Pakistan Integrated Energy Model (PAK-IEM 2.0)

Implemented by

Disclaimer

The publication has been developed and produced with the support of the German Federal Ministry for Economic Cooperation and Development (BMZ) through the Digitisation and Decarbonisation of Power Distribution Networks in Pakistan (DEDI) project implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The views expressed in this publication do not necessarily represent those of GIZ Pakistan.

Contributors:

Aftab Ahmad Awan - EPRC
Hammad Ur Rehman - EPRC
Usman Ahmed - EPRC
Jawad Ali Qadir - EPRC
Alessandro Chiodi - E4SMA
Tommaso Pillon - E4SMA
Jens Brinkmann - GIZ Pakistan
Saif Ur Rehman Memon - GIZ Pakistan
Alessia De Vita - GIZ

Design:

Faiza Batool - GIZ Pakistan

Published:

February, 2026

TABLE OF CONTENTS

01. Executive Summary

Pakistan's energy sector is at a critical juncture. Rapid population growth, urbanization, rising demand for cooling, mobility, and industrial output, combined with high dependence on imported fossil fuels, place increasing pressure on energy affordability, security, and public finances. At the same time, Pakistan has committed to ambitious climate objectives under its Nationally Determined Contributions (NDCs), requiring a fundamental transformation of how energy is produced and consumed over the coming decades. Due to the long-life time of energy infrastructure, decisions taken today will shape the country's energy system, investment needs, and emissions profile well beyond 2050.

To support evidence-based long-term decision-making, the Energy Planning and Resource Centre (EPRC), with technical support from GIZ, has developed the Pakistan Integrated Energy Model (PAK-IEM 2.0). Built using the internationally recognised TIMES-VEDA framework, PAK-IEM 2.0 provides an integrated, system-wide representation of Pakistan's energy system, covering all major demand and supply sectors. The model enables transparent comparison of alternative development pathways and assessment of trade-offs across costs, investments, energy security, and greenhouse gas emissions.

This booklet presents insights from two core scenarios. The Least Cost Baseline (LCB) scenario reflects a continuation of currently committed policies until July 2025 and cost-optimal technology adoption, without long-term decarbonization constraints. The Net-Zero Energy (NZE) scenario explores a policy-driven pathway aligned with Pakistan's climate objectives, targeting net-zero GHG emissions from the energy sector by 2050.

Even under the LCB scenario, Pakistan's energy system evolves in a more efficient and cleaner direction compared to historical data. Energy demand experiences a gradual decoupling from economic growth, i.e. around 2.5 times by 2050 compared to 2024 baseline while final energy demand only grows by 30%. Renewable energy sources expand to become the dominant source of power generation, reducing emissions from power generation significantly/to 56%. However, fossil fuels – particularly imported oil and LNG – remain central to the energy mix -particularly in residential, industry and transport sectors. Overall energy-sector emissions stabilize rather than decline, leaving long-term climate objectives unmet.

In contrast, the NZE scenario illustrates the scale and nature of transformation required to achieve deep emission reductions across the entire energy sector including supply and demand. The pathway is characterized by accelerated electrification of end uses, rapid expansion of renewable power generation (similar to the LCB scenario), strong improvements in energy efficiency, and the deployment of emerging technologies such as green hydrogen, advanced biofuels, and carbon capture and storage for hard-to-abate sectors. Electricity generation becomes fully decarbonized after 2040 and reaches net-negative emissions by mid-century through the deployment of bioenergy with carbon capture and storage (BECCS) to compensate for remaining emissions in the power, transport and residential sectors.

Achieving net-zero requires higher upfront investment compared to the LCB scenario, reflecting accelerated capital deployment across power generation, grids, transport, and industry. These higher investments are partly offset over time by substantially lower fuel expenditures and reduced exposure to international fossil fuel markets. Importantly, the NZE pathway confirms several “no-regret” options that deliver benefits under both scenarios, including electrification, energy efficiency improvements, and the expansion of solar and wind power.

Overall, the results highlight that Pakistan can meet growing energy needs while improving efficiency and reducing emissions, but that achieving net-zero by 2050 requires timely, coordinated, and sustained policy action. PAK-IEM 2.0 provides a robust analytical foundation to support this process, helping policymakers assess trade-offs, sequence interventions, and guide Pakistan’s transition toward a secure, affordable, and sustainable energy future.

02. Background & Rationale

2.1. Background

Given the rapidly evolving dynamics of the energy sector, energy modelling tools must continuously be updated and adapted to remain relevant for policy and planning. EPRC, through a dedicated modelling working group involving key energy sector stakeholders, is strengthening the capacity of Government of Pakistan (GoP) institutions to effectively use a diverse suite of energy modelling and analytical tools.

EPRC has initiated a comprehensive process of long-term energy planning and policy development by progressively employing a combination of econometric and energy system models that integrate both top-down and bottom-up approaches. In the initial phase, a customized MS Excel-based model was developed to support medium-term demand analysis. As modelling capabilities matured, EPRC transitioned to an econometric framework using STATA, incorporating key socioeconomic drivers. With the technical support from the U.S. Department of Energy and the Stockholm Environment Institute, EPRC further enhanced its analytical framework by adopting the LEAP model. This top-down approach enabled the assessment of macro-level energy supply and demand trajectories, as well as associated emissions pathways.

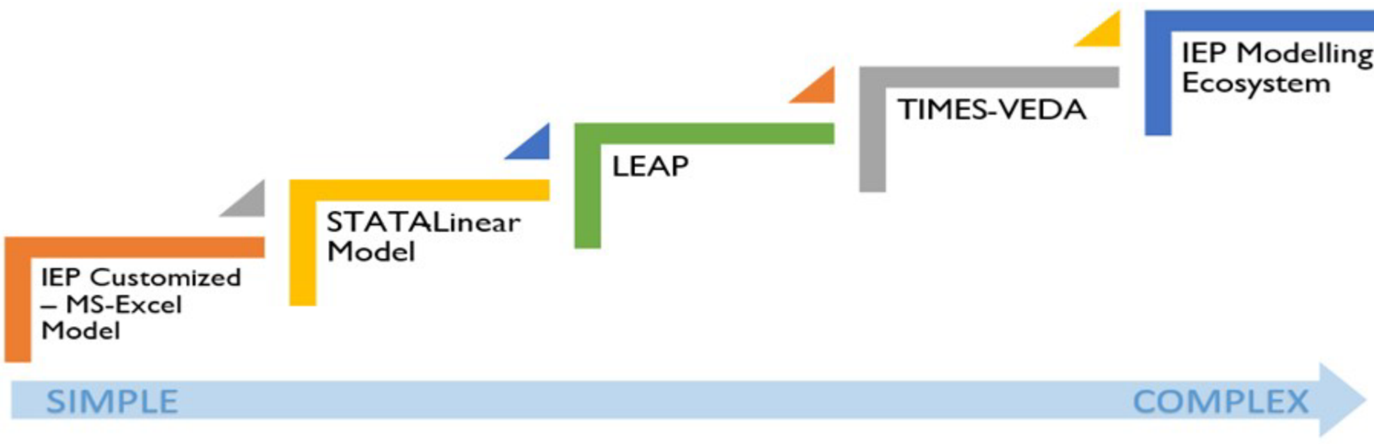

Figure 1: Development of Energy Modelling Ecosystem

Building on these earlier efforts, EPRC – funded by the German development cooperation programme, implemented by GIZ – has developed the Pakistan Integrated Energy Model (PAK-IEM 2.0). The model adopts a bottom-up, technology-rich approach, incorporating device-level representations of both commercial and non-commercial energy use. It is calibrated using base-year (FY 2023–24) national energy data and supplemented by targeted surveys and expert judgement where data gaps exist. Scenarios are being developed to address policy questions identified through the approved Terms of Reference.

Recognising that energy planning is inherently iterative and requires regular updates, EPRC aims to establish a robust and flexible national energy modelling ecosystem capable of responding to evolving energy dynamics, technological advancements, and the GoP's long-term vision for a sustainable, affordable, and secure energy sector.

2.2. Purpose and Scope of PAK-IEM 2.0

PAK-IEM 2.0 is designed as a strategic decision-support tool to inform long-term energy planning, policy formulation, and investment prioritization in Pakistan. The model provides a transparent and internally consistent analytical framework to assess how alternative policy choices, technology pathways, and external assumptions shape the evolution of the national energy system over the medium to long term.

The primary purpose of PAK-IEM 2.0 is to support the Government of Pakistan in evaluating energy transition pathways that balance affordability, supply security, and climate objectives. The model enables the comparison of baseline and policy-driven scenarios, quantifies system-wide trade-offs, and assesses implications across energy demand, supply, infrastructure investment, and greenhouse gas emissions.

The model is designed to address a wide range of policy-relevant questions, including:

- How energy demand and supply may evolve under different socioeconomic and policy assumptions
- The cost and investment implications of alternative energy transition pathways
- The role of renewable energy, electrification, efficiency, and emerging technologies in meeting long-term demand
- The impacts of climate and decarbonization targets on energy system structure and emissions
- Trade-offs between domestic resource use, imports, and resulting energy security indicators

PAK-IEM 2.0 adopts a long-term, system-wide perspective and is not intended as a short-term operational planning tool. It does not replace detailed power system dispatch, network planning, or project-level assessment models, but complements existing sectoral planning instruments and supports strategic policy dialogue. The model is designed to be flexible and iterative, allowing for regular updates as new data, technologies, and policy priorities emerge.

The following sections describe the key characteristics of the model and present selected results and insights generated through scenario analysis.

03. Overview of PAK-IEM 2.0

The Pakistan Integrated Energy Model (PAK-IEM 2.0) is a national integrated energy system model designed to support evidence-based and long-term energy planning in Pakistan. The model has been developed using the internationally recognized TIMES-VEDA framework[1] by the Energy Planning and Resource Centre, with support from German Development Cooperation through GIZ since October 2024, and with contributions from national stakeholders and sector experts.

PAK-IEM 2.0 provides a unique system-wide planning perspective by analyzing the evolution of Pakistan's energy system across the full value chain, from primary energy resources and imports to energy transformation, distribution, and final consumption.

It integrates supply-side activities, including fuel production, trade and power generation, with demand across residential, commercial, agriculture, transport, and industrial sectors.

Modelling energy as an interconnected system rather than as a set of isolated sectors, technologies, or commodities, PAK-IEM 2.0 enables the analysis of key substitution options and cross-sectoral interactions. This approach allows the assessment of system-level trade-offs – such as electrification, fuel switching, and competition between technologies – that cannot be fully understood through isolated single-sector or single-technology analyses.

[1] Model generator developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses long term energy scenarios to conduct in-depth energy and environmental analyses.

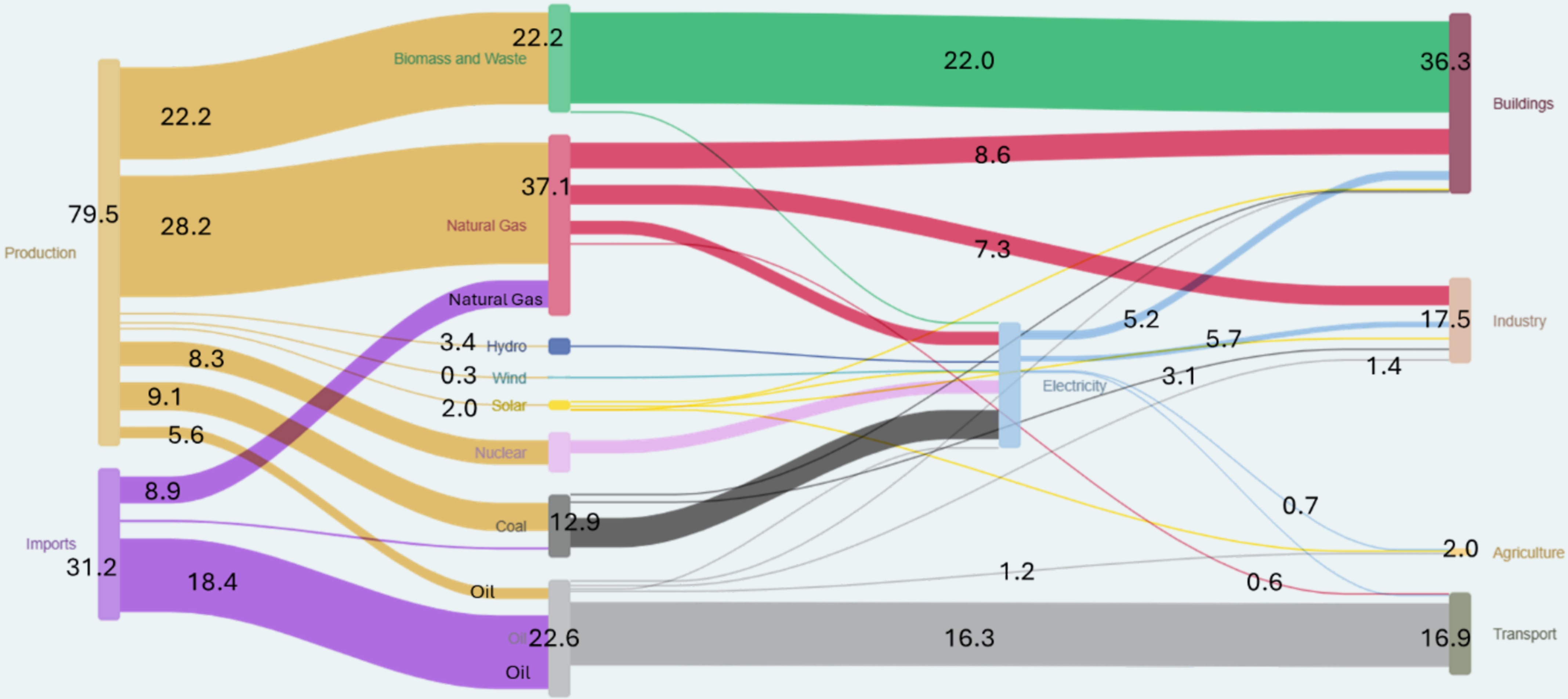

Figure 2: The Sankey diagram of Pakistan Energy Balance FY-2023-24 (MTOE)

PAK-IEM 2.0 generates scenario-based projections for the period 2024–2050, providing insights into the evolution of the energy mix, technology deployment pathways, investment needs, energy prices, and greenhouse gas emissions. The scenarios identify least-cost energy system pathways under varying assumptions on policy objectives, emission constraints, resource availability, and technology performance, supporting informed decision-making on Pakistan's long-term energy transition.

This approach provides a robust analytical foundation for assessing national energy strategies, investment plans, and climate commitments, including the implementation of NDCs, long-term decarbonization pathways, etc.

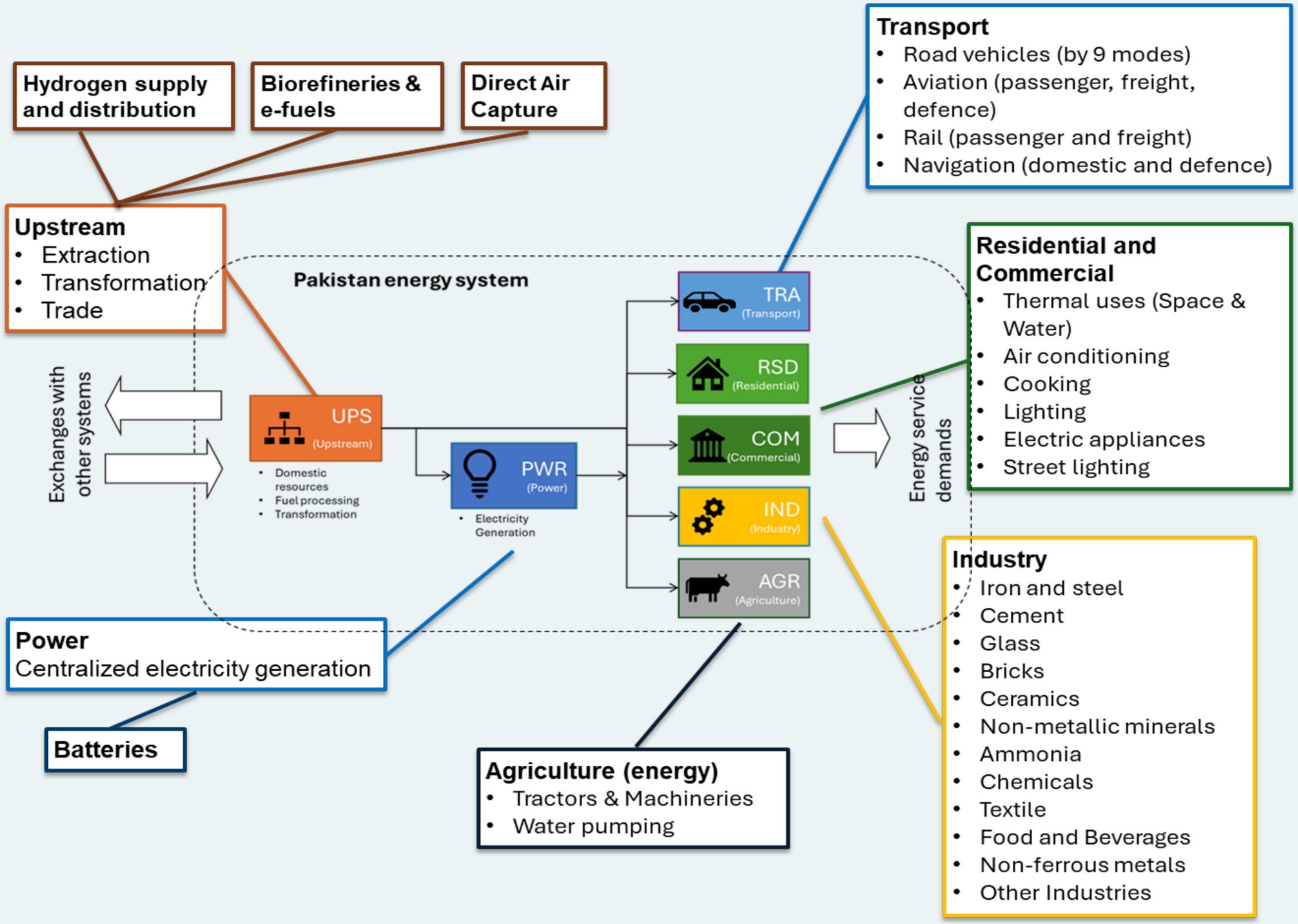

Figure 3: The Structure of PAK-IEM 2.0

PAK-IEM 2.0 is structured around seven interconnected modules, each representing a key energy sector:

Supply-side sectors

- Upstream (UPS): Domestic energy resources, extraction infrastructure, fuel imports, refineries, and existing and future energy transformation technologies (e.g. hydrogen production, hydrogen-based fuels, biofuels).
- Power (PWR): Electricity generation, transmission, and distribution.

Demand sectors

- Residential (RSD): Urban and rural buildings.
- Commercial (COM): Commercial, public, and other government.
- Industry (IND): Manufacturing sectors including iron and steel, cement, glass, bricks, ceramics, non-metallic minerals, ammonia, chemicals, textiles, food and beverages, non-ferrous metals, and other industries.
- Transport (TRA): Small and medium cars, commercial passenger vehicles, light/medium/heavy trucks, motorbikes, three-wheelers, buses, rail, aviation, and navigation.
- Agriculture (AGR) (energy-related activities): Tractors and water pumping.

Each sector is modelled as a standalone module and, where relevant, further disaggregated into sub-sectors and end-uses, as described in subsequent sections. For each sector, the model quantifies technical (technology stocks and fuel flows), economic (prices and investments), and environmental (GHG emissions) dimensions, enabling integrated energy and climate policy analysis.

04. Model Inputs

PAK-IEM 2.0 is underpinned by a comprehensive and transparent set of exogenous inputs, ensuring consistency with national planning data and international best practices.

Calibration

The model is calibrated to Pakistan's latest national energy balance (FY 2023–24) and latest available national statistics and planning documents. This ensures alignment with current system conditions, including installed capacities, fuel use, technology performance, and sectoral energy consumption.

Technologies

PAK-IEM 2.0 includes a detailed representation of more than 1,600 supply- and demand-side technologies across all sectors. Each technology is characterized by key technical and economic parameters, including efficiency, lifetime, availability, emissions, capital and operating costs, and investment discount rates. While international databases provide the primary data sources, when possible, technology parameters have been reviewed and adapted to reflect Pakistan-specific conditions.

In the power sector, the model assumes the existing and committed IGCEP projects up to 2035, alongside a moratorium on new oil- and imported-coal-based plants. Beyond 2035, capacity expansion follows a least-cost approach. Refinery development is limited to brownfield upgrades only, with no new greenfield projects. The model remains technology-neutral across sectors, except for the ban on new oil and imported coal power capacity.

Resource potential and prices

The model incorporates supply curves for primary energy commodities and renewable resources, reflecting cost variations across different levels of supply. Fossil fuel supply is constrained by recoverable reserves and a stepwise natural gas supply curve, while renewable expansion is limited to technically and economically feasible potentials. Long-term oil and gas contracts are assumed up to their current expiration date and are not extended. International fuel price projections for coal, oil, and natural gas are based on the IEA World Energy Outlook 2024 Stated Policies scenario.

Socio-Economic Drivers and Energy Service Demands

Energy service demand projections are driven by socioeconomic assumptions, including sectoral GDP growth, population trends, electricity access (NTDC and K-Electric connections), fuel and electricity prices, elasticities, and the Consumer Price Index (CPI). These projections have been developed by EPRC using ARIMA and SARIMA methodologies and translated into more than 100 distinct energy service demands across residential, commercial, transport, agriculture, and industry sectors. For each modelling period through 2050, PAK-IEM 2.0 identifies the least-cost combination of technologies and fuels to meet these service demands.

05. Modelled Scenarios

The primary insights generated from PAK-IEM 2.0 are achieved through scenario analysis. Based on stakeholder priorities and approved scope, two core scenarios have been developed:

5.1. Least Cost Baseline (LCB) Scenario

The Least Cost Baseline (LCB) scenario represents the optimal evolution of Pakistan's energy system based on least-cost principles, subject to technical constraints and currently committed policies. The scenario reflects existing and committed power sector projects, as well as recent trends in electric vehicle sales, without imposing explicit long-term decarbonization targets. The LCB scenario assumes limited adoption rates for advanced technologies, moderate energy efficiency improvements, and a continuation of prevailing policy and market conditions. Informal and non-technical energy use is gradually reduced over time and is assumed to be fully eliminated by 2050. The LCB scenario provides a reference pathway for analysing the evolution of Pakistan's energy system through 2050 in response to projected economic and population growth, in the absence of additional policy interventions.

5.2. Net-Zero Energy (NZE) Scenario

The Net-Zero Energy (NZE) scenario reflects a policy-driven transition aligned with Pakistan's Nationally Determined Contributions (NDCs) and targets net-zero greenhouse gas emissions from the energy sector by 2050 while incorporating key national policy objectives. Under the NZE scenario, energy efficiency improvements and technology substitution across demand and supply sectors are guided by cost-optimal pathways consistent with these policy targets. The scenario illustrates the system-wide implications of deep decarbonization, highlighting required changes in the energy mix, technology deployment, and investment patterns to achieve a net-zero energy system.

Following below is the summary of assumptions underpinning both scenarios:

Least Cost Baseline (LCB) Scenario

- Least-cost principles, subject to technical constraints and currently committed policies
- Incorporates existing and committed power sector projects
- Reflects recent trends in electric vehicle (EV) sales, without additional policy push
- No explicit long-term decarbonization targets imposed
- Assumes limited adoption rates of advanced and emerging technologies
- Includes moderate energy efficiency improvements
- Maintains prevailing policy and market conditions
- Informal and non-technical energy use declines gradually and is fully eliminated by 2050
- Provides a baseline pathway to 2050 in the absence of further policy interventions

Net-Zero Energy (NZE) Scenario

- Represents a policy-driven energy transition aligned with Pakistan's NDCs
- Targets net-zero GHG emissions from the energy sector by 2050
- Incorporates key national policy objectives, including:
  - 60% renewable electricity generation by 2030
  - Ban on new imported coal-fired power plants
  - Accelerated electrification of the transport sector
- Opts for progressive efficiency improvements and technology substitution through cost-optimal pathways considering policy targets
- Enables rapid deployment of low-carbon and renewable technologies across supply and demand sectors
- Illustrates system-wide implications of deep decarbonization
- Provides a clear pathway for achieving a net-zero energy system under strong policy direction

06. Modelling Results

This section presents the main results of the scenario analysis. The discussion is structured into two parts: first, a high-level overview of the key system-wide trends, followed by a more detailed breakdown of results by sector.

6.1. Background

6.1.1. Key takeaways from Least Cost Baseline (LCB)

This section summarizes the key findings generated by the LCB scenario. Figure 4 provides a summary of key milestones underpinning the Least-Cost Baseline scenario, followed by highlights of main implications.

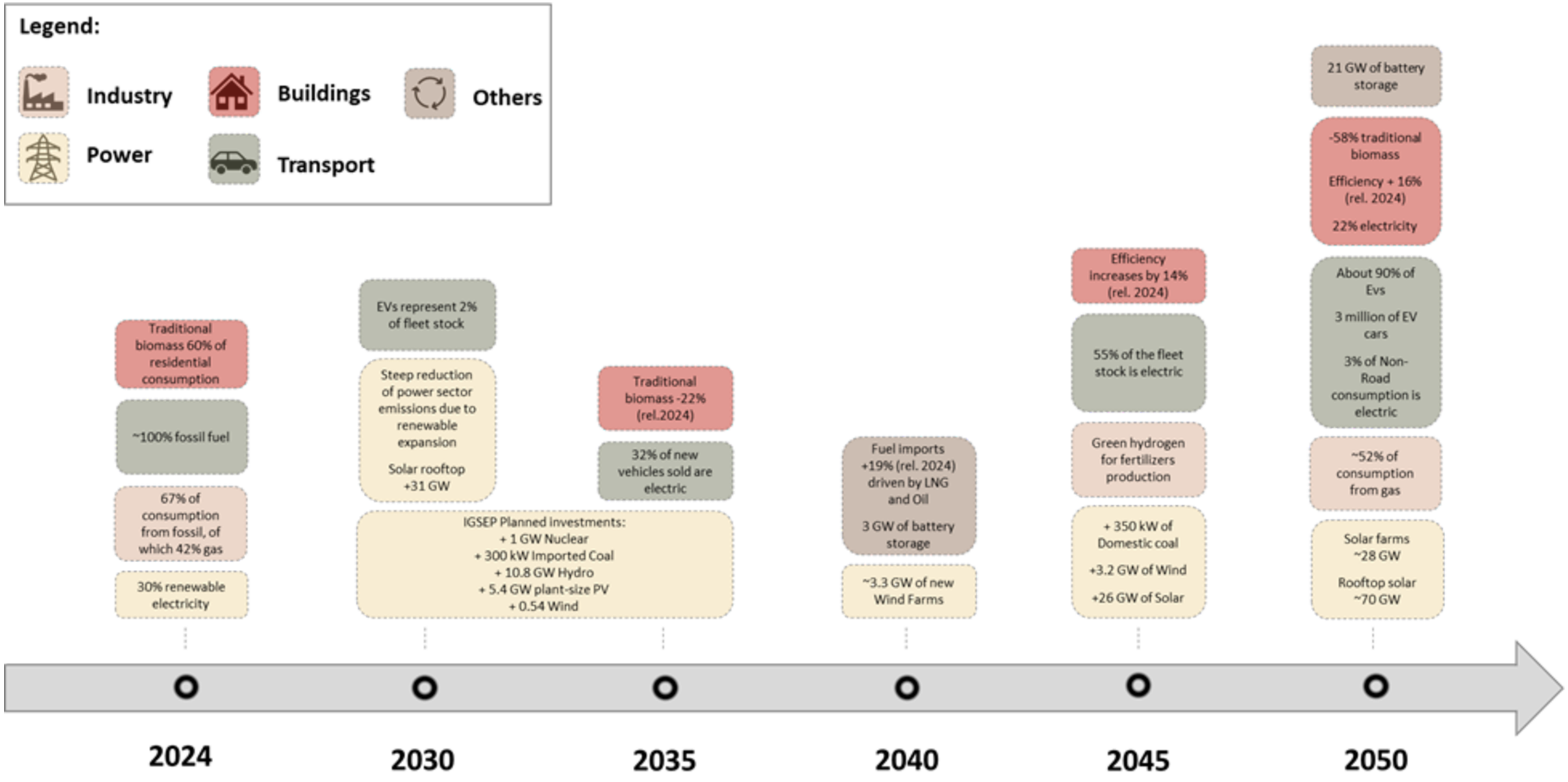

Figure 4: High-level roadmap to Least Cost Baseline

Decoupling economic growth and energy consumption

Despite projected growth in energy demand, the energy system becomes progressively more efficient and cleaner under the LCB scenario. This evolution is driven by cost-effective technology improvements, increased electrification of end uses, and the continued expansion of renewable energy.

As a result, greenhouse gas emissions from the energy sector are projected to remain broadly stable over the modelling horizon, indicating that structural efficiency gains and cleaner energy sources largely offset growth in energy use. This represents a significant shift from historical trends, during which energy-related emissions increased by about 2.5 times between 1994 and 2021.[2]

Key takeaways

- GDP growth: GDP increases by a factor of 2.5 by 2050
- Final energy demand: limited growth of around 30% by 2050
- Emissions: no structural increase despite economic expansion

Renewables expansion in the electricity sector

Renewable electricity generation expands under the LCB scenario, becoming the dominant source of generation over the long term. The potential for temporary capacity excess in the early 2030s, driven by the commissioning of planned large-scale hydropower, renewable, and nuclear projects. This overcapacity is gradually absorbed as electricity demand increases in subsequent years.

The distributed and off-grid solar solutions, which expand steadily throughout the modelling horizon, reflect strong cost competitiveness and growing demand for decentralized energy/electricity access.

Key takeaways

- Renewable share in electricity generation increases from around 35% today to approximately 80% by 2050
- Decentralized solar PV capacity grows from about 38 GW in 2025 to around 70 GW by 2050

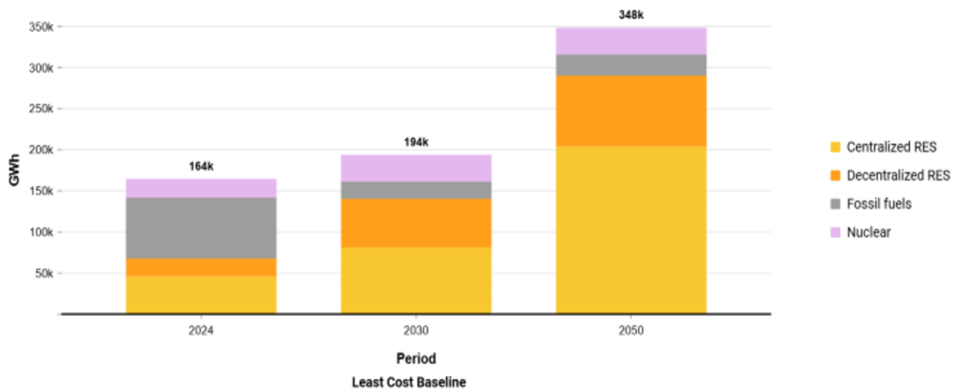

Figure 5: Power generation mix (LCB)

[2] UNFCCC, Pakistan Biennial Transparency Report (BTR), 2021.

Efficiency & electrification of end-uses

Particularly post 2030, end-use sector efficiency is projected to increase. This trend is driven by the replacement of existing technologies with improved ones, and the switch to electric modes, particularly in the transport and space heating sector. The overall energy consumption per capita is projected to decrease, increased electrification leads to growth in electricity demand, reflecting the substitution of efficient electric technologies for fossil fuel-based end uses.

Key takeaways

- Final energy consumption per capita declines by approximately 15% by 2050
- Electrification of end uses accelerates growth in electricity demand

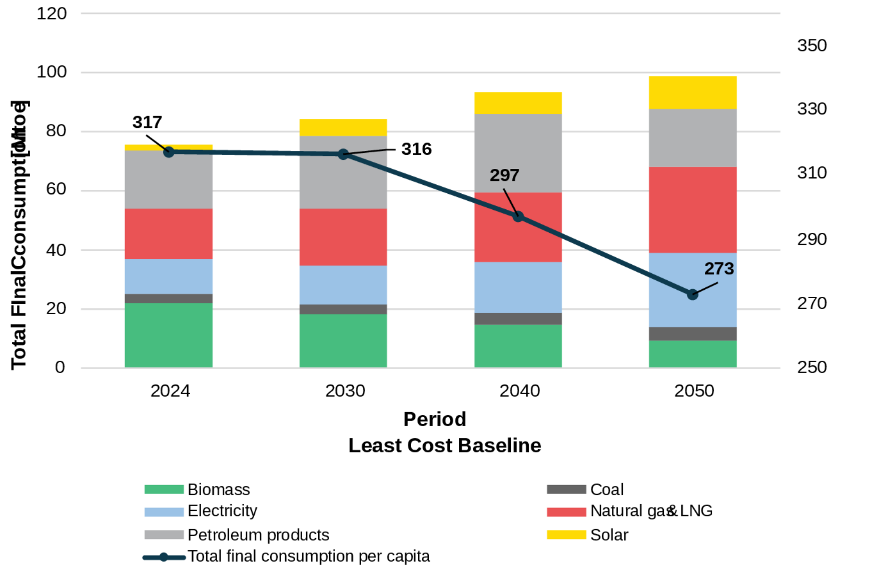

Figure 6: Evolution of Final Energy Consumption by Energy Carrier and per Capita

Electric vehicles

The LCB scenario shows a sustained increase in electric vehicle (EV) adoption across all transport modes, with particularly rapid growth after 2035. This trend reflects improving cost and technology diffusion.

Key takeaways

- Key transport modes, such as two- and three-wheelers and light trucks, become fully electrified by 2050
- Around 3 million passenger cars are electric by 2050
- By 2050, the transport sector accounts for approximately 30% of total electricity demand (compared to almost zero today)

Clean cooking

Traditional biomass remains a significant cooking fuel, despite a gradual transition towards modern cooking alternatives. The transition is primarily driven by increased adoption of natural gas and LPG stoves, leading to improved cooking efficiency and associated social and health benefits.

While progress is observed over time, the continued reliance on biomass highlights the need for targeted policy interventions to accelerate access to clean cooking solutions, particularly in rural and low-income households.

Key takeaway

- Biomass share in cooking declines from around 70% today to approximately 38% by 2050

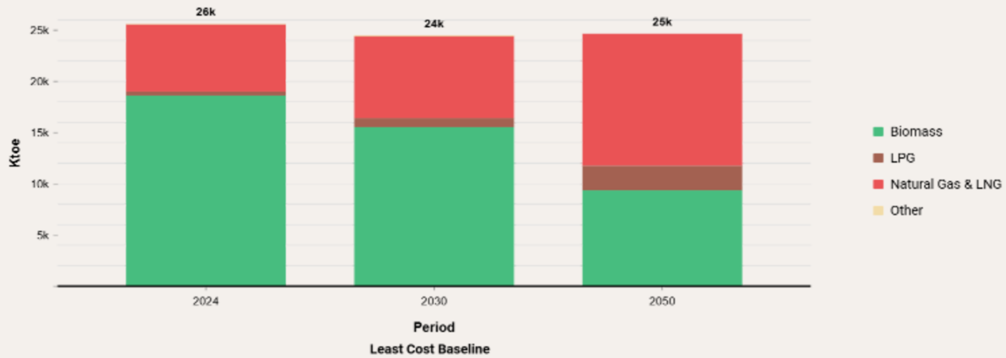

Figure 7: Energy consumption for Residential cooking (LCB)

6.1.2. Key takeaways from Net Zero Energy scenario

This section explores implications of the transition towards a deep mitigation pathway, highlighting key transformations, impacts, and system-wide implications of achieving net-zero emissions in the energy sector by mid-century. Figure 8 provides a summary of key transformations underpinning the Net-Zero Energy scenario, followed by analyses of thematics implications. For a more detailed, sector-by-sector assessment, please refer to Section 6.2.

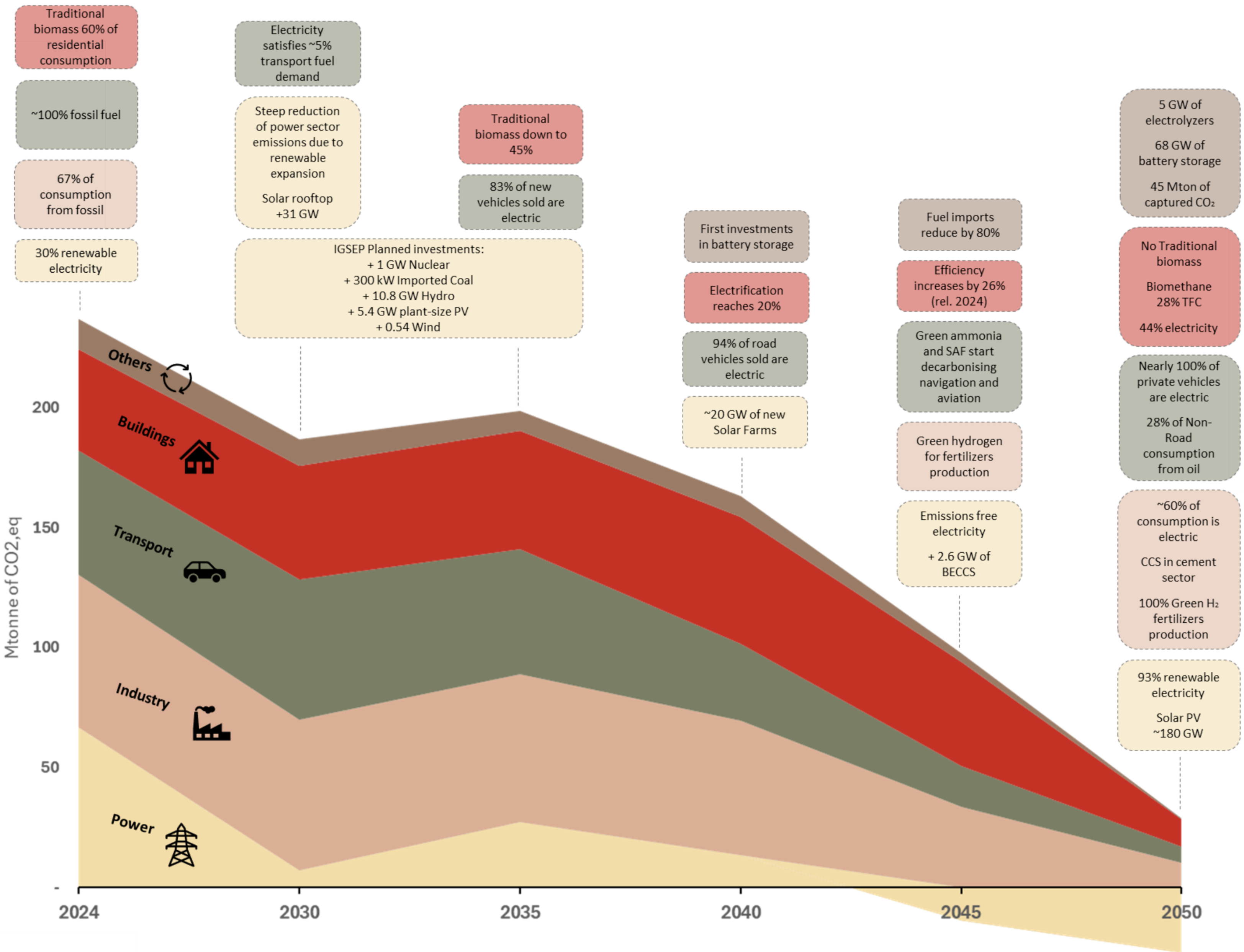

Figure 8: High-level roadmap to Net-Zero Energy

Driving the decarbonization

Achieving the Net-Zero Energy targets requires sustained and coordinated decarbonization efforts across all energy sub-sectors. Compared to the LCB scenario, additional mitigation actions are primarily concentrated in the transport and industrial sectors between 2025 and 2035, reflecting early opportunities for electrification, efficiency improvements, and fuel switching. During the subsequent decade (2035–2045), mitigation efforts broaden across the entire energy system, with significant emission reductions achieved respectively in power generation, transport, industry, and buildings. In the final phase of the transition (2045–2050), remaining abatement efforts are increasingly concentrated in hard-to-abate end uses within industry, transport, and buildings, requiring advanced low-carbon technologies. Smaller but important contributions are also delivered by the agriculture and upstream sectors, grouped under "Others".

Key takeaways

- The power sector leads the transition, reaching full decarbonization already by 2045
- Transport follows, achieving a 67% emissions reduction by 2045 (vs 2035) and approaching near-zero emissions in the final phase of the pathway
- Residential and industrial sectors decarbonize more slowly, with the most significant emissions reductions occurring after 2045

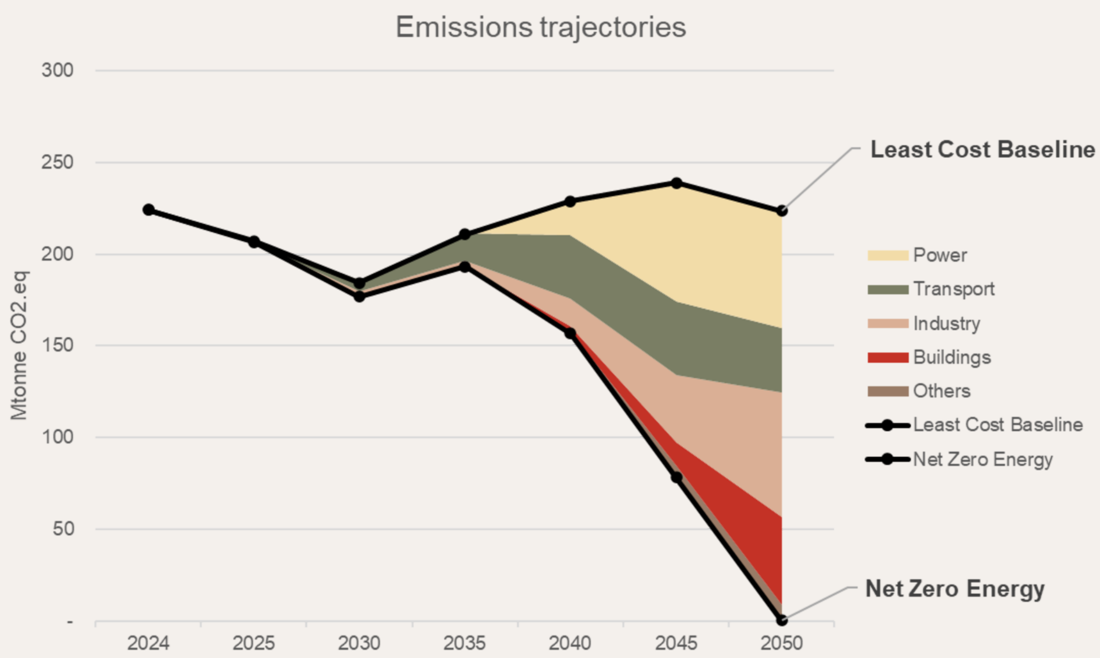

Figure 9: Emission Reductions in the Net Zero Scenario Relative to the Least Cost Pathway

Driving investments

Results indicate that the transition to Net Zero is more capital-intensive, requiring higher investments across all sectors, with particularly strong impacts in the power sector and in upstream activities such as hydrogen and advanced biofuels production. At the same time, increased capital deployment leads to lower fuel-related costs, as the large-scale expansion of renewables drives a sustained reduction in fossil fuel consumption and imports.

Key takeaway

- In 2050, annualized investment costs are around 15% higher in the NZE scenario compared to the LCB
- Fuel costs decline by about 45% relative to the base year (2024), and by roughly 30% compared to the LCB scenario in 2050

No regret options

The NZE pathway confirms the robustness of several trends already observed in the LCB scenario, which can be considered clear “no-regret” options. These include the continued electrification of end uses, sustained improvements in energy efficiency, and the large-scale expansion of solar and wind power in the electricity sector. Under the NZE scenario, the pursuit of deep emissions reductions leads to a general acceleration of these trends across all sectors.

Key takeaway

Final energy consumption per capita declines steadily over time:

- 2024–2035: -0.7% per year
- Post-2035: acceleration to -2.3% per year
- By 2050: -33% compared to 2024

Deep electrification of final energy demand is achieved by 2050:

- Transport: electrification reaches 72% of final energy demand
- Industry: electrification increases to 57%, nearly doubling from current levels (~30%)
- Residential: electricity accounts for 40% of final energy demand

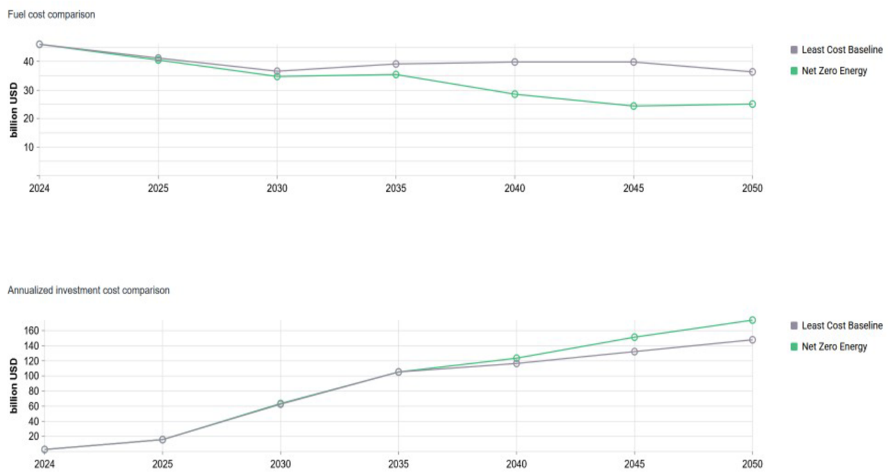

Figure 10: Annualized investment and fuel cost comparison

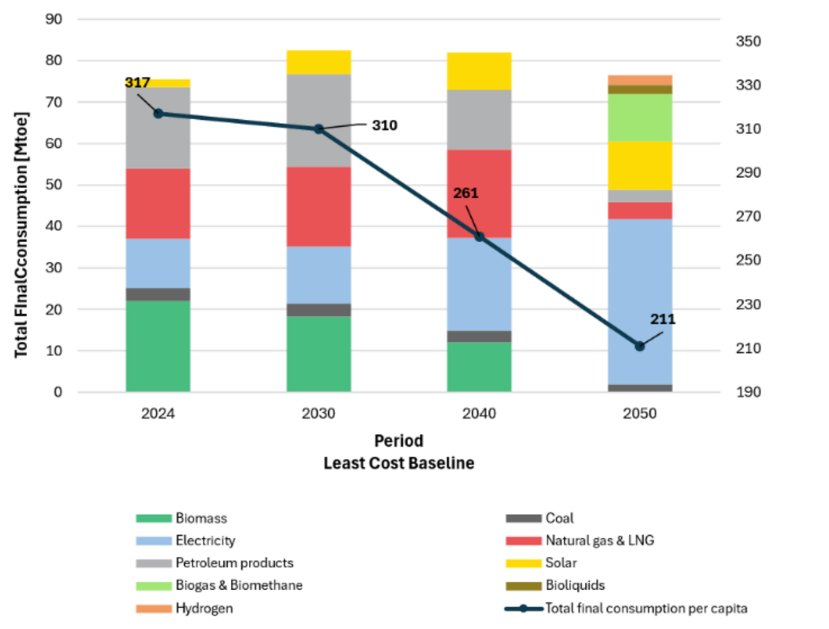

Figure 11: Evolution of Final Energy Consumption by Energy Carrier and per Capita

Decarbonized power systems

Electricity generation becomes fully emission-free after 2040 under the Net-Zero Energy pathway and reaches net-negative emissions, thereafter, driven by the deployment of Bioenergy with Carbon Capture and Storage (BECCS) from 2045. This transition is underpinned by a rapid expansion of renewable electricity generation, particularly solar and wind power.

High shares of renewables significantly increase system flexibility requirements. These are addressed through investments in dispatchable generation – both renewable and fossil-based – as well as large-scale deployment of electricity storage, primarily battery systems.

While the current analysis focuses on generation and storage technologies, the expansion and reinforcement of transmission and distribution networks are not explicitly modelled and warrant dedicated attention in future assessments to ensure system reliability under high renewable penetration.

Key takeaways

- Renewables reach 93% of electricity generation by 2050, with wind and solar as the dominant technologies
- Fossil fuels are fully phased out from power generation after 2040
- Battery storage scales up after 2040, reaching ~70 GW by 2050, nearly three times the capacity of the LCB scenario

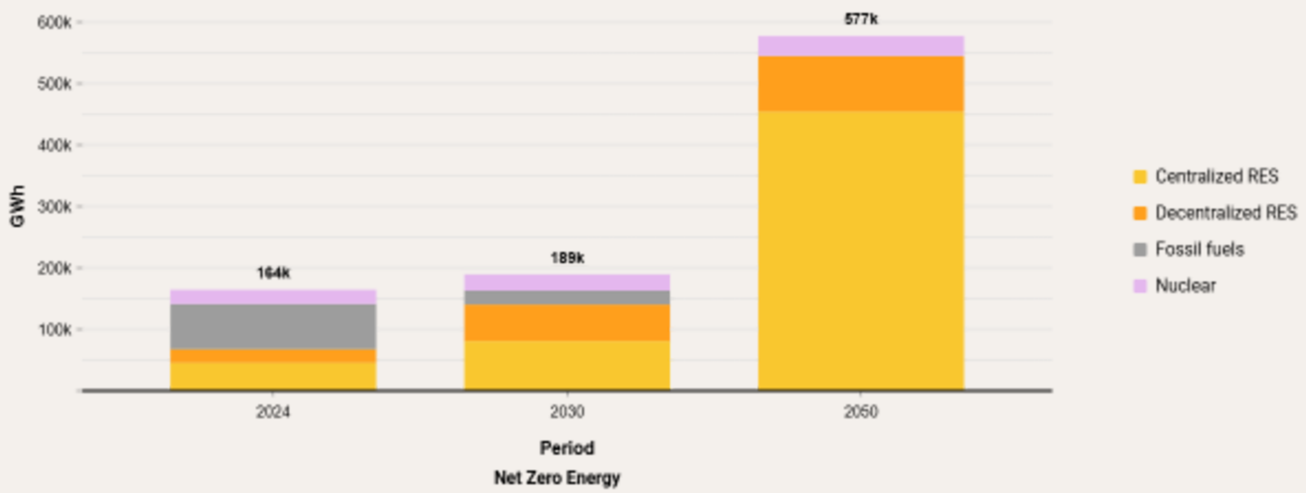

Figure 12: Power generation mix (NZE)

Clean cooking

The cooking sector undergoes a complete transition away from traditional biomass, delivering both decarbonization and modernization benefits. In the NZE pathway, clean and modern fuels progressively replace inefficient biomass, with renewable gases and electricity becoming the dominant energy carriers by 2050.

Key takeaway

Residential cooking in 2050:

- Traditional biomass fully phased out
- Cooking demands are delivered by biomethane (54%), electricity (25%), and natural gas (21%)

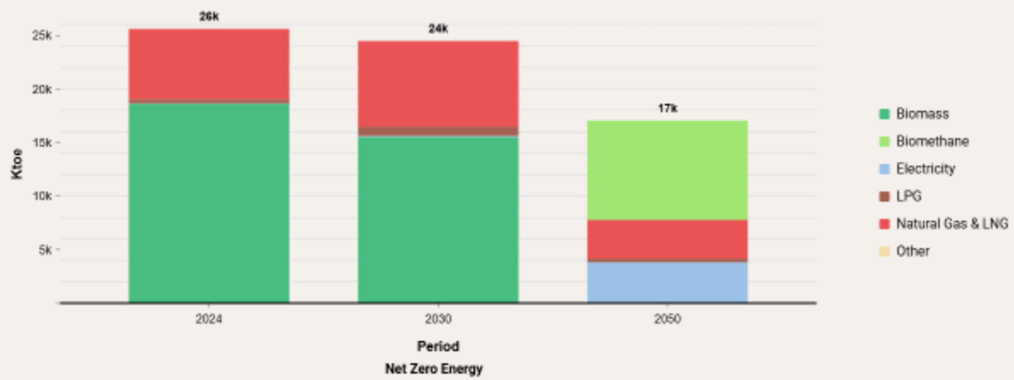

Figure 13: Energy consumption for Residential cooking (NZE)

Hard-to-abate emissions

In sectors where direct electrification is not technically or economically feasible, the NZE pathway relies on the large-scale deployment of green hydrogen, advanced biofuels, and carbon capture, utilization, and storage (CCUS). These solutions play a critical role in decarbonizing hard-to-abate sectors, including fertilizer production, high-temperature industrial processes, and non-road transport modes.

Bioenergy with carbon capture and storage (BECCS) acts as a last-resort mitigation option, providing net-negative emissions that help balance residual emissions from sectors where full decarbonization remains challenging by 2050.

Key takeaway

Green hydrogen

- Around 5 GW of electrolyser capacity installed by 2050
- 80% of fertilizer-related ammonia production supplied by green hydrogen by 2045, increasing to 100% by 2050
- Hydrogen-based ammonia also contributes to the decarbonization of the shipping sector

Advanced biofuels

- Advanced biofuels target hard-to-abate uses, focusing on clean cooking, high-temperature industry and aviation/heavy transport.

CCUS

- Power sector (BECCS): around 3.6 GW of biomass power with CCS, capturing approximately 27 Mt CO_2-eq in 2050
- Cement sector: around 75% of clinker production equipped with CCS, capturing approximately 18 Mt CO_2-eq in 2050

Exposure to international energy markets

The transition towards a low-carbon energy system has important secondary implications that are not directly targeted by the scenario design. As fossil fuel consumption declines, exposure to international energy markets is reduced, reflecting a lower reliance on imported fuels.

While import dependency alone does not provide a comprehensive assessment of energy security or macroeconomic impacts, it offers a useful indicator for evaluating changes in external vulnerability and economic exposure under alternative energy transition pathways. In this context, the results suggest that deep decarbonization can contribute to improved resilience of the energy system by reducing dependence on volatile global fossil fuel markets.

Import dependency (%)

- Total: 35% (today) → 3.5% by 2050;
- Oil: about 80% (today) → 3% by 2050;
- LNG: 30% (today) → ~0% by 2050

6.2. Detailed Sectorial Results

6.2.1. Upstream

The differences in primary energy supply and imports between the Least Cost Baseline (LCB) and Net-Zero Energy (NZE) scenarios are driven by the strength of decarbonization policies. In the LCB scenario, the absence of binding GHG targets allows natural gas, oil, and coal to remain dominant where they are cost-competitive under international price assumptions. Renewable energy expansion follows a gradual but consistent trajectory, driven by continued uptake of rooftop solar, the realization of committed hydropower projects, and selected wind energy developments. However, there is limited energy gain. As a result, energy imports remain high and stable, dominated by oil and LNG, with the latter increasing after 2035 to meet increased residential and industry demands.

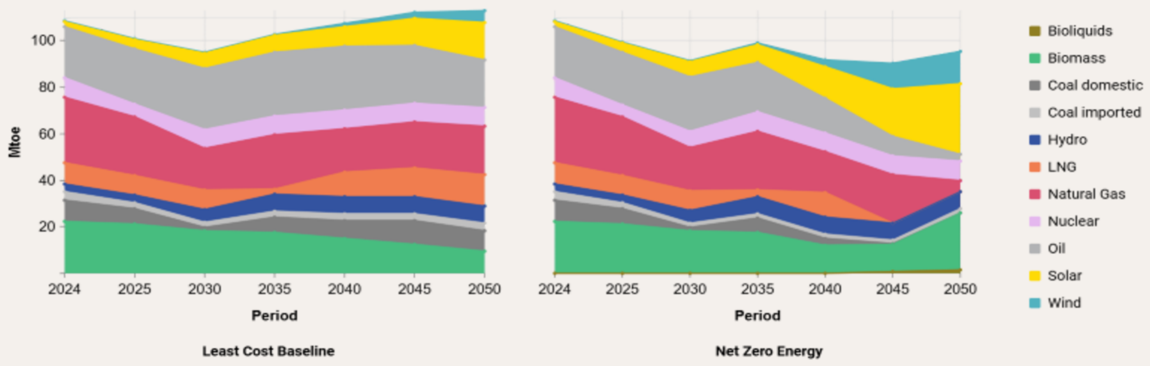

Figure 14: Primary Energy Supply

In contrast, the NZE scenario, driven by explicit emission constraints, and strong power-sector policies, shows a significant expansion of renewables, primarily solar, wind, and bio energies. High EV penetration and unrestricted efficiency adoption accelerate electrification and reduce fossil fuel demand. Consequently, both total primary energy supply and oil, LNG, and coal imports decline sharply after 2035, reaching minimal levels by 2050 due to higher efficiency, domestic renewables, and reduced exposure to international fuel markets.

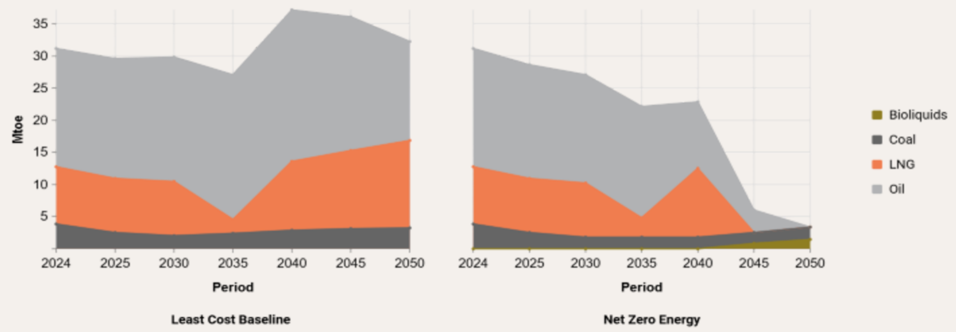

Figure 15: Fuel imports

6.2.2. Power Sector

The power-sector results highlight how the electrification of end-uses driven by policy measures such as the target of 90% electric vehicle (EV) sales by 2040, alongside cost-efficient technology adoption leads to increase in electricity demand under the NZE scenario. By 2050, total installed capacity and electricity generation in the NZE scenario approximately doubles (263 GW and 577.2 TWh) the values observed under the LCB scenario (150 GW and 348.1 TWh) for the same year.

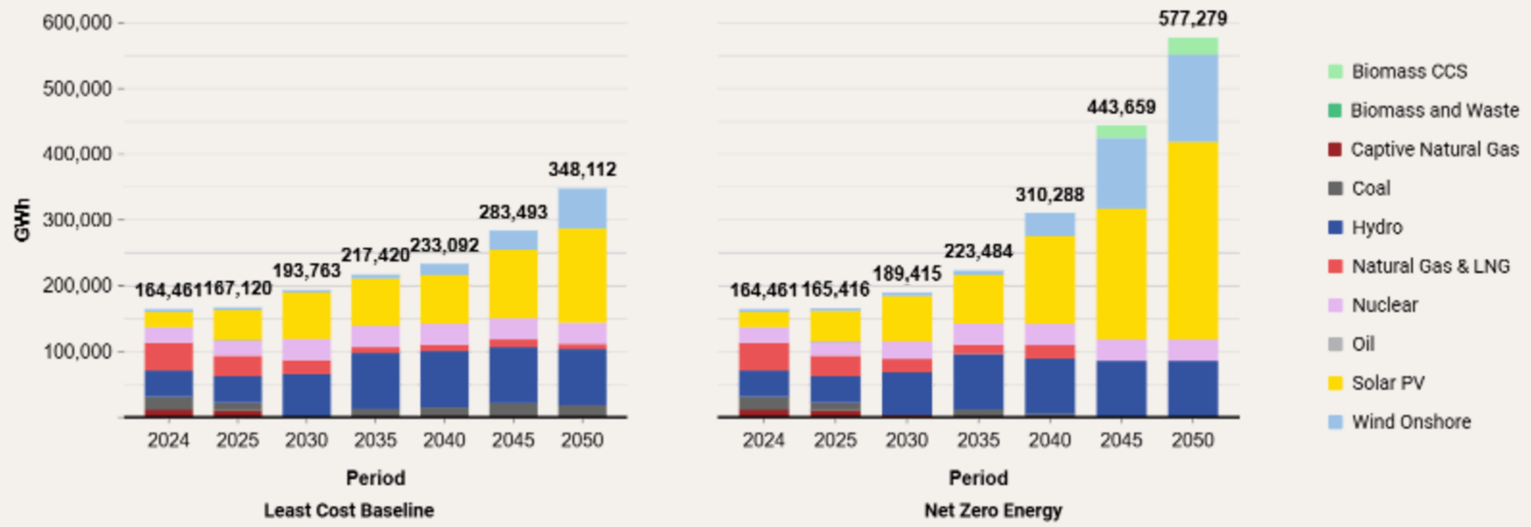

Figure 16: Electricity generation mix

Meeting this demand requires the large-scale deployment of solar PV and wind power, complemented from around 2045 by dispatchable bioenergy with carbon capture and storage (BECCS) plants. Fossil fuel-based capacity, particularly coal and gas, remains in the system primarily to provide reserve and flexibility services, while their actual electricity generation declines to near zero by mid-century.

Importantly, the results also highlight the risk of temporary capacity excess in the early 2030s. This is driven by the rapid expansion of the rooftop solar market and the commissioning of planned large-scale hydropower and nuclear projects, occurring ahead of sustained growth in electricity demand. This temporary overcapacity is gradually absorbed as electricity demand increases in subsequent years.

6.2.3. Residential

Residential sector results reveal two distinct trends across the scenarios. Under the LCB scenario, final energy consumption in the residential sector is projected to increase from 36.3 MTOE to 42.2 MTOE between 2024 to 2050, reflecting population growth and rising energy service demand. In contrast, under the NZE scenario, residential energy consumption declines to approximately 31 MTOE by 2050. As both scenarios assume identical underlying energy service demand trajectories, the divergence in energy consumption is driven entirely by differences in technology choices, most notably the accelerated uptake of high-efficiency appliances and electrified end uses in the NZE scenario.

In rural areas, households transition away from wood towards clean cooking solutions and solar water heating, supporting emissions reduction targets while delivering significant health and welfare benefits. In urban areas, the growing deployment of solar thermal water heating helps moderate peak electricity demand, complementing broader power-sector decarbonization and system flexibility objectives.

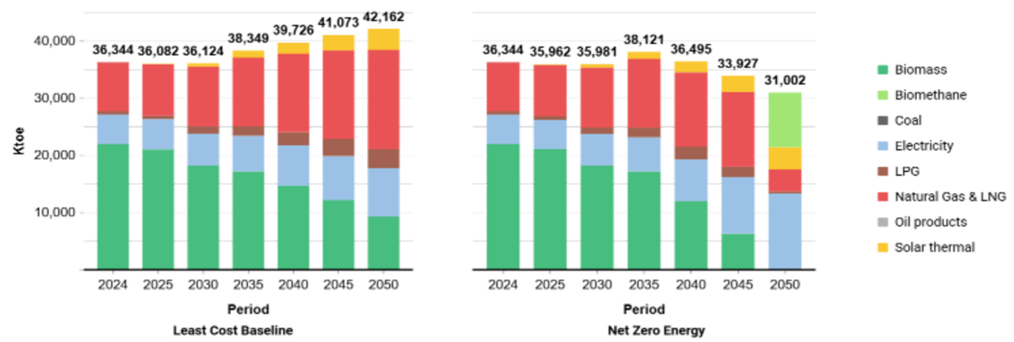

Figure 17: Final Energy Consumption in households by energy carrier

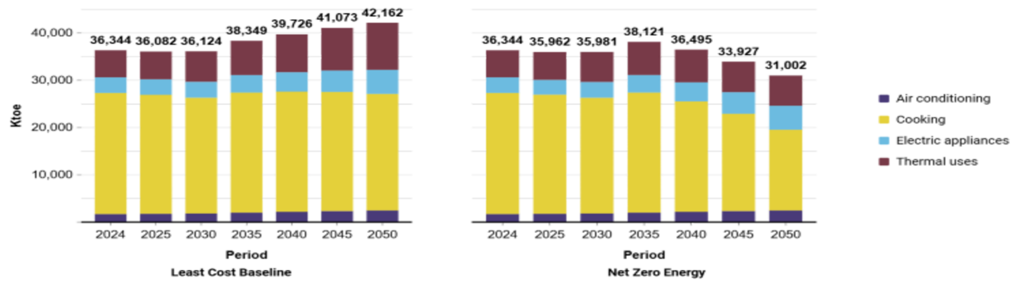

Figure 18: Energy Consumption in households by service

6.2.4. Commercial

In the LCB scenario, final energy consumption rises to a relatively higher value (4.75 MTOE) by 2050, reflecting rapid cooling demand growth and appliance use, than the NZE scenario (4.02 MTOE) for the same year despite similar service demand growth.

This divergence is driven by the unrestricted adoption of high-efficiency commercial technologies under the NZE pathway, enabling the sector to meet increasing cooling and appliance needs with substantially lower energy input. Electrification acts as the primary decarbonization lever, with electricity increasingly replacing natural gas and LPG for thermal and cooking applications.

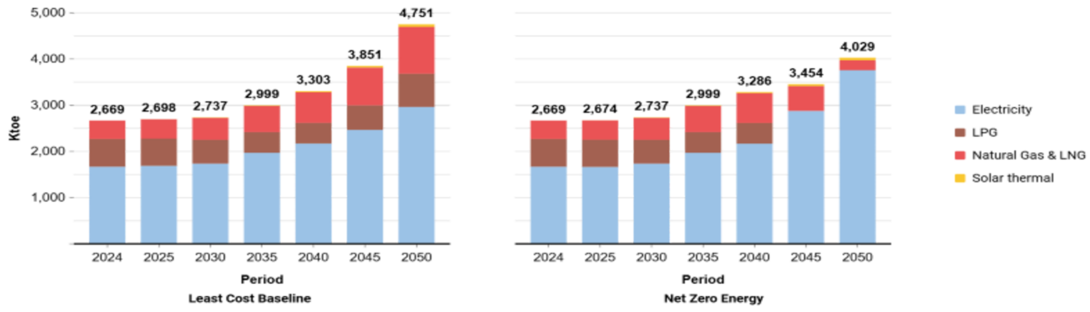

Figure 19: Final Energy Consumption in commercial sector by energy carrier

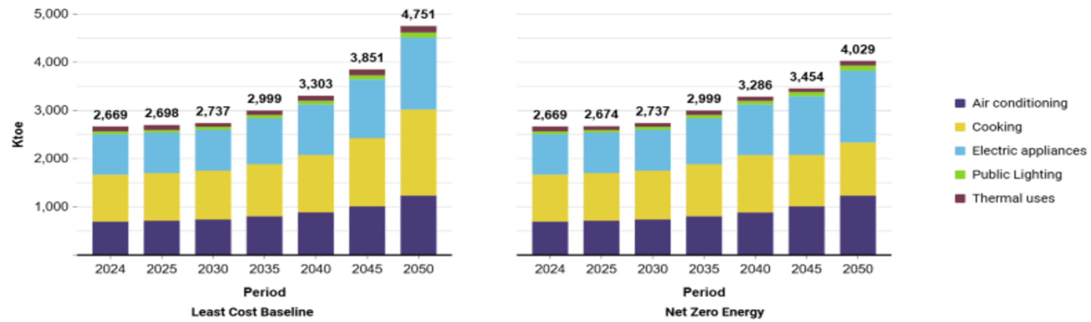

Figure 20: Final Energy Consumption in commercial sector by service

6.2.5. Industry

Under the NZE scenario, industrial energy consumption is significantly lower than in the LCB scenario, reflecting a structural transformation of energy-intensive subsectors such as iron and steel, cement, and chemicals toward near-zero-emission production processes. Electrification serves as the primary decarbonization lever, with electricity progressively replacing coal and natural gas for low- and medium-temperature process heat.

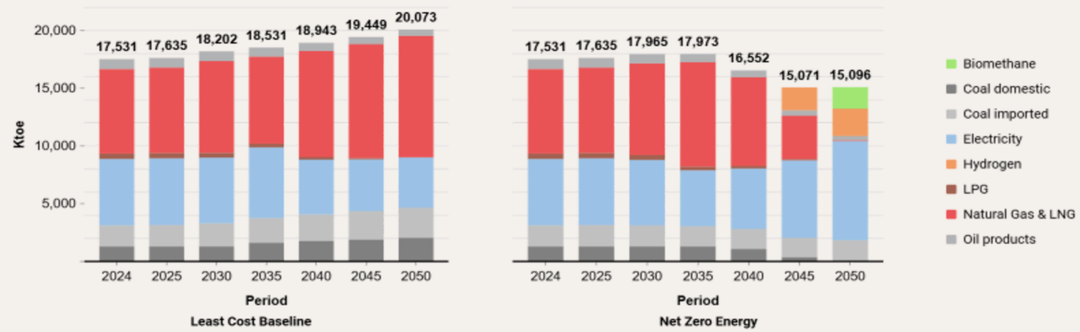

Figure 21: Final Energy Consumption in industry by energy carrier

By 2050, the industrial sector evolves into a modern, largely electrified system integrated with renewable power, green hydrogen, and low-carbon feedstocks. This structural shift enables continued industrial growth and competitiveness while decisively breaking the historical link between manufacturing output and rising carbon emissions.

6.2.6. Transport

Transport sector results indicate a profound structural transformation under the NZE scenario, driven by aggressive electrification and decarbonization mandates. Under the LCB scenario, transport energy demand continues to rise, peaking at 23.5 MTOE in 2040, followed by a gradual decline. In contrast, under the NZE scenario, transport energy demand peaks earlier at 19.757 MTOE in 2030—and declines steadily to 15.87 MTOE by 2050. This sharp reduction is primarily achieved through the implementation of the 90% electric vehicle sales target for new vehicles by 2040, combined with the removal of constraints on the adoption of high-efficiency technologies. During the transition period (2030–2040), the NZE pathway shows a rapid displacement of gasoline and diesel by electricity, as passenger cars, motorcycles, and light-duty vehicles shift to high-efficiency electric drivetrains.

The NZE scenario introduces advanced low-carbon fuels in the final decade of the modelling horizon for aviation and navigation, including e-ammonia and sustainable aviation fuels (SAF). In contrast, the LCB scenario remains largely reliant on fossil fuels through 2050.

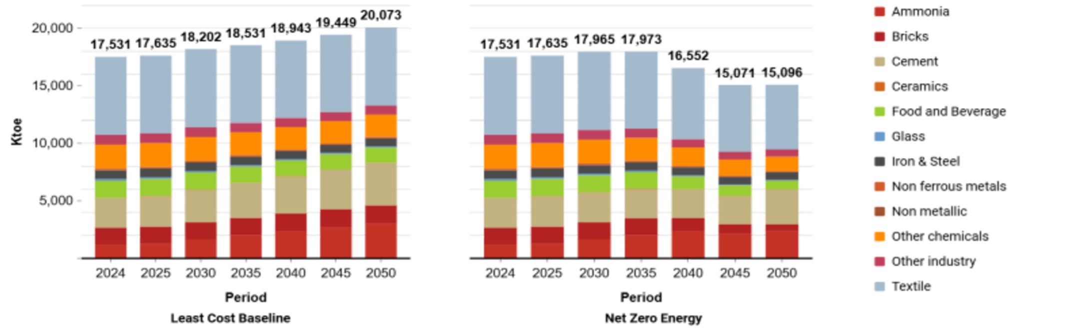

Figure 22: Final Energy Consumption in industry by industrial subsector

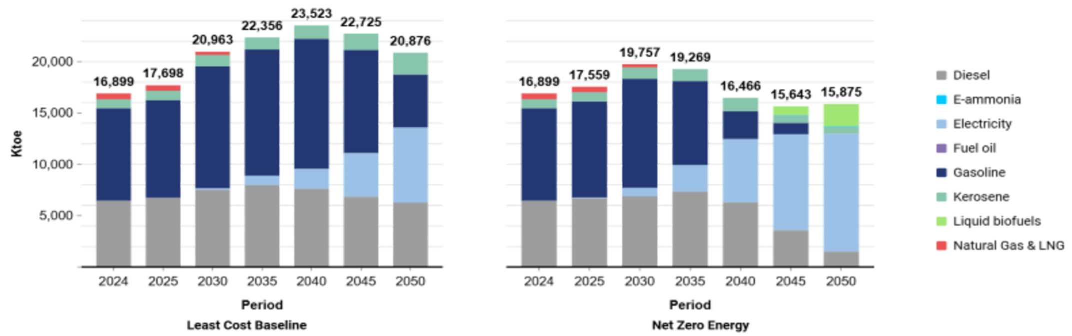

Figure 23: Final Energy Consumption in transport by energy carrier

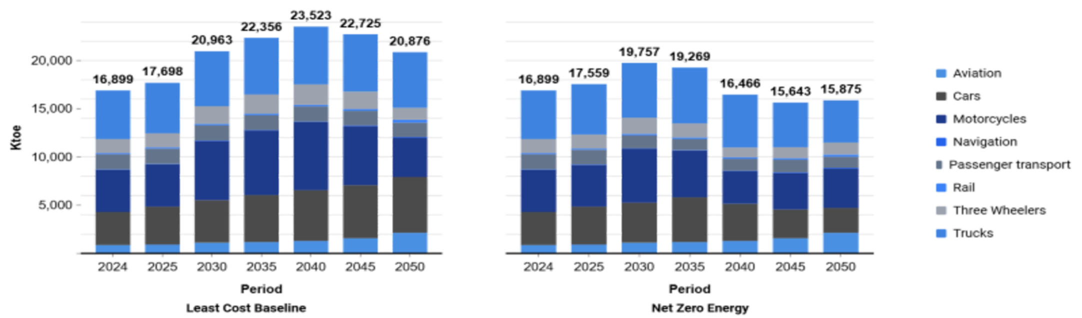

Figure 24: Final Energy Consumption in transport by mode

6.2.7. Agriculture

The agricultural sector indicates a gradual but clear shift from diesel toward electricity across both scenarios, driven primarily by increasing mechanization and the electrification of irrigation and farm machinery. Under the LCB scenario, total final energy demand in agriculture reaches 3.436 MTOE by 2050. In contrast, under the NZE scenario, energy demand is lower, reaching 2.74 MTOE by 2050, reflecting more efficient technology when pushing on the electrification.

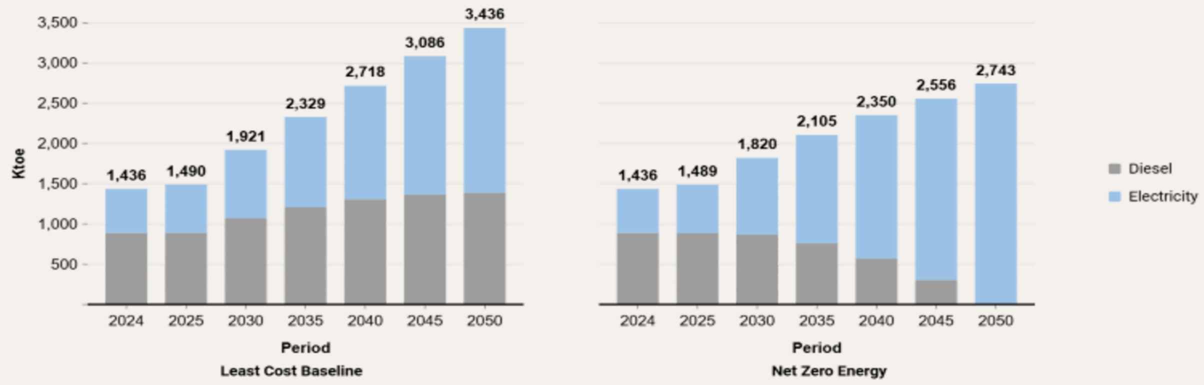

Figure 25: Final Energy Consumption in agriculture by energy carrier

6.2.8. Other: Comparing investments

When comparing investments across scenarios – here reported as overnight investments – the NZE scenario appears to be more capital-intensive, with a stronger investment need particularly emerging from 2040 onwards. Nevertheless, the LCB scenario also requires significant investment levels throughout the period, reflecting the need for ongoing capital deployment to maintain the energy system. However, it should be noted that the investment figures shown here represent both public and private expenditure, capturing the total capital required rather than implying only government spending.

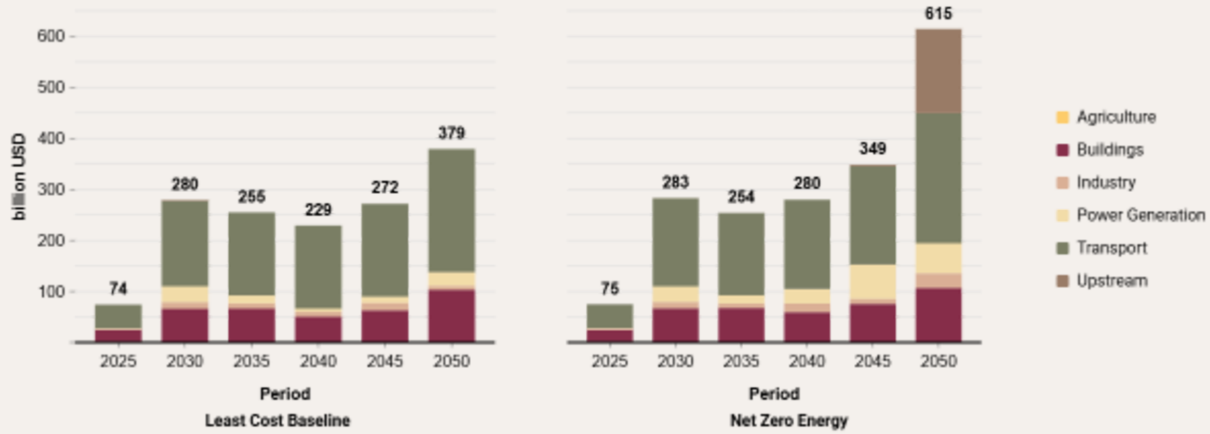

Figure 26: Overnight investments in LCB and NZE

Further comparison between investment trends across scenarios allows for the identification of sector-specific dynamics:

Power sector:

Higher investment costs are primarily associated with rapid deployment of renewable generation. Investment levels remain consistently higher than in the LCB scenario, driven both by the larger deployment of renewables and increased reliance on battery storage.

Transport sector:

Higher investments in the transport sector underpin accelerated decarbonization trends, mainly driven by electrification. The higher bulk of these investments is already visible from 2030 and remains consistently higher – except for 2035 – over the horizon.

Industrial sector:

Until 2050, no clear divergence in investment levels is observed between scenarios. The small variances seen before 2050 are mainly due to the investment timing, which occur earlier in the NZE scenario than in the LCB scenario. Towards 2050, the costs increase as deeper electrification intensifies, and additional capital is required for the deployment of CCS technologies, particularly in hard-to-abate subsectors such as cement.

Buildings sector:

A major share of required investments occurs during 2040-2045, where the buildings sector invests to sidestep from biomass and low-efficiency technologies. Additional costs are then reduced by 2050, as the final decarbonization is achieved mainly by replacing fossil-based gas with low carbon options.

Upstream sector:

Investments in upstream activities remain limited until 2050. Toward the end of the horizon, higher investment needs emerge to meet stringent decarbonization targets, mainly associated with the deployment of biorefineries and green hydrogen production facilities.

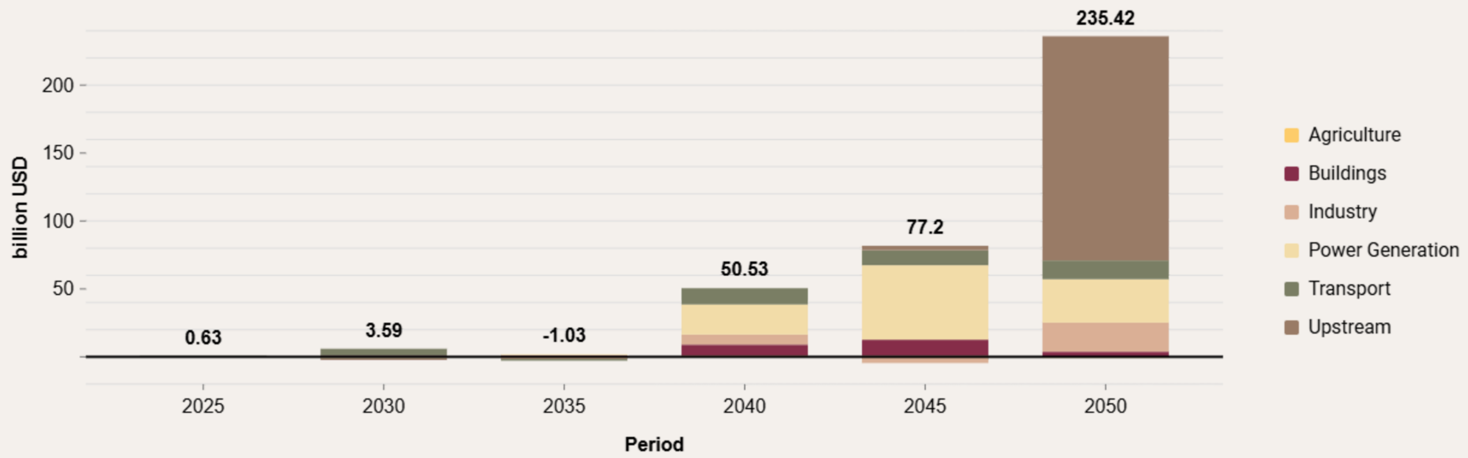

Figure 27: Additional overnight investments in NZE compared to LCB