Decarbonizing Pakistan: A MESSAGEix-Based Analysis of Low-Emission Energy Pathways, 2025-2070

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Abstract

This study constructs a low-emission pathway for Pakistan using the MESSAGEix-Pakistan energy system model by imposing a cumulative CO_2 cap of 201 $MtCO_2$/yr from 2025–2070. The constraint generates a carbon price trajectory that begins at 181 USD/tCO_2 in 2025 and rises sharply to 1428 USD/tCO_2 by 2070. Under this pathway, emissions stabilise at 170–220 $MtCO_2$/yr, in contrast to the unconstrained baseline which increases to 1320 $MtCO_2$/yr by 2070. The model responds primarily through rapid expansion of renewables, large-scale electrification, and exceptionally high deployment of CCS, peaking at 195.6 $MtCO_2$/yr. Total investment requirements nearly double, reaching 69.4 billion USD/yr by 2070. While the scenario provides insight into system behaviour under stringent carbon limits, its feasibility is low: the required investment approaches 20% of Pakistan's 2023 GDP (338 billion USD), and the scale of CCS deployment exceeds plausible national capacity.

1. Introduction

Pakistan's energy system is expanding rapidly to meet rising demand, yet this growth also drives significant increases in greenhouse gas (GHG) emissions. Understanding how the system would respond under strict climate constraints is therefore crucial for long-term planning. Energy system models such as MESSAGEix allow structured analysis of these transitions by representing technology choices, resource use, and system costs over time.

The baseline MESSAGEix-Pakistan scenario reflects a least-cost pathway with no climate policy, allowing emissions to rise unconstrained. To explore a contrasting low-emission trajectory, this study imposes a cumulative CO_2 budget on the baseline model and solves the constrained system using GAMS. The emissions cap generates a carbon price trajectory (the shadow price of CO_2) which drives fuel switching, technology substitution, and changes in investment decisions.

By comparing the unconstrained baseline with the constrained pathway, the analysis highlights how Pakistan's electricity mix, technology deployment, and emissions evolve under a tight carbon budget. Python-based exploratory data analysis is used to interpret these results and examine the structural adjustments required to achieve deep decarbonization.

2. Methods

A low emission pathway was constructed and solved using MESSAGE-ix Pakistan, developed by the Centre of Water Informatics and Technology at LUMS, and its outputs are extensively analysed using extensive exploratory data analysis with Python, using libraries such as `matplotlib` and `seaborn`.

To generate the low-emission pathway, a cumulative CO_2 emissions cap (55 Mt C or 201 Mt CO_2) is imposed on top of the baseline MESSAGEix-Pakistan model and solved using GAMS which gives a carbon price trajectory as a constraint. The baseline scenario itself contains no carbon price or regulatory limits, so emissions are unconstrained and the marginal cost of emitting CO_2 (i.e., the shadow price of the emissions constraint) is equal to zero. This carbon price was applied as an active constraint in the energy system, influencing technology choice, fuel switching, and investment decisions. The resulting solution forms the low-emission pathway, which mirrors the same baseline drivers but forces the system to remain within the emissions budget by adjusting the energy mix, deploying abatement technologies, or reducing fossil fuel use. The difference between the baseline (no constraint, zero carbon price) and the constrained solution (positive, rising carbon price) represents the system's marginal cost of decarbonization under the imposed target.

3. Results

3.1. Carbon Price

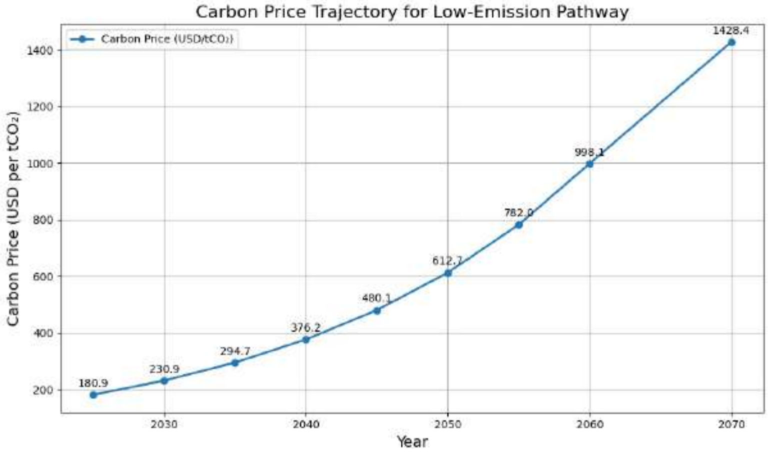

Figure 1: Carbon Price tragectory

Figure 1 illustrates the carbon price (shadow price of the emissions constraint) resulting from the imposed cumulative CO_2 emissions. The carbon price starts at 181 USD/tCO_2 in 2025 and rises sharply throughout the planning horizon, surpassing 998 USD/tCO_2 by 2060 and reaching 1428 USD/tCO_2 by 2070. This steep increase indicates that early, relatively inexpensive abatement options—such as fuel switching from coal to gas or modest renewable expansion are exhausted quickly. As the emissions cap tightens, the energy system must rely on increasingly costly measures, including large-scale deployment of renewables, enhanced electrification, and displacement of fossil generation. The rising shadow price therefore reflects the escalating marginal cost of maintaining compliance with the emissions cap as the system approaches deep decarbonization.

3.2. Emissions Trajectory

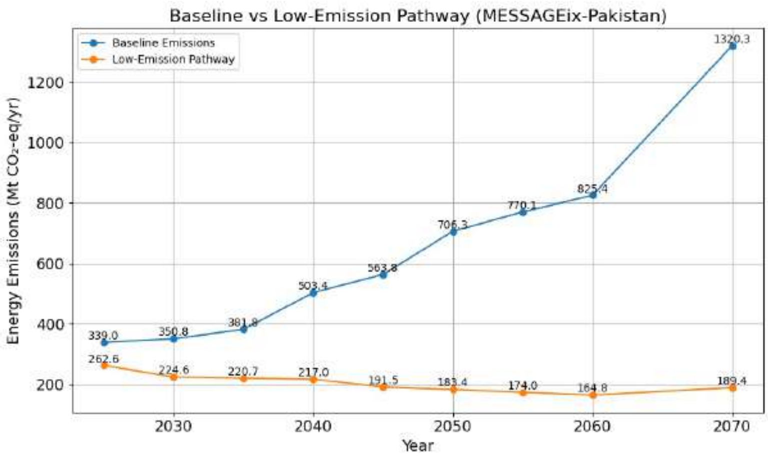

Figure 2: Total Emissions Comparison: Baseline vs Low Emission Pathway (2025–2070)

Figure 2 shows that baseline emissions increase steadily from 339.0 MtCO_2 in 2025 to 1320.3 MtCO_2 by 2070, reflecting unconstrained fossil fuel growth. In contrast, the low-emission pathway reduces emissions from 262.6 MtCO_2 in 2025 to 164.8 MtCO_2 in 2060, followed by a slight rise to 189.4 MtCO_2 in 2070. As a result, emissions in 2070 under the baseline scenario are more than seven times higher than those in the constrained pathway.

3.3. Secondary Energy Transformation

The imposition of the carbon constraint compels a fundamental reorganization of the secondary energy supply. The system shifts from a fossil-fuel-dominated mix to one driven by electrification and clean synthetic fuels, necessitating a significantly larger gross energy supply to satisfy demand.

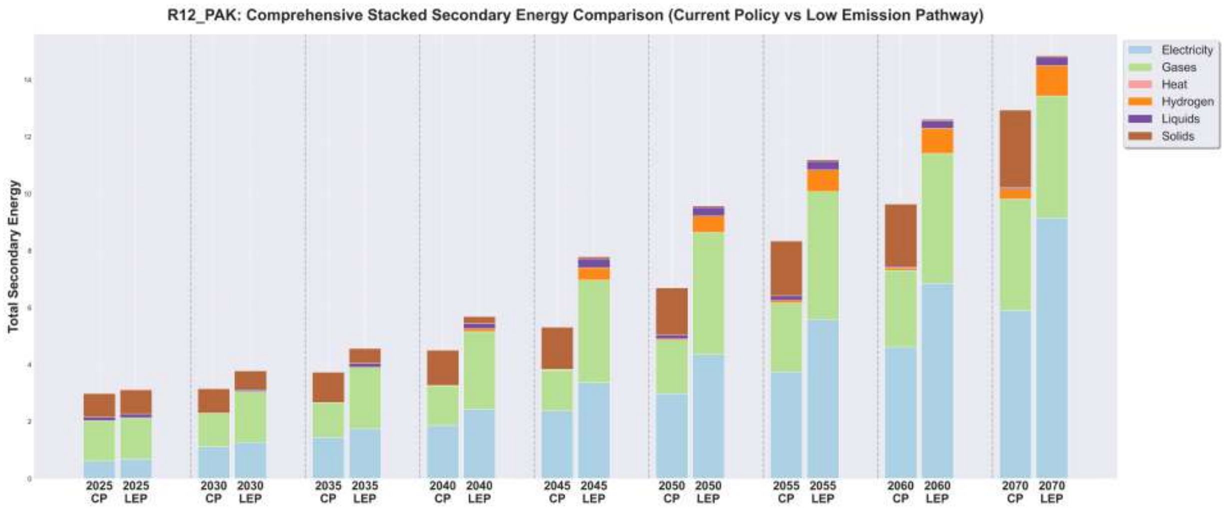

Figure 3: Total Secondary Energy Supply Volume (2025–2070): Current Policy vs Low Emission Pathway. The constrained pathway requires higher gross supply due to conversion losses.

3.3.1. Supply Volume and Conversion Burden

As shown in Figure 3, the Low Emission Pathway (LEP) is characterized by a "conversion burden", a requirement to generate more gross energy to meet the same or lower final demand. By 2070, the total secondary energy supply in the LEP reaches 14.9 EJ/yr, approximately 15% higher than the Current Policy baseline of 12.9 EJ/yr. This surplus of 2.0 EJ/yr compensates for the thermodynamic losses inherent in converting primary renewable energy into secondary carriers like electricity and hydrogen.

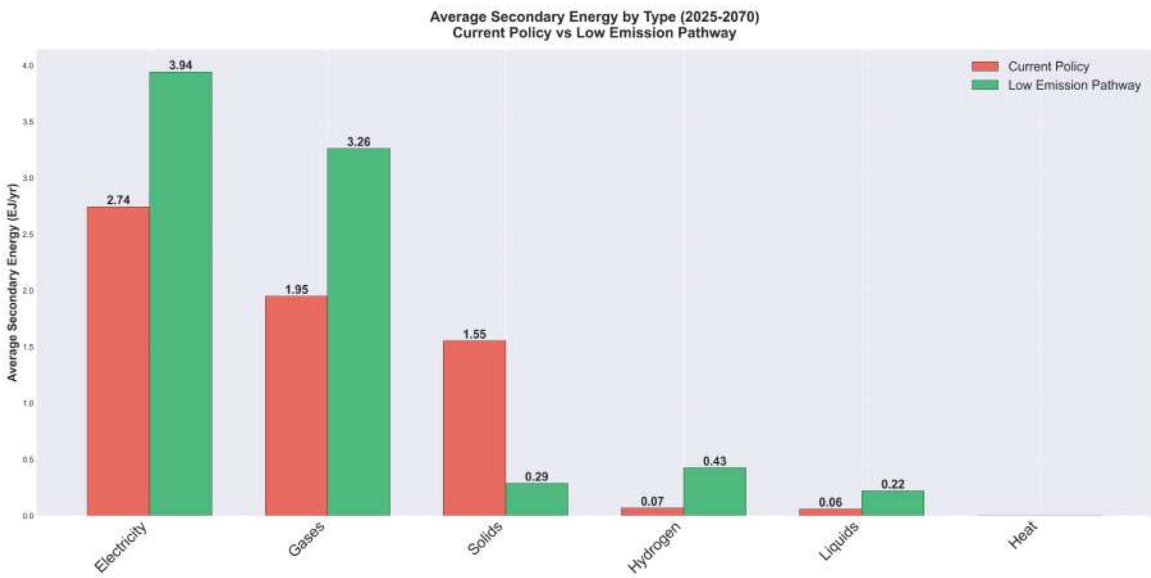

Figure 4: Average Secondary Energy Mix by Type (2025–2070).

3.3.2. Structural Shift in Energy Carriers

The composition of this supply undergoes a radical transformation, as illustrated in Figure 4:

- **Electrification (The Dominant Carrier):** Electricity supply scales massively to drive the decarbonization of end-use sectors. By 2070, electricity supply in the LEP reaches 9.15 EJ/yr, compared to only 5.90

EJ/yr in the baseline. This expansion supports the widespread adoption of electric vehicles and heat pumps.

- **Phase-out of Solids:** The most distinct divergence occurs in solid fuels (coal and coke). Under the Current Policy, solids supply grows to 2.72 EJ/yr by 2070. In the Low Emission Pathway, solids are virtually eliminated, falling to just 0.05 EJ/yr by 2070, effectively removing coal from the industrial and power sectors.
- **The Hydrogen Economy:** To address hard-to-abate sectors, the LEP necessitates the creation of a hydrogen economy. Hydrogen supply rises to 1.07 EJ/yr by 2070, a three-fold increase over the baseline's 0.35 EJ/yr.
- **Resilient Gas Supply:** Gas supply remains critical, reaching 4.29 EJ/yr in 2070 (higher than the baseline's 3.92 EJ/yr). This persistence, despite the carbon cap, reflects the system's reliance on gases for peak power flexibility and high-heat industry, likely utilizing lower-carbon gas blends or CCS-abated natural gas where permitted.

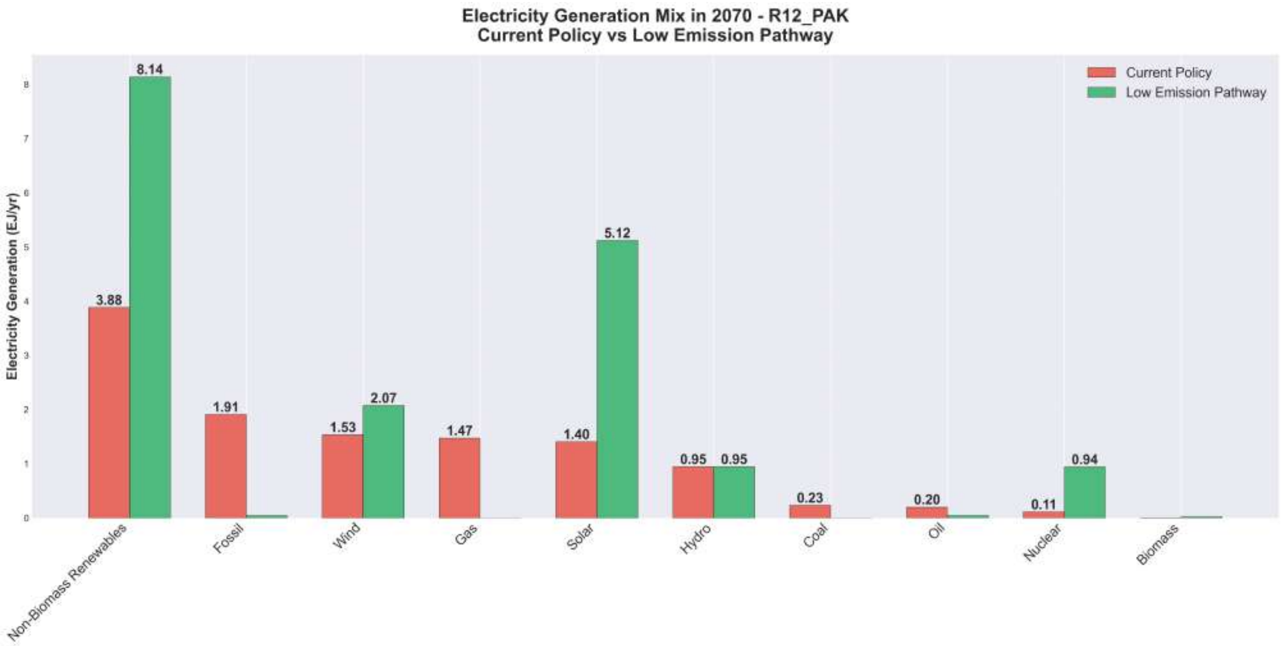

Figure 5: Electricity Generation Mix by Scenario in 2070. The Low Emission Pathway (LEP) achieves near-total decarbonization through a reliance on non-biomass renewables.

3.3.3. The Zero-Carbon Power Mix

The ambitious electrification target is underpinned by a profound structural shift in the power generation mix (Figure 5). By 2070, the Low Emission Pathway achieves near-total decarbonization:

- **Dominance of Renewables:** The share of Non-Biomass Renewables (Solar and Wind) escalates to 89% of the total generation mix in the LEP (8.14 EJ/yr), compared to only 66% (3.88 EJ/yr) in the Current Policy baseline. This is the primary driver of emissions reduction.
- **Solar and Wind Leadership:** Specifically, Solar generation reaches 5.12 EJ/yr, and Wind reaches 2.07 EJ/yr in the LEP, accounting for 79% of the total electricity generated. This massive deployment requires significant investment in grid flexibility and storage capacity.
- **Fossil Fuel Phase-out:** The use of fossil fuels for electricity generation is drastically cut. By 2070, Fossil generation collapses to only 0.04 EJ/yr in the LEP (down from 1.91 EJ/yr in the baseline), representing a 98% reduction. Critically, Coal power is completely eliminated (0 EJ/yr) in the LEP by 2070, compared to 0.23 EJ/yr in the Current Policy.
- **Nuclear's Role:** Nuclear power provides a firm, low-carbon baseload, increasing its contribution to 0.94 EJ/yr in the LEP, significantly higher than the 0.11 EJ/yr in the baseline, illustrating its role in system stability alongside variable renewables.

3.4. Investment Requirements and Capital Allocation

The structural transformation of the energy system under the Low Emission Pathway (LEP) necessitates a massive mobilization of capital, shifting investment focus from fossil fuel extraction to renewable generation and grid infrastructure.

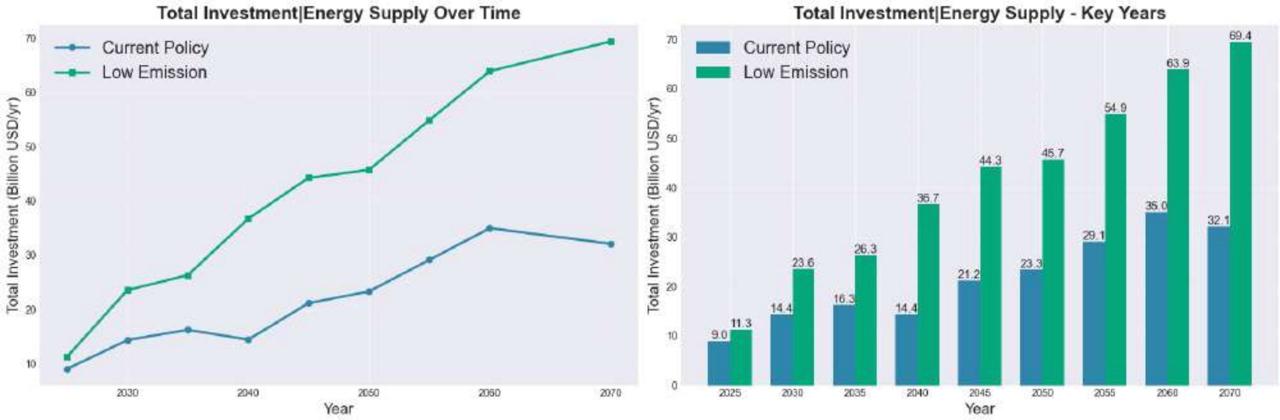

Figure 6: Annual Energy Supply Investment (2025–2070): The Low Emission Pathway requires a steep acceleration in capital expenditure to finance the transition.

3.4.1. Total Investment Gap

As illustrated in Figure 6, the annual investment requirement for the LEP diverges sharply from the baseline. By 2070, the annual investment in the constrained scenario reaches $69.4 billion, more than double the Current Policy's $32.1 billion. This represents a substantial front-loaded capital expenditure, with cumulative additional investment exceeding $400 billion over the analysis period.

3.4.2. Sectoral Capital Allocation

The data reveals a decisive shift in where this capital is deployed, driven by the need to support the 9.15 EJ/yr electricity supply:

- **Electricity Generation Dominance:** The power sector consumes the vast majority of investment. By 2070, annual investment in electricity supply reaches $62.4 billion in the LEP, compared to $23.5 billion in the baseline.
- **Renewable Energy Boom:** Within the power sector, capital is reallocated to Non-Biomass Renewables (Solar and Wind). Investment in these technologies surges to $19.7 billion/yr by 2070 in the low-emission scenario, a nearly 20-fold increase over the baseline's $1.1 billion/yr. This financing underpins the massive capacity additions required for solar PV and wind.
- **Grid Infrastructure (T&D):** To integrate this variable renewable energy, investment in Electricity Transmission and Distribution (T&D) scales significantly, reaching $26.2 billion/yr by 2070 (up from $18.3 billion in the baseline). This confirms that grid modernization is a primary cost driver of the transition.
- **Hydrogen Infrastructure:** Investment in hydrogen supply peaks mid-century (reaching $3.2 billion in 2045) to establish the initial infrastructure before stabilizing at $1.4 billion/yr by 2070, reflecting the upfront cost of building a new energy carrier system.

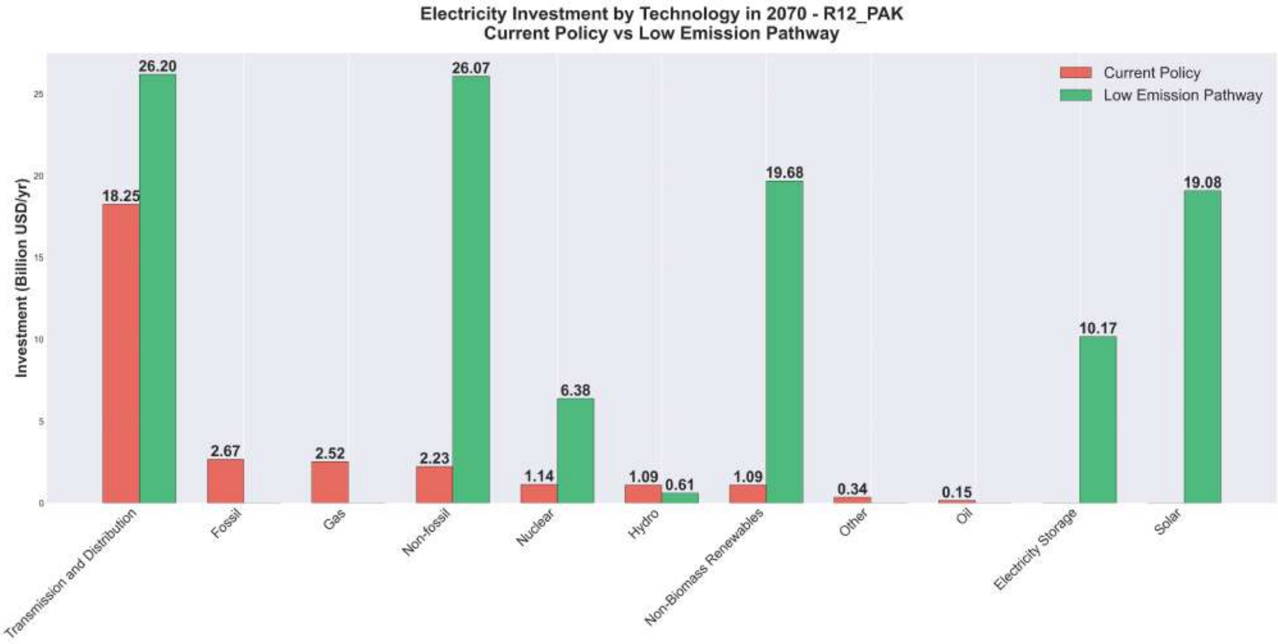

Figure 7: Electricity Supply Investment Breakdown in 2070. Note the dramatic shift from fossil fuels to renewables and T&D infrastructure in the Low Emission Pathway (LEP).

3.4.3. The Electrification Investment Focus

A deeper look at the electricity supply investments in 2070 (Figure 7) clearly illustrates the strategic capital shift:

- **Transmission and Distribution (T&D) as the Largest Share:** Infrastructure investment is paramount. The single largest category in the LEP is T&D at $26.2 billion/yr, representing 42% of total electricity supply investment. This high allocation is essential for connecting remote renewable energy sources and managing the stability of the high-VRE grid. In contrast, T&D is only 78% of the baseline's smaller total ($18.3 billion/yr).
- **Renewable Generation and Storage:** Investment in Non-Biomass Renewables and Electricity Storage accounts for $29.85 billion/yr combined (19.68 + 10.17), or 48% of the total electricity investment. This compares starkly to the baseline's much smaller combined investment of only $1.1 billion/yr into renewables and zero into storage, confirming the massive commitment to variable renewable energy sources.
- **Nuclear Capacity Investment:** Nuclear power sees a significant, sustained commitment, reaching $6.38 billion/yr in the LEP compared to only $1.14 billion/yr in the baseline. This capital allocation secures non-intermittent, low-carbon baseload power.
- **Fossil Disinvestment:** The transformation is confirmed by the complete cessation of investment into fossil fuel-based electricity generation (Coal, Gas, Oil) by 2070 in the LEP, compared to a baseline annual spend of $2.67 billion/yr into Fossil generation.

3.4.4. Fossil Disinvestment

Conversely, the LEP triggers a divestment from fossil fuel supply chains. Investment in fossil fuel extraction declines to near zero by 2070 in the constrained pathway, whereas it remains a multi-billion dollar expenditure in the Current Policy scenario. This reallocation of capital from extraction to generation and networks is the defining financial characteristic of the transition.

3.5. Final Energy

Total final energy demand differs modestly (12.2 EJ/yr vs 12.8 EJ/yr in 2070), but the carrier composition shifts dramatically. Electricity dominates final energy demand, increasing its share to 52% (more than doubling). Hydrogen production scales 20-fold, reaching 11.5 Mt H_2/yr by 2070, primarily for hard-to-abate industrial and transport sectors. This transformation is driven by the deployment of electric vehicles, heat pumps, and industrial electric boilers.

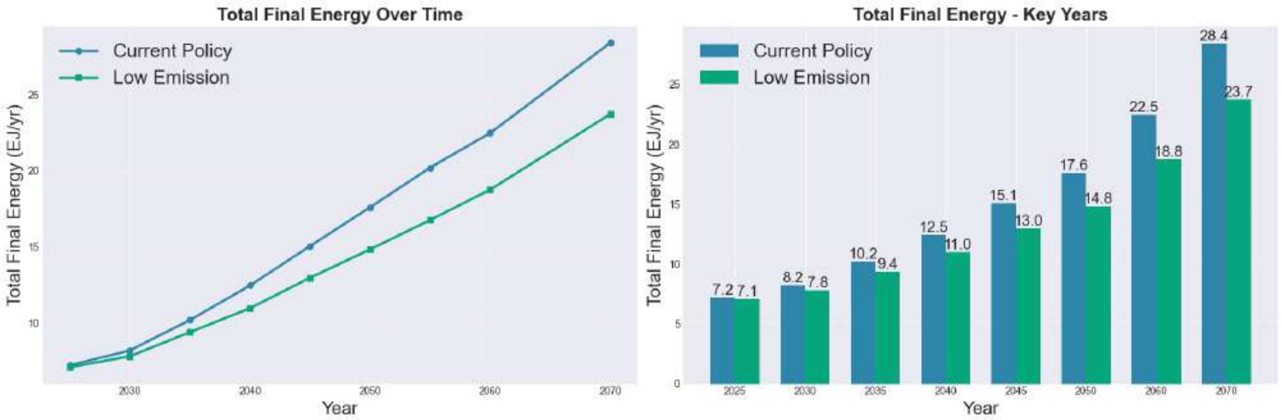

Figure 8: Total Final Energy Demand Over Time by Scenario (2025–2070). The LEP results in lower total demand due to efficiency gains from electrification.

3.5.1. Sectoral Demand Dynamics

The Low Emission Pathway (LEP) leads to an overall 6.6% reduction in total final energy demand by 2070 compared to the Current Policy (11.3 EJ/yr vs. 12.8 EJ/yr), primarily due to efficiency gains from end-use electrification (e.g., replacing combustion engines with EVs).

- **Industry Dominance:** The industrial sector remains the largest consumer in both scenarios, but its share slightly contracts in the LEP (50% vs 44.6% of total demand), driven by deep decarbonization and efficiency measures.
- **Transportation Transformation:** Transportation sees a near-zero energy change between scenarios, but the source mix shifts entirely, moving away from liquids toward electricity and hydrogen. This shift is enabled by the superior efficiency of electric motors.
- **Residential & Commercial Growth:** This sector remains a critical area of demand growth, with its share increasing slightly under the LEP. The major transition here is the direct switch from natural gas and liquids to electricity for heating and cooling.

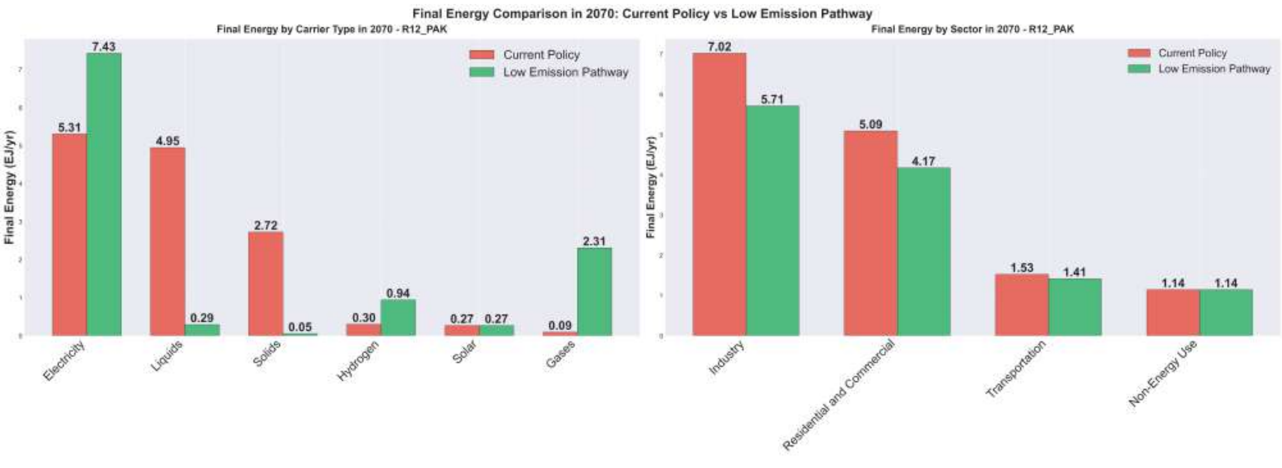

Figure 9: Final Energy Consumption by Carrier (Left) and Sector (Right) in 2070.

3.5.2. Carrier Composition Transformation

The carrier mix, as shown in Figure 9, is the most striking difference between the two scenarios, illustrating the required deep decarbonization of end-uses.

- **Electrification Surge:** Electricity becomes the dominant energy carrier, increasing from 41% (5.31 EJ/yr) in the Current Policy to 66% (7.43 EJ/yr) of final energy consumption in the LEP by 2070. This massive increase underpins all decarbonization efforts across the economy.

- **Fossil Fuel Phase-out:** The use of Liquids (petroleum products) declines by over 94%, falling from 4.95 EJ/yr in the baseline to just 0.29 EJ/yr in the LEP. The use of Solids (mainly coal) is also virtually eliminated. This change reflects the near-complete market penetration of electric vehicles and the switch to electric/hydrogen-based industrial processes.
- **Scaling Hydrogen and Gases:**
  1. **Hydrogen (H_2):** Investment successfully scales hydrogen use three-fold, from 0.30 EJ/yr to 0.94 EJ/yr (equivalent to 11.5 Mt H_2/yr). This energy carrier is strategically deployed in areas where direct electrification is difficult or impractical, notably in specific industrial processes and long-haul transport.
  2. **Gases:** Interestingly, the use of gases (likely a mix of natural gas and bio/synthetic gas) sees a substantial increase in the LEP compared to the CurPol, rising from 0.09 EJ/yr to 2.31 EJ/yr in 2070. This suggests that low-carbon gases play a crucial role, particularly in industrial sectors, for heat and feedstock purposes.

3.6. Total Carbon Capture & Storage Deployment and Source Breakdown

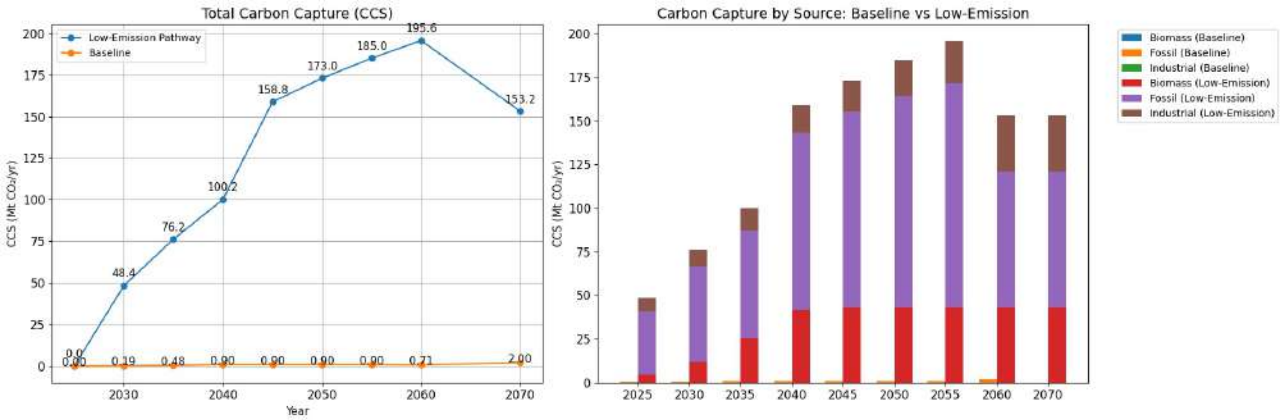

Figure 10: Carbon Capture & Storage Over time

Total carbon capture increases sharply under the low-emission pathway, rising from 0.0 $MtCO_2$/yr in 2025 to a peak of 195.6 $MtCO_2$/yr in 2060, before declining to 153.2 $MtCO_2$/yr in 2070 (Figure 10). In contrast, CCS deployment in the baseline scenario remains negligible throughout the modelling horizon, staying below 2 $MtCO_2$/yr.

Figure 10 shows that under the low-emission pathway, most CCS is applied to fossil-based processes, increasing from 40.0 $MtCO_2$/yr in 2025 to 172.0 $MtCO_2$/yr in 2055, before falling to 130.0 $MtCO_2$/yr in 2070. Biomass-based CCS grows from 5.0 $MtCO_2$/yr in 2025 to 40.0 $MtCO_2$/yr by 2055–2070, while industrial CCS rises from 8.0 $MtCO_2$/yr in 2025 to 36.0 $MtCO_2$/yr in 2070. Baseline CCS for all three sources remains close to zero.

4. Discussion

The low-emission pathway demonstrates how strongly the energy system must adjust when a cumulative emissions cap is imposed. The resulting carbon price rises sharply from \$180.9/tCO_2 in 2025 to over \$1400/tCO_2 by 2070, indicating that progressively more expensive abatement options are required as the system approaches the emissions limit. In MESSAGE-ix, such a steep shadow price reflects the growing marginal cost of reducing an additional ton of CO_2 under tight constraints.

A clear divergence emerges between the baseline and constrained pathways. Baseline emissions increase from 339 $MtCO_2$ in 2025 to 1320 $MtCO_2$ in 2070, whereas the low-emission pathway reduces emissions to 183 $MtCO_2$ by 2050 and stabilises around 170–190 $MtCO_2$ thereafter. The difference reflects the influence of the carbon budget, which forces the system to switch fuels, adopt cleaner technologies, and deploy large-scale abatement.

Emissions for 2025 differ between the two scenarios because the cumulative cap applies from the first model year onward. MESSAGE-ix therefore performs "early abatement", lowering emissions in 2025 (262.6 $MtCO_2$) to reduce the long-term cost of complying with the carbon budget. The baseline, which lacks any regulatory constraint or carbon price, simply follows the least-cost, unconstrained trajectory.

Structural Energy System Transformation

The structural transformation imposed by the binding emissions cap is reflected profoundly across the entire energy supply chain:

Secondary Energy and the Conversion Burden: In the secondary energy sector, meeting the carbon budget requires the system to absorb a "conversion burden", a 15% increase in gross energy supply by 2070 compared to the baseline. This surplus energy generation compensates for the thermodynamic losses inherent in converting primary energy (e.g., solar, wind) into high-quality secondary carriers like electricity and hydrogen. Electrification is the principal abatement mechanism, driving a final energy mix where the electricity share surges to 66% by 2070. The paradoxical resilience of gas supply (reaching 4.29 EJ/yr in secondary supply and 2.31 EJ/yr in final consumption) suggests a strategic shift to low-carbon gas use, either through CCS abatement on gas power plants (supporting peak flexibility) or through the deployment of bio/synthetic gas, particularly for high-heat industrial and feedstock demands.

Investment Requirements and Capital Reallocation: Financially, this transition is extremely capital-intensive. The annual investment requirement more than doubles by 2070, reaching $69.4 billion. This represents a massive reallocation of capital, confirmed by the near-complete fossil disinvestment by 2070. The focus is decisively shifted towards the Electricity T&D infrastructure and Non-Biomass Renewables. The large commitment to T&D ($26.2 billion/yr by 2070, or 42% of total electricity investment) is critical. It underscores that grid modernization and managing the stability of a high-VRE system are structural, multi-billion-dollar necessities that ultimately constrain the speed and cost of the transition, not just the cost of renewable generation capacity itself.

Final Energy Demand and Efficiency: The Final Energy analysis shows that the high carbon price successfully stimulates economy-wide efficiency, leading to a 6.6% reduction in total final energy demand by 2070 compared to the unconstrained baseline (11.3 EJ/yr vs. 12.8 EJ/yr). This reduction is a significant co-benefit of the aggressive carbon pricing regime. Furthermore, end-use sectors achieve deep decarbonization by virtually eliminating the use of high-carbon liquids and solids, shifting towards highly efficient electric vehicles and heat pumps.

Carbon capture and storage (CCS) becomes a central mitigation option under the low-emission pathway. Fossil CCS grows rapidly, peaking at 172–196 $MtCO_2$/yr between 2055 and 2060, whereas biomass and industrial CCS remain comparatively small. This concentration occurs because: (i) most emissions originate from fossil combustion, (ii) fossil CCS offers large-scale, continuous capture potential, and (iii) it is often the least-cost way to retain fossil energy under a binding emissions cap. In contrast, CCS use in the baseline remains negligible.

Overall, the results highlight how imposing a cumulative emissions cap fundamentally reshapes the energy system: the model front-loads abatement, dramatically shifts the generation mix, and relies heavily on CCS to maintain feasibility under stringent carbon limits.

5. Conclusions

The low-emission pathway modelled in this study demonstrates that a stringent cumulative CO_2 constraint fundamentally reshapes Pakistan's energy system. The system responds by front-loading abatement, rapidly expanding renewable electricity, electrifying end-use sectors, and deploying large-scale carbon capture and storage (CCS). The shadow carbon price increases from 181 USD/tCO_2 in 2025 to over 1400 USD/tCO_2 by 2070, reflecting the increasing marginal cost of mitigation as the system approaches the emissions limit. Compared to the unconstrained baseline, emissions in 2070 fall by more than 78%, and fossil fuel use in power and industry declines almost entirely.

However, despite the technical feasibility demonstrated within the model, the results reveal significant challenges to real-world implementation. The required annual investment reaches 69.4 billion USD by 2070, more than double the baseline and far above Pakistan's current economic capacity. For context, Pakistan's GDP in 2023 was approximately 337.89 billion USD (World Bank) so sustaining energy-sector investments equivalent to

15–18% of GDP annually is economically unrealistic. Historically, Pakistan's total public development spending has remained below 4% of GDP, highlighting the severe financing gap implied by the low-emission pathway.

Similarly, the rapid scaling of CCS to 150–195 $MtCO_2$/yr exceeds global deployment levels today and would require industrial, regulatory, and geological infrastructure that Pakistan does not yet possess. No large-scale CCS facilities currently operate in the country, and achieving such growth within the modelled timeframe is unlikely without unprecedented foreign investment, technology transfer, and institutional capacity building.

Overall, while the constrained scenario clarifies what the energy system would need to do to meet an extremely tight carbon budget, it also highlights the disconnect between optimized model pathways and practical feasibility. Deep decarbonization in Pakistan will require substantial international climate finance, phased technology development, and more moderate near-term targets aligned with economic and institutional realities. The model therefore serves not as a prescriptive roadmap, but as a boundary case illustrating the magnitude of transformation required under strict carbon limits.

References

[1] World Bank. "GDP (current US$) (NY.GDP.MKTP.CD)." *World Development Indicators*, The World Bank Group, data.worldbank.org/indicator/NY.GDP.MKTP.CD. Accessed 15 Apr. 2025.