100
COFFEE 1.0 (Comprehensive Framework for Energy and the Environment)	Energy system optimization IAM	Regionally detailed modeling of energy, land use, and GHG emissions, with emphasis on Latin America and emerging economies	National and regional decarbonization pathways; energy-environment policy evaluation; Latin America-focused mitigation assessments	Federal University of Rio de Janeiro (UFRJ), Brazil	2022	2100
iTEM (International Transport Energy Modeling)	Collaborative modeling platform	Integrates transport models, historical databases, and scenario workshops	Transport-energy system interaction studies; model intercomparison and policy support	iTEM Initiative	2023	2100

Model	Type	Key Features	Application Area	Developer	Updated Year	Projection Year
(unnamed or unknown)	Scenario-based simulation model	Exploratory scenario design; technology adoption, societal trends, and policy uncertainty	Global energy system transformation; long-term decarbonization pathways	Shell Scenarios Team	2023	2100
(unnamed or unknown)	Scenario-based simulation model	Market-driven scenario analysis; energy demand and emissions projections under alternative policy and economic conditions	Global energy transition pathways; policy and investment implications	BP Energy Outlook	2023	2050
(unnamed or unknown)	Scenario-based simulation model	Exploratory scenario design; long-term energy demand, supply, and emissions projections; policy and technology uncertainty analysis	Global energy transition pathways; strategic business and investment planning	ExxonMobil Global Outlook	2024	2050

3 Scenarios of Global Energy and Fuels Modeling Approaches

The twelve energy and fuels models and fuel companies Shell, BP and ExxonMobil mentioned above explore multiple scenario types to capture potential futures and uncertainties in climate, policy, markets, and technology. This study classifies these scenarios into six categories: baseline/reference, carbon reduction, deep carbon reduction, energy transition & technology transformation, economic growth and demand uncertainty, trade policy, geopolitical, and fossil fuel market and resource supply. There certainly could be and are overlaps between these, and most of the scenarios considered here could be placed in multiple categories; but the tendencies toward a particular type of scenario are identified.

3.1 Scenario Categories

Baseline and Reference Scenarios

Baseline and reference scenarios typically depict futures in which no new climate or energy policies are introduced beyond those already enacted or formally adopted. They often represent business-as-usual (BAU) trajectories where socioeconomic and technological trends continue without additional mitigation efforts. These scenarios are critical for benchmarking, providing a reference point against which the effects of climate policies, technological changes, or market shifts can be assessed. Examples include IEA's Stated Policies Scenario (STEPS), GCAM's Reference Scenario, and BP's Current Trajectory, all of which assume continuity in current global development patterns.

Carbon Reduction and Deep Decarbonization Scenarios

Carbon reduction and deep decarbonization scenarios model pathways in which additional policies, regulations, and technologies are introduced to achieve greenhouse gas emission reductions. These scenarios range from moderate mitigation efforts aligned with announced plans and pledges (e.g., IEA's APS) to highly ambitious pathways targeting net-zero emissions by mid-century (e.g., IEA's NZE, REMIND's cost-optimal mitigation cases), and identify policies needed to achieve this. Deep decarbonization scenarios often assume transformative changes across energy, industry, and land sectors to limit warming to 1.5 °C, making them essential for evaluating the feasibility and implications of stringent climate action, and tradeoffs between actions in different sectors.

Energy Transition and Technology Transformation Scenarios

Energy transition and technology transformation scenarios explore how variations in cost, performance, and adoption speed of clean energy technologies influence future energy systems. These scenarios assess the impact of technological breakthroughs or slowdowns in renewables, carbon capture, electrification, and hydrogen deployment, shaping the pace and scale of decarbonization. For instance, EIA's High and Low Zero-Carbon Technology Cost cases and GCAM's technology availability scenarios illustrate how accelerated innovation or persistent barriers in key technologies could fundamentally alter the energy transition trajectory.

Fossil Fuel Market and Resource Supply Scenarios

Fossil fuel market and resource supply scenarios examine the effects of changes in oil, gas, and coal markets, including price fluctuations and resource availability, on the broader energy system. These scenarios consider conditions of fossil fuel abundance or scarcity and assess how such dynamics impact the competitiveness of low-carbon technologies and the adoption of alternatives. EIA's High and Low Oil Price and Supply cases, as well as GMM's shale gas availability scenarios, exemplify how market-driven factors can either accelerate or delay transitions toward more sustainable energy systems.

Economic Growth and Demand Uncertainty Scenarios

Economic growth and demand uncertainty scenarios investigate how different macroeconomic growth pathways influence energy demand, emissions trajectories, and technological adoption. High-growth scenarios typically project higher energy consumption and emissions, while low-growth or recessionary scenarios imply slower demand increases or reductions. Analysis, including EIA's high and low economic growth cases and GCAM's Shared Socioeconomic Pathways (SSPs), are critical for understanding the sensitivity of energy system evolution to underlying economic drivers.

Trade Policy, Globalization, and Geopolitical Scenarios

Trade policy, globalization, and geopolitical scenarios explore how international cooperation or fragmentation influences energy transitions, technology diffusion, and economic development. These scenarios examine worlds characterized by open trade and multilateral collaboration versus protectionist, fragmented systems where national self-reliance dominates. Shell's Archipelagos and Horizon scenarios, along with GTAP-based trade policy simulations, illustrate how trade dynamics, tariffs, and geopolitical alliances can significantly alter emissions pathways, energy security, and the global distribution of clean technologies.

3.2 Scenario Analysis

This section analyzes many of the scenarios modeled across these global energy and transportation modeling frameworks and the outlooks mentioned above as shown in Table 2. As described above, each model varies in its structure, scope, and policy assumptions, and the range of scenarios implemented reflects these methodological differences. We classify these according to the 6 types we identify above and discuss and compare them.

- IEA GEC's three core scenarios—STEPS, APS, and NZE—represent a progressive policy ambition spectrum.
    - STEPS functions as a baseline aligned with currently enacted policies.
    - APS includes announced pledges that have not (yet) been implemented, while
    - NZE embodies a stringent net-zero target scenario by 2050, featuring deep electrification, hydrogen uptake, and advanced renewable penetration.

Notably, across these scenarios, GEC captures economic growth uncertainty but omits detailed trade or fossil market shifts.

- GCAM models a rich portfolio of scenarios:
    - The Reference scenario offers a BAU trajectory.
    - Policy Scenarios simulate carbon pricing and cap-and-trade frameworks, forming both carbon reduction and deep decarbonization scenarios.
    - The model extensively employs Shared Socioeconomic Pathways (SSPs), linking long-term socioeconomic narratives to policy ambition and technological change.
    - Additional scenario types include technology cost sensitivity (e.g., high renewables/low CCS) and energy system-specific pathways (e.g., BECCS, hydrogen adoption), offering high-resolution insights into technology-driven transitions.
- GET implements transition-specific scenarios centered on technology deployment (Lehtveer *et al*., 2019). Scenarios such as "No CCS/CSP" and "Only CCS/CSP" isolate the impact of specific low-carbon technologies under carbon constraints (Grahn *et al.*, 2009). These emphasize technology transformation and decarbonization via CCS, although the model omits broader socioeconomic or geopolitical dimensions.
- GMM includes a standard Reference scenario and several resource-focused variations, such as high shale gas and restricted access, as well as CO_2 tax cases, which serve as carbon reduction levers. While not designed for deep decarbonization scenarios, GMM provides valuable insight into resource supply sensitivity and price-responsive technology choices.
- ITEDD, primarily a demand-side model, includes Reference and High/Low Liquids Demand scenarios, reflecting sensitivity to macroeconomic and vehicle usage trends. It also includes Natural Gas Subsidy scenarios to explore policy-driven technology shifts in vehicle fuel types, capturing the interplay between policy incentives and demand profiles.
- GTAP's scenario space centers on trade and macroeconomic shocks, with scenarios focused on GHG-related tariffs, supply chain disruptions, and climate-related trade policy impacts. While not a typical energy transition model, GTAP adds critical value in evaluating policy interactions across borders.
- MESSAGEix simulates multiple deep decarbonization trajectories through carbon budget, policy-driven mitigation, and technology mandates. It also includes fossil fuel phaseout and resource cost scenarios and is known for long-term net-zero alignment under least-cost system planning. The model's flexibility enables both policy instrument analysis and technology pathway exploration.
- REMIND-MAgPIE scenarios—such as Cost-Optimal Mitigation, Overshoot, and Sustainable Development Pathways (SDPs)—represent some of the most ambitious deep mitigation scenarios. They assess integrated land-energy-climate pathways, including electrification, CCS, and renewable integration, and their interactions with food security and land-use change.
- IMAGE emphasizes policy and environmental co-benefit scenarios, including NDC-aligned, low-demand sustainable development, and biodiversity-focused cases. While it models deep carbon reduction, its unique strength lies in integrating land-use, biodiversity, and lifestyle shift dimensions into decarbonization narratives.

- WITCH's scenario suite includes cost-effectiveness mitigation, strategic cooperation vs fragmentation, and carbon budget constraints. Notably, the model features scenarios with explicit damage modeling, adaptive behaviors, and endogenous technological change, offering a game-theoretic perspective on emissions reduction efforts.
- AIM incorporates Reference, NDC-aligned, and Sectoral Development Policy scenarios. These assess regional and global decarbonization under carbon budgets and end-use transformation, including strong sector-specific focus (e.g., transport, industry), making it highly relevant for targeted climate strategies in Asia-Pacific and beyond.
- COFFEE focuses on Latin American and emerging economies and includes scenarios such as:
  - Current Policy Extension (reference),
  - Paris-aligned (1.5°C or 2°C pathways)
  - Low-BECCS, which tests mitigation under limited negative emissions potential. This set is particularly suited for evaluating bioenergy constraints and region-specific decarbonization feasibility.
- EIA has no transformative scenarios and focuses on a reference case, but produces sensitivity scenarios driven by macroeconomic and market dynamics:
  - High/Low Economic Growth, Oil Price, and Zero-Carbon Technology Cost assumptions offer insights into energy use volatility.
  - These scenarios are valuable for near- to mid-term energy forecasting and emphasize the influence of economic structure on fuel choices, though they lack detailed carbon mitigation pathways.
- Shell's Archipelagos, Horizon (Sky 2050), and Surge scenarios capture geopolitical fragmentation, strong global cooperation, and disruptive tech transformation, respectively. These are strategic foresight narratives rather than formal optimization models, designed to explore qualitative uncertainty in global energy evolution.
- BP's Current Trajectory and Net Zero scenarios represent a policy inertia baseline and a high-ambition transition, respectively. Although built from internal models, they serve as energy company benchmarks for public discourse on future energy markets and emissions.
- ExxonMobil considers multiple scenarios to inform strategic planning, reflecting uncertainty in policies, technology development, and consumer behavior. These scenarios explore a range of pathways based on market and technology trends rather than prescribing specific outcomes. Unlike normative approaches that work backward from targets (e.g., IPCC or IEA NZE), ExxonMobil's projections assess how economic efficiency and technology deployment—such as CCS, hydrogen, and biofuels—could evolve under different policies and market conditions.

These are considered in Table 2 in a manner that attempts to compare scenarios across a range of dimensions. One principal takeaway is that no two scenarios are defined in quite the same way, making comparisons generally "apples-oranges", though at least those that are scenarios of similar types can be compared in a more general way, as we do further below.

Table 2 Scenarios Modeled in Global Energy and Fuels Models (dashed lines indicate there is no known scenario of that type)

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
GEC	STEPS	Stated Policies as of current year	Moderate GHG reductions from current policies	—	—	Reflects current uncertainty in growth trends	—	—
	APS	—	Policies reflecting announced pledges	—	—	—	—	—
	NZE	—	—	Net-zero CO_2 by 2050 with high ambition	High renewable and electrification deployment	—	—	—
GCAM	Reference	Current policies and technologies continue	—	—	—	—	—	—
	Policy Scenarios (e.g., Carbon Tax, Cap-and-Trade, Net Zero Targets)	—	GHG pricing mechanisms (carbon tax, ETS)	Deep decarbonization pathways	Technology shifts driven by policy signals	—	—	—
	SSPs (e.g., SSP1 Sustainability)	Middle-of-the-road to sustainable development pathways	Climate action tied to socioeconomic narratives	Net-zero consistent pathways	Integrated technology changes by socioeconomic storyline	Includes assumptions of population and GDP uncertainty	Explores international collaboration under SSPs	—

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
	Technology Cost and Availability (High Renewables, Low CCS)	—	Reduced emissions from renewables and low-carbon tech	Enhanced tech-driven mitigation	Varies renewable deployment and CCS costs	—	—	—
	Energy System-Specific (Hydrogen, Electrification, BECCS Deployment)	—	Fuel-specific decarbonization (e.g., hydrogen)	BECCS and electrification integration	High shares of hydrogen and electrification	—	—	—
GET	No CCS/CSP	No carbon capture or solar thermal assumed	—	—	Renewable-led energy transformation	—	—	—
	Only CCS / Only CSP / Both	CCS and/or CSP technology deployment	Decarbonization via CCS and/or CSP	Near-total elimination of fossil use	Tech-specific transition paths modeled	—	—	—
GMM	Reference	Business-as-usual projections	—	—	—	—	—	—
	High Shale Gas / Restricted Access / CO_2 Taxes	—	Emissions pricing via CO_2 tax	—	—	—	—	Resource supply sensitivity analysis (shale access)

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
ITEDD	Reference / Updated Reference	Business-as-usual global transport projections	—	—	—	Incorporates revised demand projections over time	—	—
	High/Low Liquids Demand	—	—	—	—	Scenarios reflect upper and lower bounds of transport fuel demand	—	—
	Natural Gas Subsidy Cases	—	—	—	Subsidy-driven increase in natural gas vehicle uptake	Evaluates cost/price uncertainty of fuels	—	—
GTAP	Trade Policy / Climate and Energy Policy	—	GHG-related tariff or subsidy policies	—	—	—	Evaluates global trade and border adjustment policies	—
	Food Security, Global Supply Chain, Economic Shocks	—	—	—	—	Economic resilience under shocks, yield changes, or crises	International trade disruptions and supply chain modeling	—

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
MESSAGEix	Climate Policy / Energy Transition	—	Policy-driven carbon pricing and technology mandates	Long-term net-zero consistent trajectories	Electrification and renewable adoption pathways	—	—	—
	Fossil Fuel Markets	Fossil resource constraints and pricing baselines	—	—	—	—	—	Exploration of fossil fuel phaseout trajectories
REMIND-MAgPIE	Cost-Optimal Mitigation / Sustainable Development / Overshoot	—	Optimized GHG pathways under different constraints	1.5–2°C mitigation with overshoot and sustainable development variants	Electrification, CCS, renewable integration	—	—	—
IMAGE	Current Policy Scenarios	Continuation of currently implemented climate policies	—	—	—	—	—	—
	Moderate Mitigation Scenarios	—	Nationally Determined Contributions (NDCs) level ambition	—	—	—	—	—
	Sustainable Development (Low Demand) Scenarios	—	Demand-side mitigation under sustainable assumptions	Deep mitigation with lifestyle and efficiency shifts	Tech and demand-side synergies	—	—	—

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
	Biodiversity and Land-Use Focused Scenarios	—	—	—	—	—	Land and ecosystem impact of global energy transitions	—
WITCH 5.0	Cost-Effectiveness Mitigation / Cooperation-Non-Cooperation	—	Optimal GHG reduction pathways under international collaboration vs fragmentation	Strong policy alignment for deep emissions cuts	Tech innovation and R&D investment dynamics	—	—	—
	Carbon Budget Constraint / Adaptation & Damage	—	Constrained emissions scenarios with damage modeling	Severe reduction targets under damage valuation	Technology deployment under constrained emissions	—	—	—
AIM	Reference / Baseline	BAU or NDC-aligned emission trajectories	—	—	—	—	—	—
	NDC Scenarios / Carbon Budget	—	Emission reductions aligned with NDCs and global carbon budgets	Deep mitigation aligned with Paris Agreement	Energy system transformation modeled	—	—	—
	Sustainable Development / Sectoral Policy	—	Sectoral GHG targets and development-focused mitigation	Strong mitigation combined with development goals	End-use energy transformation in transport, industry, etc.	—	—	—

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
COFFEE	Current Policy Extension	Continuation of existing national policies	—	—	—	—	—	—
	Paris-aligned / Carbon Budget Tight Scenarios	—	Climate commitments consistent with <2°C or 1.5°C	Carbon budget-constrained trajectories	Power and fuel system decarbonization	—	—	—
	Low-BECCS Scenarios	—	Climate mitigation with limited bioenergy CCS availability	Net-zero under limited negative emissions options	Electrification and efficiency emphasized	—	—	—
EIA	High/Low Economic Growth, Oil Price/Supply	Macroeconomic and price sensitivity analysis	—	—	—	Reflects uncertainty in growth rates and oil price volatility	—	Exploration of oil market responses
Shell	Archipelagos	National-first fragmented pathway	—	—	Gradual, region-specific clean tech deployment	Economic divergence and regional uncertainties	Weak global coordination and trade	—
	Horizon (Sky 2050)	—	Strong global climate cooperation	Full decarbonization, net-zero by 2050	Rapid, coordinated energy system transition	—	—	—

Model	Scenario	Baseline / Reference	Carbon Reduction	Deep Carbon Reduction	Energy Transition & Technology Transformation	Economic Growth and Demand Uncertainty	Trade Policy, Globalization, and Geopolitical	Fossil Fuel Market & Resource Supply
	Surge	—	Aggressive tech leap driven by innovation	Disruptive low-carbon tech adoption	Rapid, innovation-led energy system change	—	—	—
BP	Current Trajectory	Status based on current policies and market signals	—	—	—	—	—	—
	Net Zero	—	Pathways consistent with net-zero target	Full-scale emissions abatement	Sector-wide transitions to low-carbon energy adoption	—	—	—
ExxonMobil	Global Outlook bases	—	—	—	Existing and anticipated climate-related public policy along with assumptions of technological improvement	Considering population and GDP growth impacts on energy demand	—	Continued oil & gas role, supply investment

4 Comparison of Global Energy Projections in Transportation Sectors to 2050 or Beyond

In this section, we make comparisons of specific energy and fuel use projections, across models and for transportation in general as well as for specific transportation sectors. We find a range of scenario types and details leading to a wide range of projections for these various specific variables and indicators. We first consider long-term energy consumption and demand projections by fuel type in the transportation sector overall, to the year 2050 (or further). This includes a range of integrated assessment models and forecasting agencies as discussed above. We start with a review of scenarios from two major agencies, namely the IEA and the EIA, and consider the implications of their scenarios. We then compare a range of other scenarios, setting projections “side by side” to understand similarities and differences.

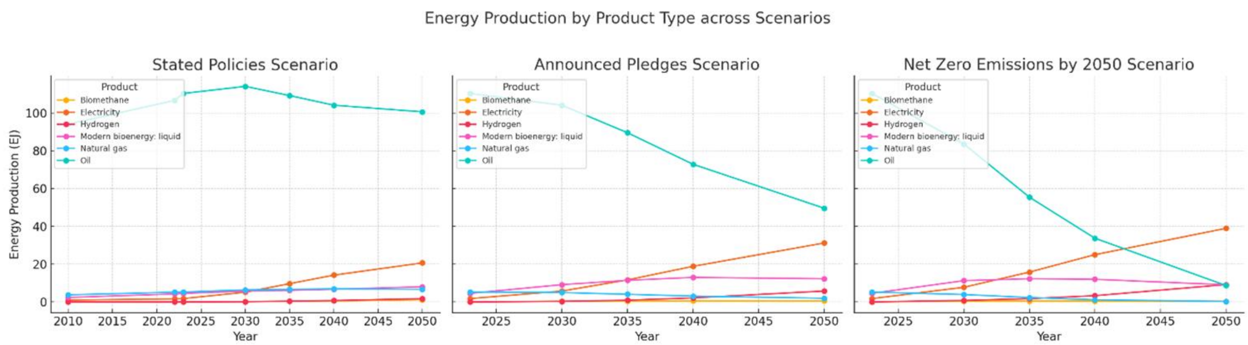
4.1 IEA GECM Projections

The Global Energy and Climate Model developed by IEA projects the energy production by fuel type in the transport sector under three key policy scenarios: the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE2050) as shown in figure 1. Some observations include:

- In the STEPS, which reflects current policy settings and trajectories, energy production for transport is predominantly supplied by conventional liquid fuels throughout the projected period. While electricity exhibits moderate growth, reaching approximately 5 EJ by 2030 and continuing to rise modestly thereafter, its share remains secondary relative to fossil-based energy. Other low-carbon fuels, such as hydrogen and advanced biofuels, remain negligible within this scenario, indicating that current policy frameworks are insufficient to catalyze a significant shift toward alternative energy carriers in the transport sector.
- Under the APS, which incorporates additional pledges and targets announced by governments, including those not yet supported by detailed policy frameworks, does have considerably more uptake of low-carbon energy sources. Notably, electricity production for transport applications shows accelerated growth post-2030, indicating that policy ambition beyond the status quo begins to yield structural changes in the energy mix. Biofuels and hydrogen also show some increases, yet their absolute contributions remain limited, suggesting that further policy mechanisms or economic incentives would be necessary to scale these technologies meaningfully.
- The most transformative changes are observed under the NZE2050 scenario. In this pathway, electricity becomes a dominant energy source for transport by mid-century, with a steep upward trajectory beginning around 2030. This scenario reflects a substantial uptake of hydrogen and advanced biofuels as well, aligning with global decarbonization objectives. The convergence of these low-carbon fuels in the NZE2050 scenario highlights the critical role of strong, integrated policies and coordinated investments in enabling a deep energy transition. Key policies include comprehensive carbon pricing mechanisms, stringent vehicle efficiency and emissions standards, zero-emission vehicle (ZEV) mandates, renewable energy portfolio requirements, and large-scale public and private investment in charging and refueling infrastructure for electric and hydrogen-powered vehicles. This scenario also illustrates the magnitude of the shift required in fuel supply chains to meet net-zero

goals, with advanced fuels collectively surpassing conventional energy carriers in their contribution to transport energy by 2050.

Figure 1: Energy production projection in transportation sector to 2050 by product type under stated policies, announced pledges, and net zero emissions by 2050 scenarios Global Energy and Climate Model by IEA



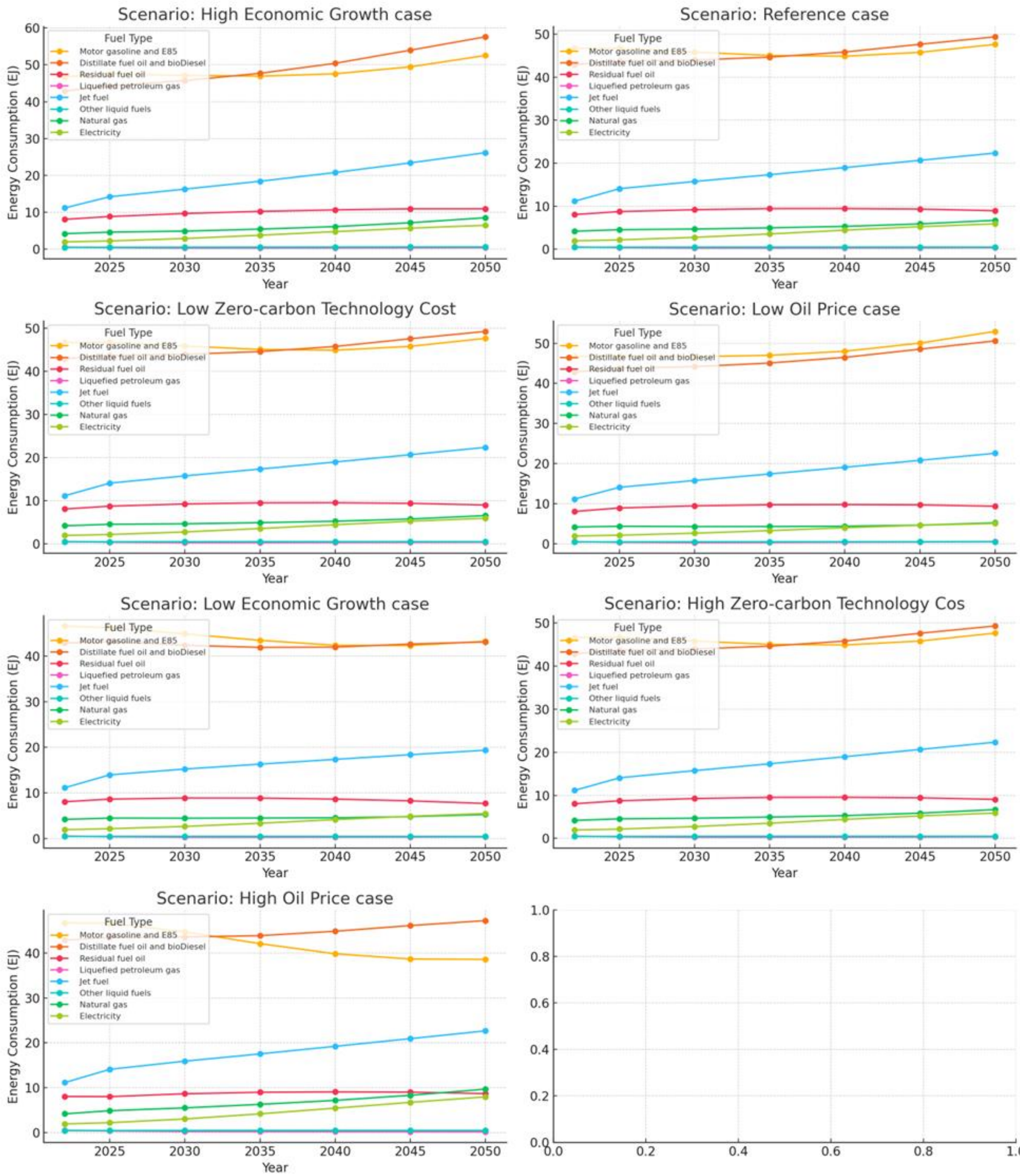
4.2 EIA IEO Projections

EIA projects transport energy consumption from 2020 to 2050 across seven scenarios reflecting differences in macroeconomic growth, oil prices, and the cost of zero-carbon technologies. Fuel types include conventional fossil fuels (e.g., motor gasoline, diesel, jet fuel), low-carbon alternatives (e.g., biofuels, other liquids), and electricity. Gasoline and ethanol blends remain dominant in all cases, though their trajectories vary: higher in the High Economic Growth scenario and flatter under Low Economic Growth. In the High Oil Price case, gasoline demand peaks around 2040 before declining slightly, suggesting modest fuel substitution due to cost pressures.

Electricity consumption increases in all scenarios, particularly under low zero-carbon technology cost assumptions, signaling the importance of technological affordability for electrification. By contrast, high technology costs constrain electricity uptake. Natural gas grows moderately, while LPG, residual fuel, and jet fuel remain largely flat, indicating limited potential for expansion under current assumptions. Distillate fuels and biodiesel grow steadily, especially where overall fuel demand is strong.

Overall, EIA's results suggest that energy demand in transport is highly sensitive to macroeconomic and market conditions. Scenarios with high growth and low fossil fuel prices reinforce reliance on petroleum, whereas high fossil prices and affordable clean technologies support a gradual transition to electricity and biofuels. These patterns highlight the critical role of policy, pricing, and innovation in accelerating low-carbon fuel adoption and overcoming structural barriers to decarbonization.

Figure 2. Energy consumption projection in transportation sector to 2050 by product type under current, macroeconomic growth, oil prices change, and the cost of zero-carbon technologies change scenarios from EIA



4.3 Total Transportation Energy Consumption and Demand across all Models/scenarios

4.3.1 Overview of scenarios

Next, we compare the energy projections in the transportation sector from different models under different scenarios within the same time horizon. For this we borrow a comparison provided by the IPCC Sixth Assessment Report (AR6), that includes all the models and scenario types we describe above. Figure 3 illustrates the projected final transportation energy demand trajectories (expressed in exajoules per year, EJ/yr) from 2000 to 2100 across the stated scenarios. Each trajectory reflects a distinct combination of model structure, socio-economic assumptions, technological development, and climate policy ambition, revealing substantial variation in global energy system evolution under different pathways.

- The WITCH 5.0 – CO_Bridge scenario assumes an internationally coordinated mitigation strategy that combines near-term carbon pricing with long-term emissions targets. It includes strong policy alignment across regions, early investment in low-carbon technologies, significant improvements in energy efficiency, and behavioral shifts such as reduced energy service demand in transport and buildings. Cooperation between regions reduces global mitigation costs and supports rapid deployment of clean energy solutions.
- The REMIND-MAgPIE 2.1–4.3 – DeepElec_SSP2_HighRE_Budg900 scenario is built on the SSP2 socio-economic narrative and is constrained by a carbon budget of 900 $GtCO_2$. It assumes rapid electrification of end-use sectors, large-scale deployment of renewables, stringent climate policies including high carbon prices, and the removal of fossil fuel subsidies. Technology adoption is accelerated through policy support and market incentives.
- The REMIND-MAgPIE 2.1–4.2 – SusDev_SDP-PkBudg1000 scenario integrates the Sustainable Development Pathway with a 1000 $GtCO_2$ peak-and-decline carbon budget. Assumptions include strong equity and redistribution measures, inclusive economic growth, behavioral changes such as reduced meat consumption and shared mobility, and policies supporting sustainable lifestyles. Emphasis is placed on access to clean energy and minimizing reliance on carbon removal technologies.
- The GCAM 5.3 – NGFS2_Current Policies scenario assumes that no new climate policies are introduced beyond those already implemented as of the early 2020s. It reflects a continuation of current technological trends, moderate improvements in energy intensity, and persistent use of fossil fuels. There are no explicit assumptions about behavioral change or structural transformation.
- The AIM/CGE 2.2 – EN_NPi2020_900f scenario assumes that countries maintain their 2020 nationally determined contributions (NDCs) and extend them to achieve a cumulative carbon budget of 900 $GtCO_2$. It includes incremental policy tightening, moderate increases in renewable energy shares, and some energy efficiency improvements, but without large-scale structural or behavioral shifts.
- The IMAGE 3.0 – EN_INDCi2030_3000f scenario is based on the Intended Nationally Determined Contributions submitted around 2015, with limited additional policy ambition. It assumes modest improvements in technology and energy efficiency, continued reliance on fossil fuels, and no significant lifestyle or demand-side changes.

- The MESSAGEix-GLOBIOM 1.0 – LowEnergyDemand_1.3_IPCC scenario includes strong assumptions about lifestyle change, energy sufficiency, and demand reduction. It incorporates compact urban development, modal shifts, reduced material throughput, energy-efficient technologies, and diets with lower environmental impact. It assumes minimal reliance on BECCS or other negative emissions technologies and prioritizes low-energy service delivery.
- The MESSAGEix-GLOBIOM_GEI 1.0 – SSP2_openres_lc_50 scenario reflects an SSP2 socioeconomic pathway with open access to fossil resources and relatively low climate policy ambition. It assumes low carbon prices, minimal behavioral change, and a gradual shift to low-carbon technologies based mainly on market competitiveness rather than policy mandates.
- The COFFEE 1.1 – EN_NPi2020_400f_lowBECCS scenario assumes a very tight global carbon budget (400 $GtCO_2$) while minimizing reliance on BECCS. Instead, it focuses on rapid deployment of renewables, strong demand-side measures, widespread electrification, and robust energy efficiency standards. Policy assumptions include high carbon prices, targeted subsidies, and regulatory support for non-fossil energy systems.

4.3.2 The three types of energy projections

Across all of these scenarios, it can be observed that they fall into three broad categories: those that achieve enduring deep reductions in energy use after 2050 and going to 2100 (light green, orange, red); those that achieve some reductions in the 2050 or 2060 time frame but eventually turn upward again and do not reach deep long term reductions (purple, dark blue, brown); and those that see generally rising energy use throughout the projection period to 2100 (light blue, pink, dark green).

Scenarios that achieve deep enduring reductions

These scenarios reflect the most ambitious climate and energy assumptions. They combine strong international coordination, high carbon prices, early and sustained investment in clean energy infrastructure, and major shifts in technology, behavior, and policy. Examples include WITCH CO_Bridge, REMIND-MAgPIE DeepElec_SSP2_HighRE_Budg900, REMIND-MAgPIE SusDev_SDP-PkBudg1000, MESSAGEix-GLOBIOM LowEnergyDemand_1.3_IPCC, and COFFEE EN_NPi2020_400f_lowBECCS.

Common drivers behind their sustained decline in energy use include:

- Aggressive electrification of transport and buildings,
- Large-scale deployment of renewables (especially in REMIND and COFFEE),
- High carbon pricing and removal of fossil fuel subsidies,
- Behavioral and lifestyle shifts, such as reduced private car use, shared mobility, or dietary change (as in MESSAGEix and SusDev scenarios),
- Equity and redistribution-focused development, which promote low-energy, high-welfare outcomes,
- Minimized reliance on negative emissions technologies, especially in COFFEE and MESSAGEix scenarios.

These combined elements reduce both the volume and carbon intensity of energy use, supporting a steady long-term decline in transport energy demand.

Scenarios that achieve reductions but then increases again

These scenarios exhibit some emissions and energy reductions typically around mid-century due to moderate policy improvements, technological improvements, or incremental electrification. However, they lack the structural shifts or policy intensity required to maintain those reductions over time. Examples include AIM/CGE EN_NPi2020_900f and MESSAGEix-GLOBIOM_GEI SSP2_openres_lc_50.

Key reasons for the eventual rebound in energy use include:

- Limited policy ambition: scenarios maintain NDCs or adopt only marginal additional policies.
- Insufficient behavioral change: personal and freight transport demand continues to grow.
- Ongoing fossil fuel access and affordability, especially under "open resource" assumptions.
- Technological transitions that stall or plateau due to infrastructure or cost constraints.

As a result, these scenarios show initial improvements but fail to lock in long-term reductions—energy demand eventually creeps upward as fossil-based growth resumes or electrification stagnates.

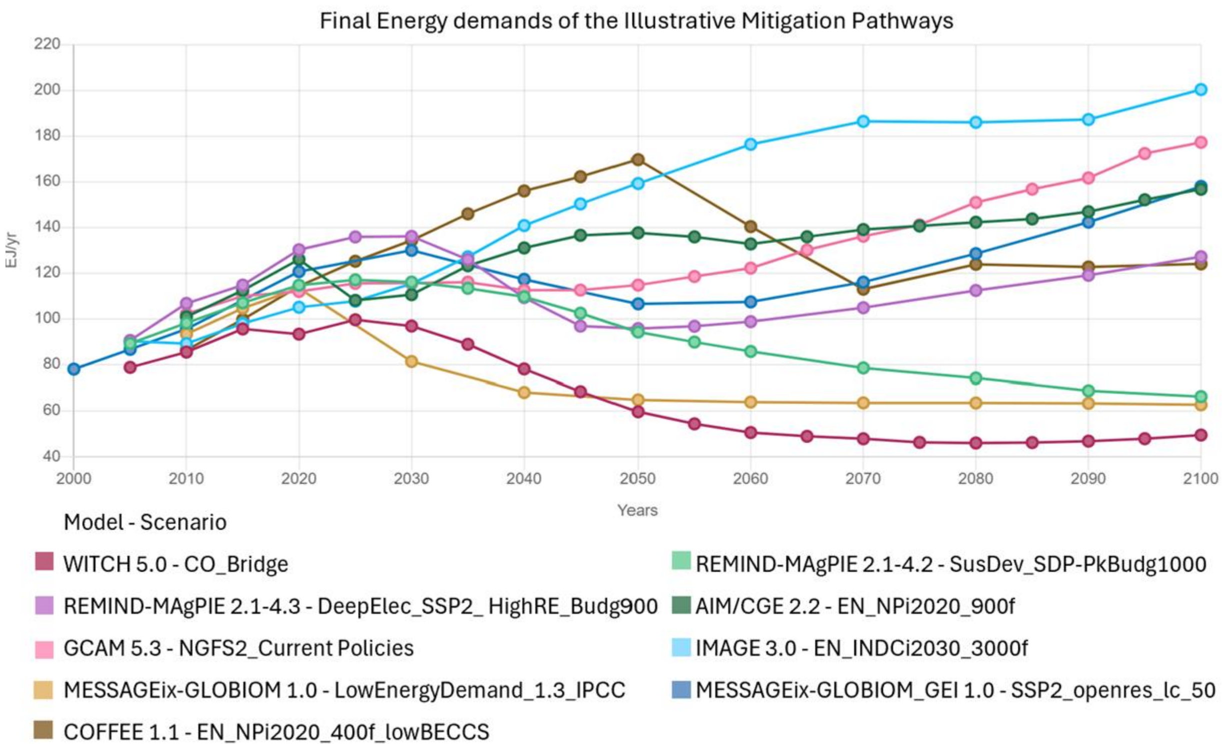
Scenarios that show generally rising energy use through 2010

These scenarios, such as GCAM 5.3 NGFS2_Current Policies and IMAGE EN_INDCi2030_3000f, assume little to no new policy interventions beyond what is already implemented. Technological change continues along historical trends, and fossil fuels remain dominant due to cost advantages, lock-in infrastructure, and weak incentives for alternative fuels.

These outcomes are primarily shaped by:

- No new climate policies beyond early 2020s standards,
- Persistent reliance on fossil fuels, with only minor efficiency gains,
- Absence of structural or behavioral transformation, including unchanged patterns of personal vehicle ownership and aviation growth,
- Minimal incentives for fuel switching, especially in sectors like freight and aviation.

Figure 3. Final energy demands of 9 illustrative mitigation pathways in transport sector



Consequently, energy demand continues to rise to 2100, driven by economic and population growth, along with the continued energy intensity of transport activity.

The MessageIX LowEnergyDemand_1.3_IPCC, developed for the IPCC AR6, represents a scenario with strong lifestyle and behavioral changes, aggressive energy efficiency improvements, and low material and energy demand across sectors. It features compact urban design, modal shifts in transport, digitalization to reduce travel needs, and stringent building and appliance standards, all contributing to a steep decline in final energy demand after 2020. Similarly, REMIND-MAgPIE's DeepElec_SSP2_HighRE_Budg900 assumes a high level of electrification and renewable energy penetration in end-use sectors under a well-regulated SSP2 socioeconomic pathway with tight carbon budgets. The SusDev_SDP-PkBudg1000 scenario combines moderate carbon constraints with sustainable development narratives from the Shared Development Pathways (SDPs), integrating equity-focused policies, behavioral change, dietary shifts, and structural reductions in demand intensity. AIM/CGE's EN_NPi2020_900f scenario, which is based on nationally determined contributions (NDCs) strengthened to limit warming to below 2°C, shows moderate demand decline due to greater emphasis on electrification and efficiency. Meanwhile, COFFEE's EN_NPi2020_400f_lowBECCS achieves even sharper reductions, explicitly minimizing reliance on bioenergy with carbon capture and storage (BECCS), instead advancing energy demand reductions through technology, behavior, and low-energy service provision.

In contrast, scenarios such as GCAM 5.3 – NGFS2_Current Policies and IMAGE 3.0 – EN_INDCi2030_3000f reflect continuation of current or modestly enhanced policies. These rely on existing technology trajectories, limited electrification uptake, and weaker efficiency standards. As a result, they project sustained or increasing final energy demand throughout the century, lacking deeper mitigation levers such as structural lifestyle shifts, accelerated demand-side efficiency, or transformative sectoral changes.All in all, the lower-demand scenarios (e.g., LowEnergyDemand_1.3_IPCC, DeepElec_SSP2_HighRE_Budg900, SusDev_SDP-PkBudg1000) incorporate explicit assumptions about strong policy coordination, rapid technology deployment, structural shifts in consumption, and behavioral change. In contrast, the higher-demand scenarios (e.g., GCAM NGFS2_Current Policies, IMAGE EN_INDCi2030_3000f) reflect limited mitigation ambition, weaker policies, continued fossil fuel dominance, and no significant shifts in end-use behavior, leading to persistently high energy demand.

4.4 Energy Consumption and Demand by Fuel Type

4.4.1 Overview of scenarios

To take these comparisons one step deeper and compare actual types of energy used, and the potential for energy substitution (along with technology change affecting energy use), we turn to the comparison of models and scenarios undertaken by the International Transport Energy Modeling (iTEM) group, from their 2023 comparison effort. The projections for fuel-type-specific energy demand stem from scenarios developed by models such as GCAM, IMAGE, ITF, MoMo, Prometheus, and Shell within the iTEM comparison framework (*International Transport Energy Modeling 3rd&4th ITEM Intercomparisons*, 2019) as shown in Figure 4. Each scenario reflects distinct assumptions regarding policy ambition, technological innovation, socio-economic development, and behavioral change:

GCAM Scenarios:

- GCAM Baseline assumes continuation of current policies and technological trends, resulting in prolonged dominance of petroleum-based fuels.
- GCAM_2p6 represents a stringent climate mitigation pathway aligned with a 2.6 W/m² forcing target, characterized by deep electrification, hydrogen adoption in freight, and gradual integration of biofuels and synthetic fuels.

IMAGE Scenarios:

- SSP1 reflects a sustainability-focused narrative emphasizing strong policy coordination, rapid electrification, and modal shifts, leading to significant reductions in total energy demand.
- SSP2 embodies a more conventional development pathway with moderate efficiency gains and slower fuel transitions.

ITF Scenarios:

- Current Ambition aligns with existing policy pledges, projecting moderate uptake of low-carbon fuels.
- High Ambition envisions aggressive decarbonization through behavioral shifts (e.g., modal shifts) and technology deployment, substantially reducing fossil fuel dependency.

MoMo Scenarios:

- New Policies Scenario (NPS) models incremental policy tightening, maintaining significant reliance on liquid fuels.
- EV30@30 assumes accelerated electric vehicle deployment, significantly boosting electricity demand in road transport.

Prometheus Scenarios:

- Include Baseline_COVID and 2DEG_COVID pathways, with the latter integrating recovery-driven clean energy investment and accelerated electrification.

Shell Sky Scenario:

- A long-term pathway toward net-zero emissions by 2070, incorporating deep electrification, extensive hydrogen deployment, and large-scale carbon removal measures, supported by technological innovation and societal transformation.

4.4.2 The three types of energy projections

Baseline or Low Ambition Scenarios

Examples: GCAM Baseline, MoMo NPS, ITF Current Ambition, Prometheus Baseline_COVID.

Characteristics and Reasons:

These pathways represent a continuation of current policies with minimal additional climate measures. Projections show petroleum-based fuels dominating through mid-century because:

- Weak policy signals: No significant carbon pricing or zero-emission mandates are assumed, resulting in continued investment in internal combustion engine (ICE) vehicles.
- Infrastructure inertia: Lack of large-scale charging or hydrogen refueling infrastructure limits alternative fuel deployment.
- Slow technological cost declines: Electric and hydrogen technologies remain relatively expensive, reinforcing fossil fuel competitiveness.
- Behavioral continuity: No major modal shifts or reductions in travel demand are included, sustaining oil demand in road and aviation sectors.

As a result, liquid fuels maintain a near-monopoly, electricity remains a small share confined to niche markets, and hydrogen/biofuels barely emerge before 2050.

Moderate Ambition Scenarios

Examples: ITF High Ambition, IMAGE SSP2, MoMo EV30@30, Prometheus 2DEG_COVID.Characteristics and Reasons:

Moderate ambition scenarios project notable—but partial—fuel substitution away from petroleum, largely in light-duty vehicles, because:

- Policy enhancements: Introduction of stricter efficiency standards and partial ZEV mandates accelerates EV adoption, particularly for passenger vehicles.

- Cost improvements in EV technology: Battery price declines make electrification more competitive, though high upfront costs and charging infrastructure gaps slow complete market penetration.
- Limited structural changes: Freight, aviation, and shipping remain reliant on liquid fuels due to the absence of aggressive hydrogen or synthetic fuel deployment.
- Behavioral measures: Some scenarios include moderate modal shifts (e.g., from cars to public transit), slightly reducing overall petroleum use.

Consequently, electricity demand grows rapidly post-2030 in passenger transport, but liquid fuels still account for the majority share by 2050, particularly in freight and aviation.

High Ambition or Deep Decarbonization Scenarios

Examples: GCAM_2p6, IMAGE SSP1, Shell Sky.

Characteristics and Reasons:

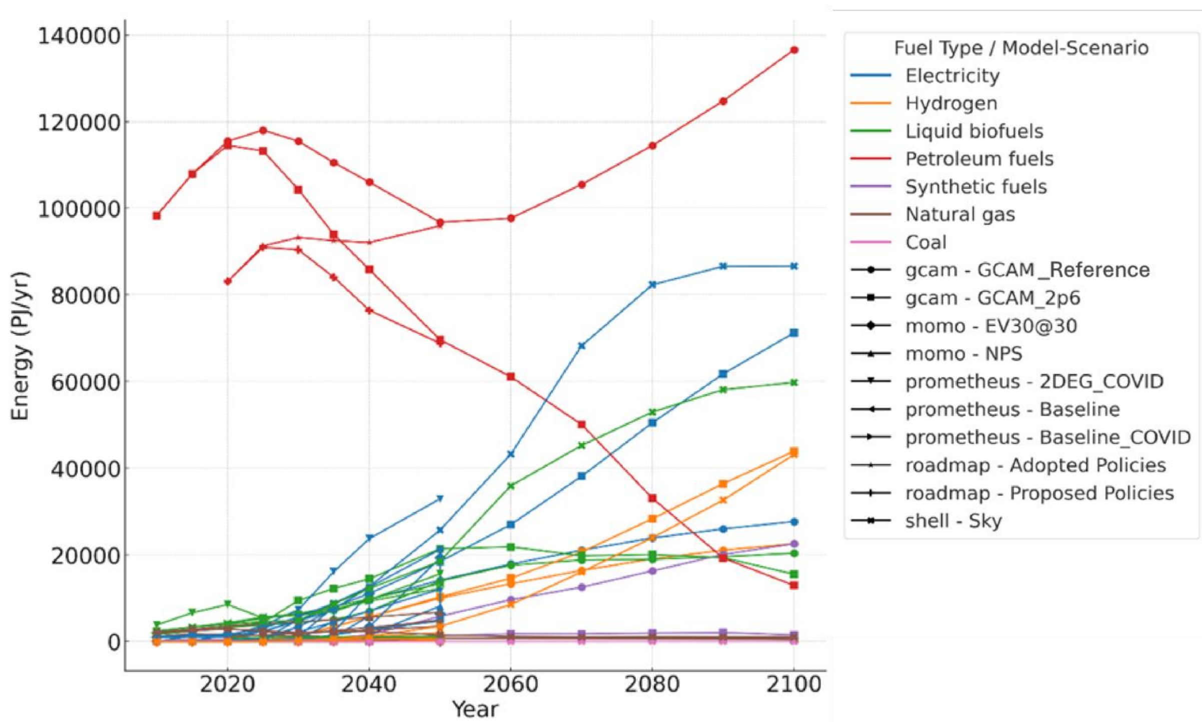
These scenarios forecast a fundamental restructuring of transport energy systems, with electricity, hydrogen, and advanced biofuels replacing most petroleum-based fuels. The drivers include:

- Strong policy packages: Aggressive carbon pricing, zero-emission vehicle mandates, and stringent fuel economy standards make fossil fuels economically uncompetitive.
- Rapid technological learning: Breakthroughs in battery energy density and hydrogen production lower costs and enable scale-up across light- and heavy-duty transport.
- Coordinated infrastructure deployment: Large-scale public and private investments accelerate the buildout of EV charging networks and hydrogen refueling stations.
- Behavioral and systemic changes: High assumptions for lifestyle changes (e.g., shared mobility, urban densification) and modal shifts reduce energy demand while supporting electrification.
- Targeted sectoral strategies: Aviation and shipping adopt advanced biofuels and synthetic fuels where electrification is impractical, while heavy trucks shift to hydrogen.

By 2050, electricity becomes dominant in road and rail, hydrogen penetrates heavy freight, and petroleum demand falls sharply. These scenarios exhibit the steepest divergence from historical trends, reflecting alignment with net-zero targets.

Across all models and scenarios, several common patterns and divergences emerge. Electricity consistently appears as the cornerstone of transport decarbonization in medium- and high-ambition pathways, driven by declining battery costs, strong zero-emission vehicle mandates, and infrastructure expansion. In these cases, electricity adaptation accelerates after 2030, becoming the dominant energy carrier in road and rail segments by mid-century. Hydrogen emerges as the preferred solution for hard-to-electrify sectors such as heavy freight and long-haul aviation under deep decarbonization scenarios, where robust policy support and cost breakthroughs enable its deployment at scale. Biofuels and synthetic fuels play a complementary role, primarily in aviation and maritime transport, although their overall contribution remains smaller than electricity and hydrogen due to production cost constraints and sustainability concerns. In contrast, baseline and low-ambition scenarios maintain heavy reliance on petroleum-based liquids, reflecting the reinforcing effects of weak climate policy, slow technology cost reductions, and limited behavioral or structural changes. These scenarios highlight the persistence of fossil fuel lock-in where policy and investment signals are insufficient. Natural gas, although occasionally positioned as a transitional fuel, retains only a marginal role across most projections, declining sharply under stringent carbon targets. The comparative analysis underscores that the pace and extent of fuel switching depend critically on policy ambition, infrastructure readiness, and technology learning curves. High-ambition pathways combine strong regulatory frameworks, carbon pricing, and behavioral shifts with rapid technological innovation, producing transformative changes in the fuel mix, while lower-ambition trajectories fail to deviate substantially from historical trends, locking transport systems into high-carbon futures.

Figure 4. Total energy consumption and demand projection by fuel type in transportation sector from 2010 to 2025 and 2100 under different models and scenarios from iTEM. Fuel types are distinguished by color, while models and scenarios are indicated by different markers.



4.5 Energy Demand of Rail, Road, Ship and Air Sectors

In this section, the study examines energy demand projections by fuel type and transport mode, as reported by various models and international agencies. The comparative assessment of energy consumption trajectories across the Rail, Road, Ship, and Air sectors under various integrated assessment models (IAMs) and scenarios from iTEM reveal divergent trends in fuel use intensity and decarbonization progress as shown in Figure 5, 6, and 7. The analysis spans from 2010 to 2050 and 2100 and includes GCAM, MoMo, Shell, and Roadmap models, with scenarios that represent a spectrum of policy ambition and technological adoption. These scenarios analyzed for modal energy demand (rail, road, ship, and aviation) are the same as those discussed in Section 3.4 and are grouped here by carbon reduction ambition.

Baseline / Low Ambition Scenarios

Examples: GCAM Baseline, MoMo NPS.
Energy demand patterns in these scenarios remain heavily fossil-dependent across all modes. Road transport exhibits the highest energy consumption, dominated by refined liquids due to the persistence of internal combustion vehicles and minimal policy incentives. Rail energy demand grows modestly with only incremental electrification, while aviation and maritime sectors remain locked into petroleum fuels. These outcomes reflect weak policy pressure, limited infrastructure for electrification or hydrogen, and cost disadvantages for alternative fuels, all of which constrain fuel switching.

Moderate Ambition Scenarios

Examples: MoMo EV30@30, Roadmap Adopted Policies.
Moderate ambition scenarios show accelerated electrification of passenger vehicles and rail, driven by efficiency mandates and falling battery costs, while liquid fuels continue to dominate freight and long-haul modes. Hydrogen and advanced biofuels penetrate slowly, primarily post-2040, constrained by infrastructure and cost barriers. While total energy demand declines compared to low-ambition pathways, high travel activity and insufficient modal shifts prevent deeper reductions.

High Ambition / Deep Decarbonization Scenarios

Examples: GCAM_2p6, Shell Sky, Roadmap Proposed Policies.
These scenarios project transformative fuel shifts across all modes, with road and rail nearly fully electrified by mid-century. Maritime shipping and aviation adopt hydrogen, synthetic fuels, and biofuels at scale, reducing fossil fuel reliance substantially. Key drivers include strong policy packages (carbon pricing, ZEV mandates), accelerated technology cost declines, and robust infrastructure development for hydrogen and charging networks. Behavioral changes such as shared mobility and reduced travel demand further amplify energy savings.

Rail sector projections consistently show a modest but steady increase in total energy demand as shown in Figure 5. A notable trend across all models is the growing share of electricity in rail energy use, especially in GCAM_2p6 and Roadmap scenarios, indicating alignment with decarbonization objectives through electrification. Petroleum fuel use remains persistent in several baseline pathways (e.g., momo_NPS) but begins to decline after mid-century. Synthetic fuels and hydrogen contribute marginally to most cases, signaling their limited role unless strong policy support materializes.

The road transport sector exhibits the highest energy demand among the four, with stark differences across scenarios as shown in Figure 6. GCAM_2p6 and roadmap_Proposed Policies project sharp reductions in petroleum fuels post-2040, with substantial increases in electricity and hydrogen, illustrating deep electrification and fuel switching. Conversely, momo_NPS and GCAM baseline scenarios sustain high levels of petroleum dependency, reflecting more incremental policy pathways. Liquid biofuels see moderate uptake across models but do not displace petroleum fuels at scale. The diversity in trajectories emphasizes the sector's sensitivity to policy stringency and technology penetration rates.

The shipping sector remains heavily reliant on petroleum fuels in most scenarios throughout the century. However, the Shell_Sky and GCAM_2p6 pathways suggest increasing contributions from hydrogen and synthetic fuels post-2050, reflecting innovation-driven or net-zero aligned strategies. Electricity and natural gas are projected to play negligible roles. The inertia in fuel transition for shipping highlights the sector's technological and infrastructural challenges, as well as its lag in decarbonization compared to land-based transport.

In aviation, petroleum fuels continue to dominate across all models, underscoring the sector's reliance on high-density liquid energy carriers as shown in Figure 7. Nonetheless, scenarios such as GCAM_2p6 and Shell_Sky display a notable rise in liquid biofuels and, to a lesser extent, hydrogen after 2040. The gradual diversification suggests the integration of sustainable aviation fuels (SAFs) and emerging propulsion systems under more ambitious climate targets. Electricity use remains minimal, reflecting the limitations of current battery technology for long-haul flights.

Figure 5. Energy consumption and demand projection by fuel type for Rail and Road sectors from 2010 to 2050 and 2100 for different models and scenarios from iTEM. Fuel types are distinguished by color, while models and scenarios are indicated by different markers.

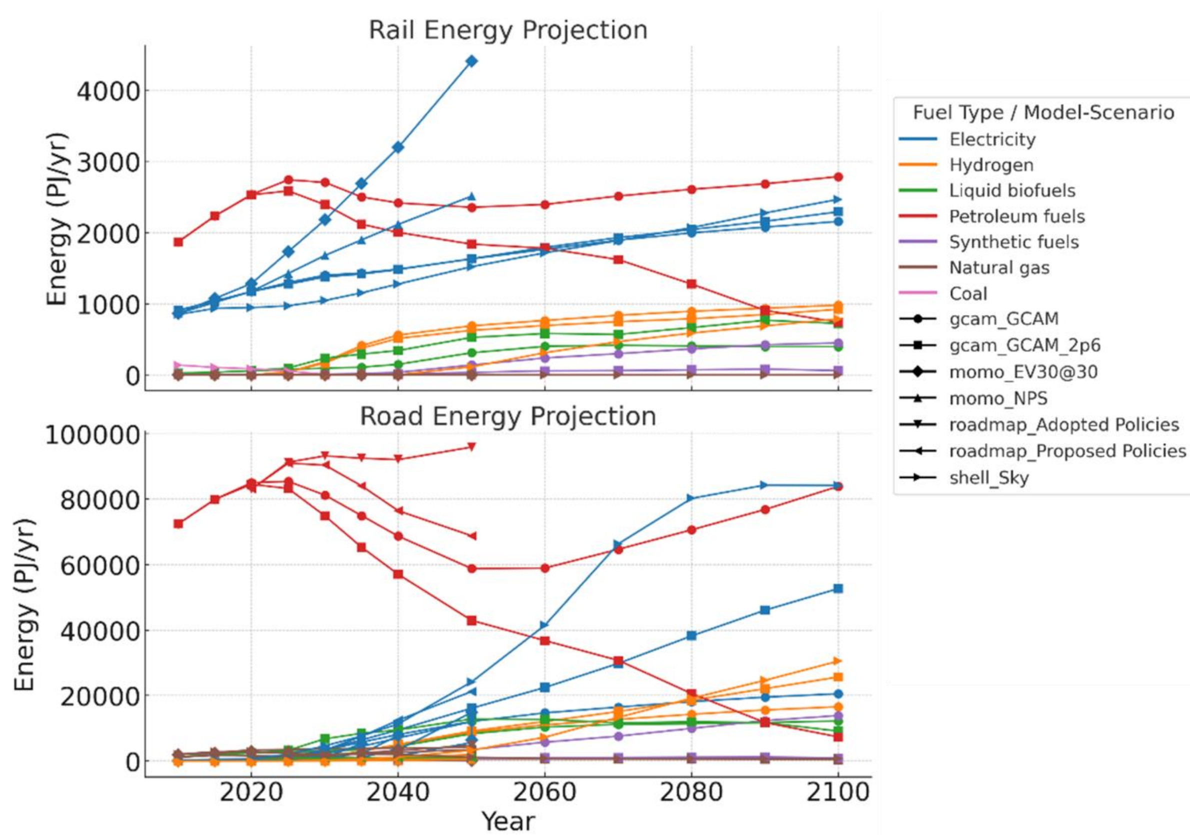


Figure 6. Energy consumption and demand projection by fuel type for Ship sector from 2010 to 2050 and 2100 for different models and scenarios from iTEM. Fuel types are distinguished by color, while models and scenarios are indicated by different markers.

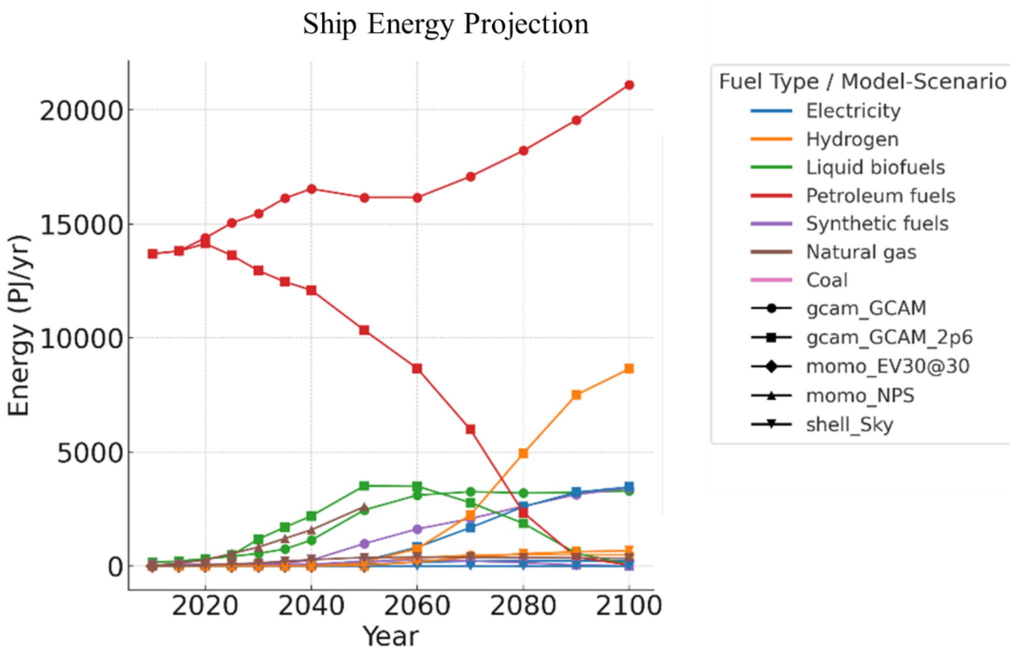
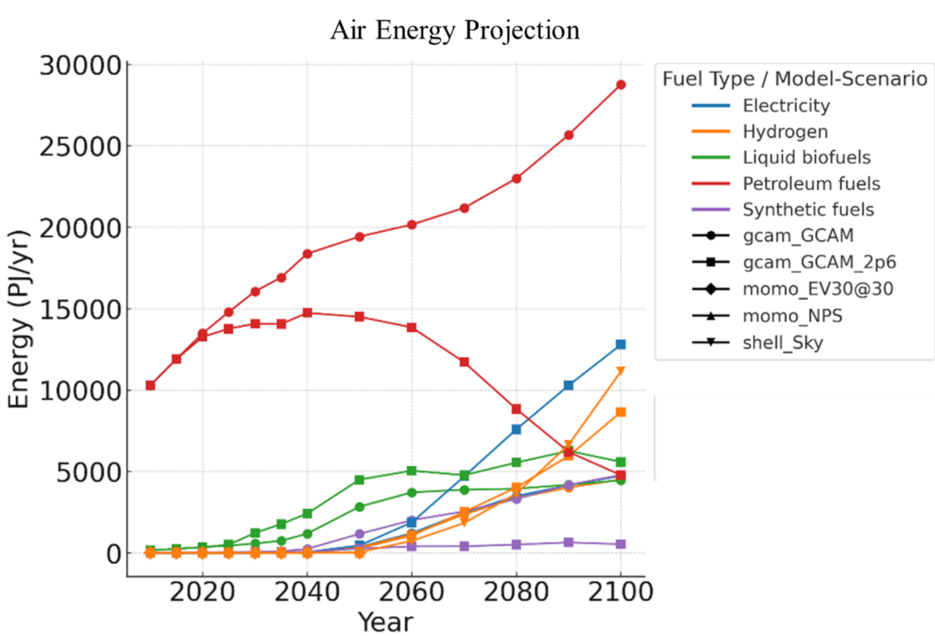


Figure 7. Energy consumption and demand projection by fuel type for Air sector from 2010 to 2050 and 2100 for different models and scenarios from iTEM. Fuel types are distinguished by color, while models and scenarios are indicated by different markers.



4.6 Freight Energy Demand by Transport Modes

Figure 8 illustrates the projected freight energy demand across various transport modes, categorized by fuel type, based on the Global Change Assessment Model (GCAM) under deep decarbonization RCP 2.6 scenario. The data presented shows a long-term projection up to 2100 for different types of vehicles and transport modes, including 2W and 3W, bus, car, rail, HSR (high-speed rail), and truck. The GCAM RCP 2.6 scenario is a deep decarbonization pathway where global emissions peak early and fall to net-zero or below by 2100, driven by rapid energy transitions, widespread electrification, efficiency gains, bioenergy with carbon capture, and reforestation to limit warming well below 2 °C.

A consistent feature across all modes of transport is the dominance of oil refining in the early decades, followed by gradual but significant transitions toward alternative energy carriers. Cars, trucks, and buses remain the largest consumers of refined liquids through mid-century, yet all three show a clear long-term decline as electricity and hydrogen-based fuels expand their shares. Two- and three-wheelers also shift quickly from refined liquids to electricity, reflecting the feasibility of electrification in light-duty transport segments.A consistent feature across all modes of transport is the dominance of oil refining in the early decades, followed by gradual but significant transitions toward alternative energy carriers. Cars, trucks, and buses remain the largest consumers of refined liquids through mid-century, yet all three show a clear long-term decline as electricity and hydrogen-based fuels expand their shares. Two- and three-wheelers also shift quickly from refined liquids to electricity, reflecting the feasibility of electrification in light-duty transport segments.

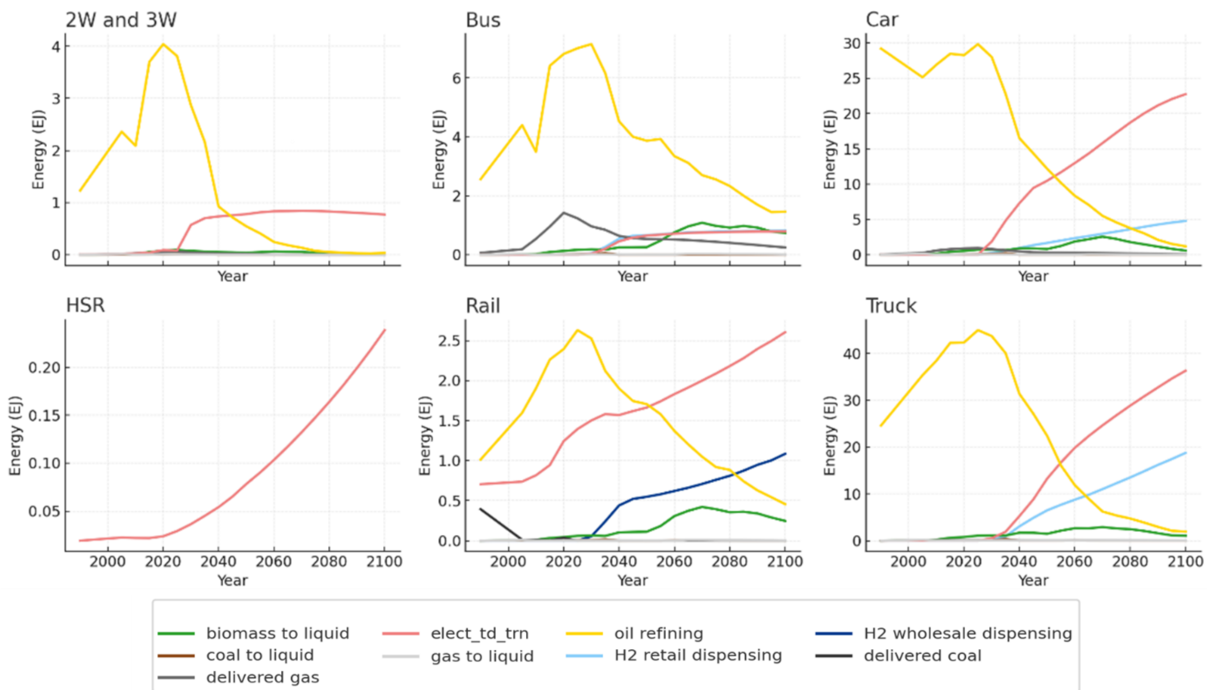
High-speed rail stands apart, demonstrating a strong and exclusive reliance on electricity from the outset. This aligns with the mode's infrastructure-driven electrification and positions it as a leading example of early decarbonization in transport. Conventional rail, meanwhile, follows a more mixed trajectory: refined liquids remain prominent for decades but are steadily replaced by both electricity and hydrogen, highlighting its hybrid energy future.

In freight-oriented modes, trucks illustrate a more complex transition. Refined liquids dominate through mid-century, but electricity and hydrogen both grow sharply after 2040, eventually overtaking oil products in importance. Delivered gas emerges as a supporting option, though its long-term contribution is modest. Biomass-based liquids gain traction across both rail and trucks, gradually displacing a fraction of refined liquid demand, whereas coal- and gas-to-liquids remain marginal and fade over time.

In the context of the GCAM RCP 2.6 deep decarbonization pathway, the projected energy transitions across transport modes reflect both the opportunities and challenges of aligning freight and passenger systems with a net-zero trajectory. Liquid fuels remain widespread in the near term, especially in high-demand segments such as cars, buses, and trucks, but their dominance erodes steadily as the scenario's stringent climate constraints drive large-scale electrification and the adoption of hydrogen. Electricity takes on a central role in modes with strong infrastructure compatibility, such as high-speed rail and two- and three-wheelers, while hydrogen emerges as a critical long-term option for rail and heavy freight, where direct electrification is more difficult.

The persistence of biomass-derived liquids in freight modes highlights the scenario's emphasis on integrating low-carbon substitutes into established liquid fuel systems, balancing technological feasibility with the rapid emissions reductions required under RCP 2.6. Similarly, the limited and declining role of coal- and gas-to-liquids demonstrates how carbon-intensive pathways are phased out to stay within the scenario's carbon budget. Overall, the evolution of transport energy demand under this scenario illustrates that while liquid fuels remain embedded in the system for decades, the transition to electricity, hydrogen, and bio-based alternatives is both essential and inevitable, ensuring that transport contributes meaningfully to the broader decarbonization agenda necessary for limiting warming well below 2 °C.

Figure 8. Transportation energy demand by fuel type and mode projection to 2100 under deep decarbonization (RCP2.6) scenario by GCAM



5 Model Applications for Policy Analysis and Decision-Making

Global energy and fuels models are essential tools for policymakers, providing valuable insights into the potential pathways for achieving climate goals, such as the transition to low-carbon fuels and the decarbonization of various sectors, including transportation. These models offer an integrated framework for understanding how different energy policies can affect future energy demand, fuel adoption, and emissions outcomes under various scenarios. By simulating complex systems and long-term dynamics, these models support strategic decision-making by offering a clearer picture of the potential impacts of various policy measures, technological developments, and market conditions. The following applications highlight the specific roles these models play in policy analysis and decision-making as shown in Table 3.

Assessment of climate policy scenarios

GCAM, MESSAGEix, REMIND-MAgPIE, WITCH 5.0, MoMo, Prometheus, and corporate outlooks such as Shell, BP, and ExxonMobil support comprehensive analysis of climate policy measures and market dynamics. These tools enable policymakers and industry leaders to evaluate the impacts of interventions, including:

- Carbon pricing mechanisms such as carbon taxes and cap-and-trade systems
- Subsidies for low-carbon technologies
- Regulatory standards for emissions and efficiency

Many of these models and outlooks simulate how carbon pricing policies influence:

- Fuel demand patterns
- Greenhouse gas emissions reductions
- Adoption of clean technologies across transport and energy sectors

By comparing policy-driven scenarios, these models and outlooks help identify cost-effective and practical pathways to achieve long-term climate goals, including global net-zero emissions by 2050.

Socio-economic impacts of energy transitions

IMAGE, GCAM, MoMo, and corporate outlooks like Shell, BP, and ExxonMobil assess trade-offs between decarbonization, food security, land-use change, and economic resilience. These insights help ensure that policies focus not only on emissions reduction but also on maintaining energy affordability and promoting equitable development. They evaluate the economic consequences of decarbonization, such as:

- Costs of transforming the energy system
- Fuel price dynamics
- Employment and sectoral shifts

National and regional energy strategy development.

REMIND-MAgPIE, GCAM, MESSAGEix, MoMo, and corporate scenarios from Shell, BP, and ExxonMobil help policymakers assess trade-offs between:

- Technology adoption and infrastructure readiness
- Economic growth objectives
- Sustainability and climate commitments

These models and outlooks simulate interactions among:

- Policy measures
- Technological advancements
- Market dynamics

By capturing these interdependencies, they provide critical guidance for designing strategies that align climate goals with economic development priorities, particularly in emerging economies where growth and decarbonization must progress in parallel.

Infrastructure and investment planning

Models like ITEDD, GET, GTAP, MoMo, and outlooks from Shell, BP, and ExxonMobil provide critical insights into the timing and scale of these investments, helping avoid infrastructure bottlenecks and underinvestment risks. Transitioning to low-carbon energy systems, such as hydrogen and advanced biofuels requires significant investment in:

- Refueling and charging networks
- CCS and storage facilities
- Renewable integration

Long-term planning and scenario analysis

Models such as GTAP, WITCH 5.0, GCAM, MoMo, and corporate scenarios from Shell, BP, and ExxonMobil support strategic decision-making at national and international levels, including analysis of trade policies, energy subsidies, and global market dynamics. They assess the potential impacts of:

- Economic crisis
- Technological breakthroughs
- Geopolitical disruptions

Additionally, models like WITCH, with its focus on innovation, help policymakers evaluate how R&D and cost learning influence the speed and scale of low-carbon technology deployment, shaping long-term decarbonization strategies.

Trade Policy and Global Energy Interactions

GTAP, MESSAGEix, REMIND-MAgPIE, and corporate outlooks like Shell and BP analyze the implications of trade policies and geopolitical dynamics on energy systems. These models help assess how international cooperation, tariff adjustments, and carbon border measures influence energy security and technology diffusion. They provide insights into how global market shifts affect competitiveness and policy design. Specifically, they examine:

- Impacts of carbon border adjustments on trade flows
- Effects of tariffs and subsidies on energy technology deployment

- Risks of trade fragmentation versus benefits of global cooperation

Technology and Innovation Pathways

WITCH 5.0, GCAM, MESSAGEix, and outlooks from Shell, BP, and ExxonMobil evaluate the role of technological progress in achieving deep decarbonization. These models assess how investments in research and development (R&D) and learning-by-doing influence technology costs and adoption rates. Insights from these analyses guide policy strategies to accelerate innovation and scale-up. They examine:

- Cost reductions from R&D and technology learning
- Deployment of emerging technologies such as hydrogen, CCS, and advanced biofuels
- Impact of innovation on achieving long-term carbon neutrality

Table 3 Applications of Global Energy and Fuels Models in Policy Analysis and Decision-Making

Application Area	Description	Model Examples
Climate Policy Assessment	Evaluates the impacts of climate policies such as carbon pricing (carbon tax, cap-and-trade), subsidies, and emissions regulations.	GCAM, MESSAGEix, REMIND-MAgPIE, WITCH 5.0, MoMo, Prometheus, Shell, BP, ExxonMobil
Socio-economic Impact Assessment	Assesses the economic consequences of energy transitions, including fuel price changes, employment shifts, and socio-economic trade-offs.	IMAGE, GCAM, MESSAGEix, MoMo, Prometheus, Shell, BP, ExxonMobil
National and Regional Strategy Design	Supports the design of national and regional energy strategies by simulating interactions between policy, technology, and market dynamics to meet development and climate goals.	REMIND-MAgPIE, GCAM, MESSAGEix, MoMo, Shell, BP, ExxonMobil
Infrastructure and Investment Planning	Provides insights into the timing and scale of infrastructure investments needed for fuel adoption (e.g., refueling stations, storage facilities).	ITEDD, GET, GTAP, MoMo, Shell, BP, ExxonMobil
Long-term Planning and Scenario Analysis	Simulates the long-term impacts of global events such as economic crises, technological breakthroughs, and geopolitical shifts on energy systems.	GTAP, WITCH 5.0, GCAM, REMIND-MAgPIE, MoMo, Prometheus, Shell, BP, ExxonMobil
Trade Policy and Global Energy Interactions	Assesses the effects of global trade policies, tariffs, and energy subsidies on energy systems and their interactions with broader economic activities.	GTAP, MESSAGEix, REMIND-MAgPIE, MoMo, Prometheus, Shell
Technology and Innovation Pathways	Evaluates the role of technological development and innovation in driving decarbonization, including research and development impacts on fuel adoption.	WITCH 5.0, GCAM, MESSAGEix, MoMo, Prometheus, Shell, BP, ExxonMobil

6 Future Challenges and Emerging Trends in Energy and Fuels Modeling

As global energy systems transition toward decarbonization, the role of energy and fuels models in shaping policy decisions has become more critical than ever. However, despite their significant contributions, these models face several challenges that must be addressed to enhance their accuracy, reliability, and policy relevance. This section explores the future challenges and emerging trends in energy and fuels modeling, particularly in the context of advancing climate policy, technological innovation, and the increasing complexity of energy systems.

One of the primary challenges in energy and fuels modeling is the growing uncertainty associated with the pace and scale of technological advancements. The development and deployment of low-carbon technologies, such as hydrogen, carbon capture and storage (CCS), and next-generation biofuels, are highly uncertain and context-dependent. Energy models must account for the rapid evolution of these technologies, including shifts in their cost-effectiveness, efficiency, and scalability. This requires continuous updating of assumptions related to technological progress and market adoption. Models that do not adapt quickly to such advancements may fail to provide realistic projections, undermining their utility for long-term policy planning.

Another significant challenge is the increasing complexity of global energy systems, which require models to simulate a broader range of factors. The integration of renewable energy sources, such as wind and solar power, into the grid introduces new uncertainties, particularly around variability and intermittency. Energy systems are also becoming more interconnected, with cross-border energy trade, supply chain dependencies, and geopolitical factors playing an increasingly important role in determining fuel availability and pricing. Models need to incorporate more granular data on regional energy systems, as well as the interactions between different sectors, such as transportation, industry, and residential energy consumption. The integration of these complexities into a single modeling framework presents both technical and conceptual challenges, requiring new approaches to system integration, data analysis, and scenario generation.

In addition, the role of social and behavioral change is becoming increasingly important in shaping energy demand and transport activity. Urban form, teleworking practices, lifestyle choices, and shared mobility all have the potential to alter travel patterns and fuel use just as much as new technologies. Yet, many global models continue to emphasize supply-side transitions while underrepresenting demand-side transformations. Bridging this gap will require closer integration of transport demand models, such as microsimulation, agent-based, and land-use transport frameworks with energy system and integrated assessment models. Doing so would enable a fuller representation of behavioral and infrastructural factors, ensuring that scenarios capture both demand- and supply-side levers of decarbonization.

In terms of emerging trends, one of the most significant is the increasing use of artificial intelligence (AI) and machine learning (ML) in energy modeling. These technologies have the potential to enhance the accuracy and efficiency of energy models by automating the process of scenario generation, improving data analysis, and identifying hidden patterns in large datasets. AI and ML can also help improve model calibration and validation by providing more robust approaches to testing model assumptions and identifying discrepancies between model projections and real-world data. However, integrating AI and ML into energy models requires careful consideration of model transparency, interpretability, and validation, as these advanced techniques often operate as "black boxes" that may limit their usefulness in policymaking if their outputs cannot be clearly understood or explained.

Another emerging trend is the move towards open-source modeling and collaborative modeling frameworks. As the demand for more flexible and accessible tools grows, there is increasing interest in developing open-source models that allow for greater transparency and participation from diverse stakeholders. Open-source modeling platforms enable collaboration across different sectors, regions, and academic disciplines, facilitating a more holistic and inclusive approach to energy modeling. These platforms can also support model intercomparison studies, enabling the assessment of different modeling approaches and helping to identify best practices. However, the success of open-source modeling depends on the development of standardized methodologies, data-sharing protocols, and quality control mechanisms to ensure that these models are reliable and accurate.

Furthermore, as the global energy landscape becomes more dynamic, energy models will need to incorporate a broader set of external drivers. Climate change impacts, including extreme weather events and natural disasters, are becoming more frequent and severe, which can disrupt energy production and distribution. Energy models will need to account for the resilience of energy systems in the face of these disruptions and incorporate adaptive strategies for mitigating the impacts of climate change. Similarly, the role of finance and investment in energy transitions is growing, as private capital plays an increasingly important role in funding low-carbon infrastructure projects. Models will need to integrate financial considerations, including investment risks, returns, and capital flows, into their projections to provide a more comprehensive view of the energy transition.

In conclusion, the future of energy and fuels modeling is marked by both significant challenges and exciting opportunities. Addressing the uncertainties related to technological advancements, system complexity, and the interactions between supply- and demand-side transformations will require models to evolve and become more flexible, dynamic, and integrated. At the same time, emerging trends, such as the use of AI and machine learning, open-source platforms, and the integration of external drivers like climate impacts and financial considerations, offer promising avenues for improving the accuracy, relevance, and accessibility of energy models. To remain effective tools for policymakers, energy models must continue to evolve and adapt to the rapidly changing energy landscape, ensuring that they can support informed decision-making in the face of growing global challenges.

7 Conclusions

This study has provided a comprehensive analysis of global energy and fuels modeling approaches, with a particular focus on their role in assessing low-carbon fuel transitions in the transportation sector. Through a comparative evaluation of various integrated assessment models (IAMs) and other energy system frameworks, we have highlighted the diverse methodologies, assumptions, and policy scenarios that underpin different modeling approaches. The comparative analysis has revealed significant variations in projected energy demands, fuel transitions, and emissions outcomes, underscoring the complexity of accurately predicting the future of global energy systems.

The models demonstrate considerable variability in projected energy demand, particularly in the transportation sector, as different scenarios assume varying levels of policy ambition, technology availability, and regional constraints. For instance, under more ambitious climate scenarios such as those modeled by WITCH 5.0 – CO_Bridge and MESSAGEix-GLOBIOM – LowEnergyDemand_1.3_IPCC, there is a clear shift towards electrification and hydrogen, with substantial declines in energy demand post-2020. This is in stark contrast to the more moderate pathways, such as GCAM 5.3 – NGFS2_Current Policies and IMAGE 3.0 – EN_INDCi2030_3000f, which project a steady increase in energy demand due to the limited adoption of low-carbon technologies and the continued reliance on fossil fuels. These projections underscore the critical role that policy measures and technological development play in shaping future energy transitions. A key takeaway from the comparative analysis is the significant role of hydrogen and electrification in decarbonizing heavy transport sectors like freight and aviation. Hydrogen is expected to emerge as a crucial fuel for sectors where electrification faces limitations, such as long-haul freight and aviation. Models like REMIND-MAgPIE and Shell's projections show a clear rise in hydrogen demand in these sectors, reflecting its growing importance in the energy mix. Conversely, lighter modes of transportation, such as passenger rail and electric vehicles, are expected to see more immediate and widespread adoption of electricity, driving substantial declines in conventional fuel use. These projections indicate that while some sectors are likely to transition rapidly, others may face longer adoption timelines due to technological, economic, and infrastructure constraints. The study also highlights the importance of infrastructure development in supporting the transition to low-carbon fuels. Models such as ITEDD and GET underscore the need for significant investments in refueling stations, charging infrastructure, and storage facilities to accommodate the increasing demand for electricity and hydrogen. The timing and scale of these investments will be crucial in ensuring a smooth transition, avoiding potential bottlenecks in fuel availability, and supporting the widespread adoption of low-carbon technologies. As the energy landscape continues to change rapidly, models must also embrace new methodologies and technologies. Artificial intelligence and machine learning offer promising avenues for enhancing the accuracy and efficiency of modeling processes, while open-source platforms and collaborative modeling frameworks promote transparency and inclusiveness. These emerging trends will be critical in supporting the transition to a sustainable energy future, enabling more robust, flexible, and adaptable models that can inform policy decisions in an increasingly uncertain world.

In conclusion, global energy and fuels models are vital tools for guiding the transition to a low-carbon future. Their ability to simulate different policy interventions, technological developments, and socio-economic changes provides valuable insights for decision-makers across all levels. However, to remain relevant and effective in the face of rapidly changing global dynamics, these models must evolve, incorporating new technologies, broader socio-economic factors, and emerging global challenges. Only through continuous improvement and adaptation will energy models be able to effectively support the complex and ambitious task of decarbonizing the global energy system.

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