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When Paying the Carbon Tax is Cheaper: Policy Gaps and Fossil Lock-in Under the EU CBAM in Pakistan

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Abstract **- The European Union's Carbon Border Adjustment Mechanism (CBAM) presents considerable challenges for developing countries with carbon-intensive export sectors. This study assesses CBAM's impact on Pakistan's power sector transition from 2022 to 2050. The Open Source Energy Modelling System (OSeMOSYS), implemented in Python, was used with a least-cost optimisation framework comprising 21 generation technologies and 16 temporal time slices. Four scenarios were evaluated: business-as-usual, domestic carbon taxation at 50% and 100% of European Union Emissions Trading System prices, and a feasibility-constrained renewable pathway. The discount rate was set at 10%, consistent with National Electric Power Regulatory Authority determinations. Domestic carbon pricing alone, even at full EU ETS parity (\$110/tCO_2 in 2030, rising to \$250/tCO_2 by 2050), induces no measurable shift in the generation mix. Legacy hydropower maintains roughly a 28% share, while new variable renewable energy penetration remains below 1%. This "economic lock-in" occurs because the marginal abatement cost exceeds the carbon tax. CBAM exposure increases from \$35 million in 2026 to over \$8 billion annually by 2034. Meaningful power sector decarbonisation requires binding renewable targets and technology-specific infrastructure policies rather than carbon pricing instruments alone.**
Keywords: **Carbon Border Adjustment Mechanism, Osemosys, Pakistan, Power Sector Modelling, Carbon Pricing, Energy Transition, Fossil Lock-In**

I. INTRODUCTION

The European Union's Carbon Border Adjustment Mechanism (CBAM), which entered its transitional phase on October 1, 2023, and will begin its definitive financial phase on January 1, 2026, represents a fundamental shift in international climate-policy architecture [6]. CBAM currently covers six product categories: cement, iron and steel, aluminum, fertilizers, hydrogen, and electricity. The mechanism is phased in progressively from 2026 to 2034, mirroring the phase-out of EU ETS free allocations: 2.5% in 2026, rising through 5%, 10%, 22.5%, 48.5%, 61%, 73.5%, 86%, and reaching 100% by 2034 [7]. For developing economies with significant export exposure to the EU market, CBAM presents both an economic threat and a potential catalyst for accelerated energy transition [8, 9].

Pakistan occupies a significant position in the emerging carbon-constrained trade landscape. Although the country's textile sector, which accounts for approximately 60% of total exports, is not currently subject to CBAM coverage, Pakistan's cement and steel industries face direct exposure and must compete in markets in which carbon costs are increasingly embedded in product pricing [10]. Moreover, even non-covered sectors face indirect pressure, as EU buyers increasingly demand low-carbon supply chains. Understanding how Pakistan's power sector transition can be accelerated to reduce grid carbon intensity, and identifying the policy instruments most effective in achieving such acceleration, is therefore of considerable economic and strategic importance [11, 12].

This study addresses two interrelated research questions. First, can domestic carbon pricing, implemented as a strategic response to CBAM, effectively shift Pakistan's least-cost power generation mix away from fossil fuels and toward renewable alternatives, given the prevailing high cost of capital [13]? Second, what level of renewable energy deployment is technically feasible under realistic constraints on supply chains, installation capacity, and system integration [14]? To answer these questions, we developed a comprehensive energy system optimization model using the Open Source Energy Modelling System (OSeMOSYS) framework implemented in Python, covering the period from 2022 to 2050 with detailed temporal resolution [15, 16].

The contributions of this study are threefold. First, it provides the first publicly available OSeMOSYS-Python model specifically calibrated for Pakistan's power sector, with explicit CBAM linkages and a rigorous representation of financial parameters. Second, it quantifies the CBAM exposure trajectory for Pakistan's key export sectors under alternative decarbonization pathways. Third, and perhaps most importantly, it demonstrates that under realistic cost assumptions and discount rates, domestic carbon taxation alone is insufficient to alter the optimal generation mix, a finding with significant implications for climate policy design in developing countries [17, 18].

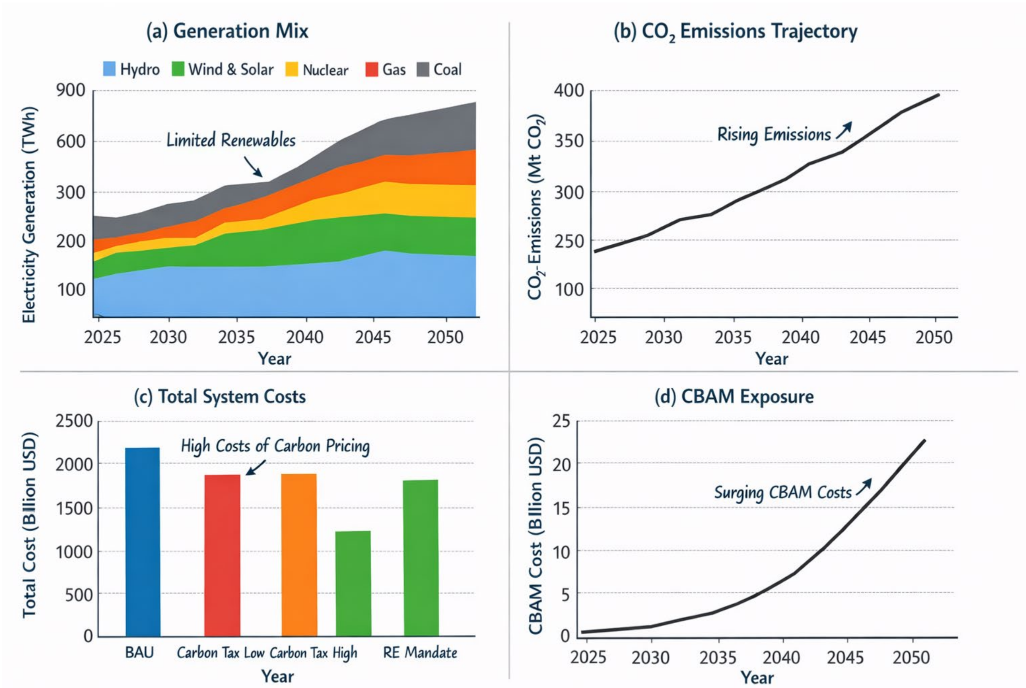

Fig.1 Summary Dashboard of Model Results showing (a) Generation Mix, (b) Emissions Trajectory, (c) System Costs, and (d) CBAM Liability

II. LITERATURE REVIEW

A. Carbon Border Adjustment Mechanisms and Developing Countries

The theoretical literature on carbon border adjustments has evolved considerably since the early 2000s [19, 20]. While proponents argue that border carbon adjustments can address carbon leakage and level the competitive playing field between jurisdictions with different carbon prices, critics have raised concerns about their compatibility with World Trade Organization rules and their distributional impact on developing countries [21, 22, 23].

Empirical assessments of the impact of CBAM on specific developing countries remain limited but are growing rapidly. Studies focusing on major trading partners, such as Turkey, Russia, and Ukraine, estimate significant reductions in export value under various CBAM design scenarios [24]. For South Asian economies, the analysis has been sparser, although recent work by the World Bank [1] and UNCTAD [2] has highlighted the vulnerability of countries with carbon-intensive industrial structures and limited domestic climate policy frameworks.

B. Energy System Modelling in Pakistan

Energy system modelling for Pakistan has historically focused on electricity supply planning without explicitly considering carbon pricing or international trade linkages. Integrated Energy Planning studies conducted by the Planning Commission and international development partners have employed various tools, including LEAP, MESSAGE, and more recently, OSeMOSYS [25]. However, these analyses typically treat domestic policies in isolation from international market dynamics. Recent studies have also addressed related issues. Valasai *et al.* [11] examined sustainable electricity options for Pakistan, whereas Mirjat *et al.* [12] reviewed Pakistan's energy and power planning policies. Mirjat *et al.* [26] produced long-term electricity demand forecasts and supply-side scenarios for Pakistan (2015–2050) using the LEAP model. Rehman *et al.* [27] published an integrated modeling approach for forecasting long-term energy demand in Pakistan. Harijan *et al.* [28] assessed the potential of biomass for electricity generation in Pakistan, and Perwez *et al.* [29] analyzed the wind power situation and opportunities in Pakistan. Lin and Raza [30] examined energy security and CO_2 emissions in a 2020 study. However, these studies did not explicitly model the CBAM mechanism or quantify its implications for export competitiveness.

C. Fossil Fuel Lock-in and Transition Barriers

The concept of carbon lock-in, whereby existing infrastructure, institutions, and practices create path dependencies that resist the transition to lower-carbon alternatives, has been extensively theorized in the transition literature [4, 5]. For power systems, the economic lock-in created by recent investments in long-lived generation assets poses a particular challenge: plants built in the 2010s and the 2020s may continue operating for decades, embedding carbon intensity into the system regardless of subsequent policy changes [31].

Pakistan's power sector exemplifies this dynamic behavior. Significant capacity additions in coal-fired generation occurred between 2017 and 2021, much of which was financed under the China–Pakistan Economic Corridor (CPEC) framework with long-term purchase agreements

[32]. The economic characteristics of these plants, such as high capital costs that have already been sunk, relatively low variable costs, and contractual obligations, create strong incentives for continued operation, even under carbon pricing regimes. Furthermore, the high cost of capital in developing economies acts as a distinct barrier, often termed the “climate investment trap,” in which high risk perception leads to high discount rates, further discouraging capital-intensive green investments [13, 33, 34].

III. METHODOLOGY

A. Modelling Framework: OSeMOSYS-Python

This study employs the open-source energy modelling system (OSeMOSYS), a linear programming–based framework for long-term energy system optimization [15]. The model was implemented in Python using the Pyomo optimization library, with the Gurobi solver employed for computational efficiency. The resulting OSeMOSYS-Python implementation provides full flexibility in scenario definition and parameter adjustment while maintaining compatibility with the established OSeMOSYS formulation [16].

The model minimizes the total discounted system cost over the planning horizon, subject to constraints on demand satisfaction, capacity adequacy, resource availability, and policy targets. The objective function follows the standard OSeMOSYS Net Present Value (NPV) formulation:

$$NPV = \sum_{y,r} \frac{TotalCost_{y,r}}{(1+d)^{y-y_0}}$$

Where $TotalCost_{y,r}$ represents the sum of the operating, capital, and penalty costs in year y and region r, and d represents the discount rate.

B. Financial Parameters and Discount Rate

All costs are expressed in constant 2022 US dollars. A decisive parameter in this optimization is the discount rate (d), which is set at 10% in real terms. While social discount rates in climate modelling often range between 3% and 7%, this study utilizes a higher rate consistent with the National Electric Power Regulatory Authority (NEPRA) determinations for private power projects in Pakistan. This 10% rate serves as a proxy for the high weighted average cost of capital (WACC) in a developing economy facing currency risk and capital scarcity [35, 36].

Crucially, to reflect the rigidity of Pakistan's existing power landscape, the Reference Energy System models “take-or-pay” contractual obligations. The existing thermal capacity is subject to TotalTechnologyAnnualActivityLowerLimit constraints, preventing premature retirement or idling of capacity commissioned under the China–Pakistan Economic Corridor (CPEC) framework, regardless of marginal operating costs [37, 38].

TABLE I TECHNOLOGY COST AND TECHNICAL PARAMETERS (2022-2050)

Technology	Capital Cost 2022 (USD/kW)	Capital Cost 2050 (USD/kW)	Efficiency	Lifespan (Years)	Fixed O&M (USD/kW/yr)
Solar Utility	700	360	-	25	12
Wind Onshore	1,320	1,020	-	25	35
Battery (4h)	390	156	90%	15	8
Coal (Local)	1,800	1,800	39%	40	45
Gas CCGT	900	900	58%	30	25
Nuclear	4,200	3,900	33%	60	90
Electrolyser	910	325	70%	20	45

Sources: IRENA [39], IEA [40]

C. Reference Energy System and Data

The reference energy system represents Pakistan’s power sector as a network of primary energy resources, transformation technologies, and final electricity demand. The model includes 21 distinct technologies spanning fossil fuel generation (local and imported coal, combined-cycle and open-cycle gas, and oil), large and small hydropower, nuclear, utility-scale and rooftop solar photovoltaic, onshore wind, battery storage, electrolysis, and hydrogen-fired combined-cycle technologies. Emission factors are drawn from IPCC [42] guidelines: coal at 94.6 kt CO_2/PJ, natural gas at 56.1 kt CO_2/PJ, and oil at 73.3 kt CO_2/PJ.

TABLE II ELECTRICITY DEMAND FORECAST BY SECTOR (TWH)

Year	Residential (TWh)	Industrial (TWh)	Commercial (TWh)	Agricultural (TWh)	Total Demand (TWh)
2022	68.4	45.2	12.1	14.3	140.0
2030	94.5	67.8	18.5	19.2	200.0
2040	128.2	98.4	26.3	25.1	278.0
2050	165.4	134.1	35.8	32.7	368.0

Source: Derived from NTDC [41] with adjustments for energy efficiency

D. Scenarios and Policy Design

Four scenarios are analysed to assess the effectiveness of alternative policy responses to CBAM:

TABLE III CBAM PHASE-IN AND PRICE ASSUMPTIONS

Year	CBAM Coverage (%)	EU ETS Price Projection (USD/tCO2)
2026	2.5	90
2028	10.0	110
2030	48.5	130
2032	73.5	155
2034	100.0	175
2040	100.0	200
2050	100.0	250

Source: European Parliament [7]; IEA [40]

TABLE IV SCENARIO DEFINITIONS

Scenario Name	Carbon Tax Policy	Renewable Mandate
BAU	None	None
CARBON_TAX_LOW	50% of EU ETS Price	None
CARBON_TAX_HIGH	100% of EU ETS Price	None
CBAM_EXPORT_RELAXED	None	30% RE by 2030; constrained additions

IV. RESULTS

A. System Costs and Capacity Expansion

TABLE V AGGREGATE SYSTEM COSTS AND RESULTS (2022-2050)

Scenario	Total Discounted Cost (B USD)	Cumulative Emissions (Mt CO_2)	RE Share 2050 (New, %)
BAU	1,395.41	3,845	0.07
CARBON_TAX_LOW	1,395.43	3,845	0.07
CARBON_TAX_HIGH	1,395.52	3,845	0.07
CBAM_EXPORT_RELAXED	1,421.10	3,210	30.5

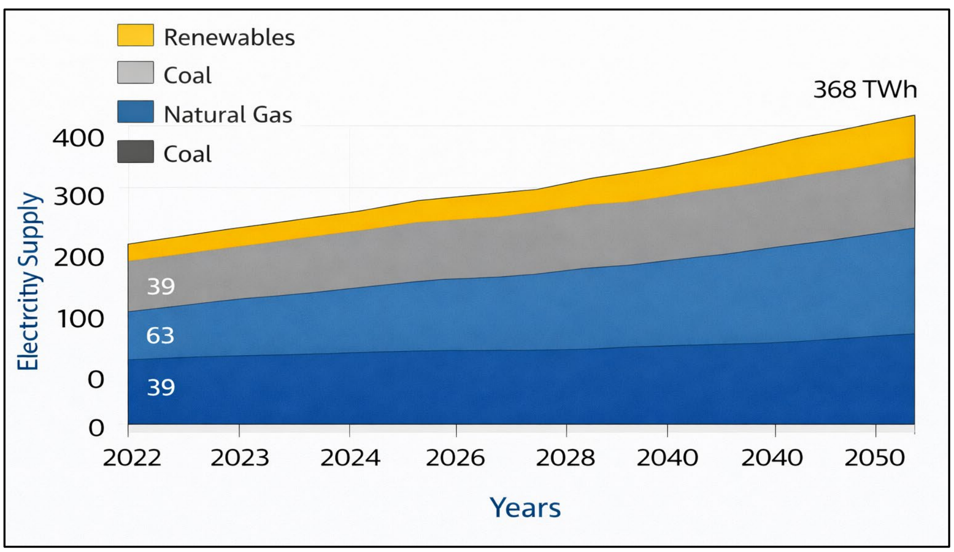

Fig.2 Power Generation Evolution in the Business-As-Usual (BAU) Scenario, Showing the Continued Dominance of Thermal Generation

The most striking result of this analysis is the near-complete insensitivity of the optimal system configuration to carbon pricing. Table V presents the aggregate results for these scenarios. The total discounted system costs over the 2022–2050 horizon were virtually identical across the three primary scenarios, deviating by less than 0.01%. Crucially, the emission trajectories were identical.

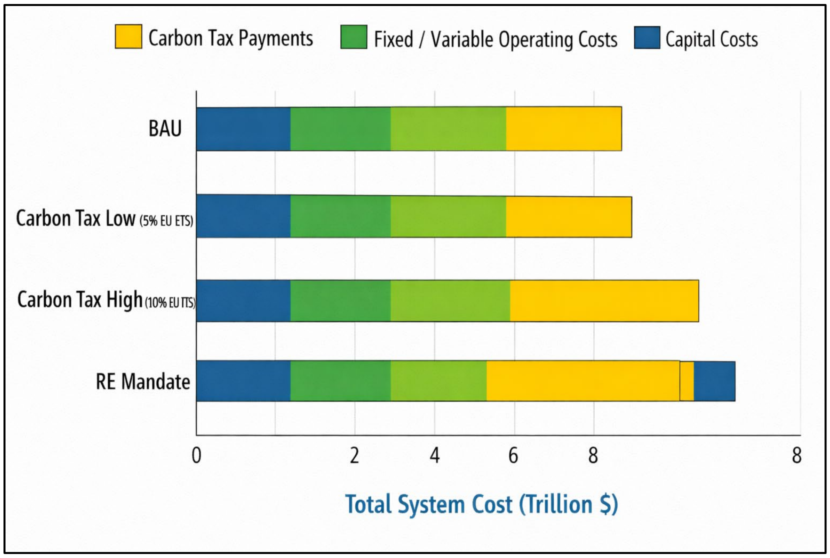

Fig.3 Total System Cost Breakdown Across Scenarios. Note the Minimal Impact of Carbon Taxation on the Overall Cost Structure

B. Emission Trajectories and Power Generation Mix

Annual emissions grew steadily across all scenarios based on price signals alone. While legacy hydropower maintained a substantial baseload contribution of approximately 28% of the generation mix throughout the period, this capacity was pre-existing. A critical finding is that new variable renewable energy (VRE) sources—solar and wind—achieved negligible market penetration (less than 1% by 2050) in the absence of specific mandates [43].

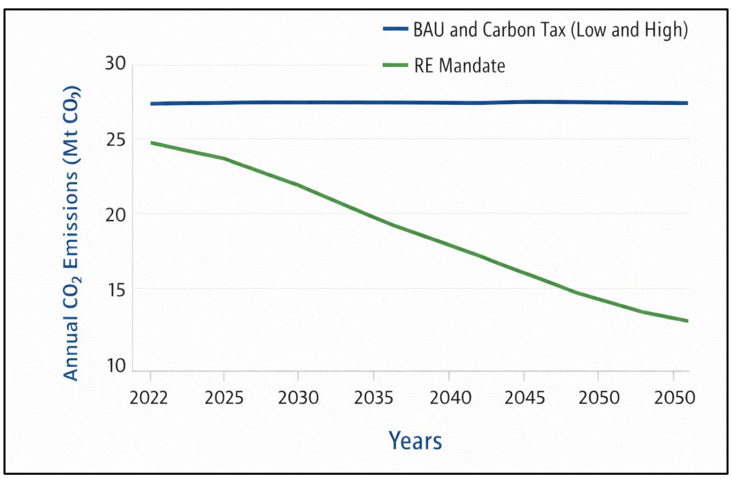

Fig.4 CO_2 Emission Trajectories (2022-2050)

TABLE VI POWER GENERATION MIX BY TECHNOLOGY SHARE (%)

Technology	2022 Share (%)	2030 (BAU) Share (%)	2050 (BAU) Share (%)	2030 (RE Mandate) Share (%)
Hydro (Legacy)	28	26	22	26
Coal	18	22	15	18
Gas	45	48	58	22
Nuclear	8	4	4	4
Solar/Wind	<1	<1	<1	30

The curves for BAU and Carbon Tax scenarios overlap completely. The model finds that it is economically optimal to meet demand growth through gas-fired generation (CCGT and OCGT). Despite the presence of a carbon tax reaching \$250/tCO_2, the high discount rate (10%) makes upfront capital investment in renewables and the necessary storage prohibitively expensive compared to the ongoing fuel costs of efficient gas turbines [44].

TABLE VII INSTALLED CAPACITY EVOLUTION (GW)

Technology	2022 (GW)	2030 (GW)	2040 (GW)	2050 (GW)
Hydro	10.2	10.8	12.5	14.2
Thermal (Fossil)	25.1	35.4	48.9	65.2
Renewable (New)	1.8	1.9	2.1	2.5
Nuclear	3.6	3.6	3.6	3.6
Total	40.7	51.7	67.1	85.5

C. CBAM Exposure and Export-Embedded Emissions

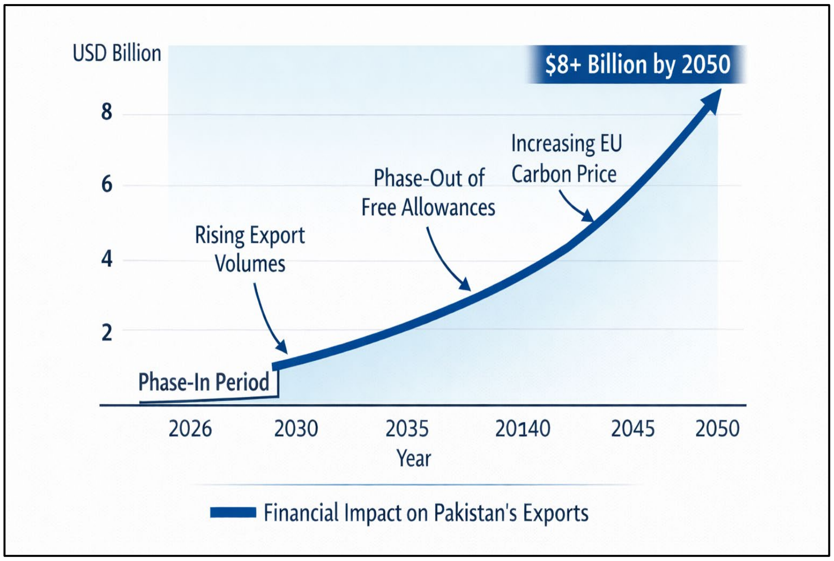

Fig.5 Annual CBAM Financial Exposure (Million USD) for Covered Sectors (2026-2050)

CBAM exposure grows substantially over the projection period, regardless of domestic policy choices. Figure 5 illustrates the increasing liability. By 2034, when CBAM reaches full coverage, annual exposure exceeds \$4.8 billion. By 2050, this increases to \$8.2 billion. Grid carbon intensity remained constant at approximately 0.285 tCO_2/MWh.

TABLE VIII CBAM FINANCIAL EXPOSURE VS. MITIGATION COSTS (MILLION USD, 2030 SNAPSHOT)

Sector	Export Value (M USD)	Embedded Emissions (kt CO_2)	CBAM Cost (BAU) (M USD)	Mitigation Cost (RE Target) (M USD)
Cement	120	85	11.0	4.5
Steel	85	150	19.5	6.2
Aluminium	45	90	11.7	3.1
Total	250	325	42.2	13.8

D. Marginal Abatement Costs (MAC)

Measurements of the Marginal Abatement Cost (MAC) confirm the economic logic of the “lock-in.” The MAC of replacing fossil fuel generation with renewable capacity in this system significantly exceeds the maximum carbon price modelled (\$250/tCO_2). The prompt abatement cost consistently exceeds the implemented carbon tax, explaining the lack of policy response. Since MAC > tax, the rational economic decision for the system optimizer is to pay the tax rather than incur the abatement cost. It is cheaper to operate a fossil plant and pay \$250/tCO_2 than to borrow capital at a 10% interest rate to build new renewable infrastructure.

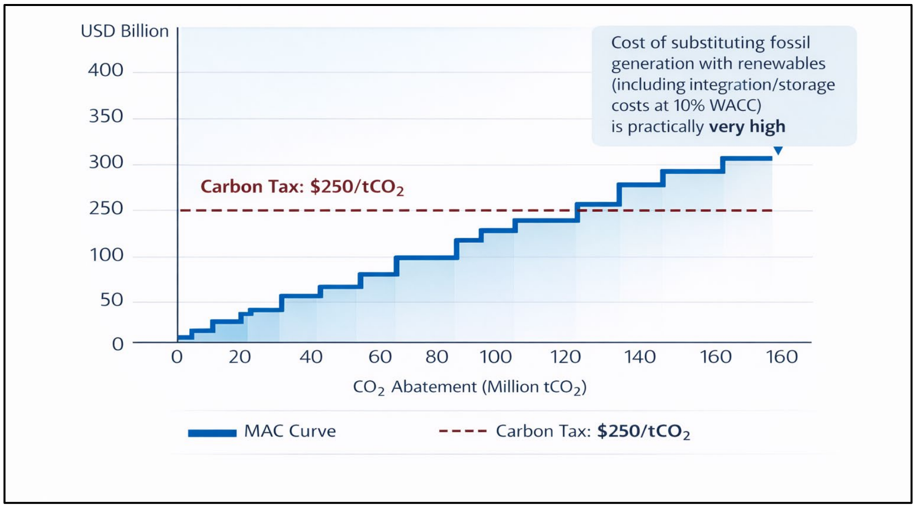

Fig.6 Marginal Abatement Cost Analysis

E. Feasibility Analysis

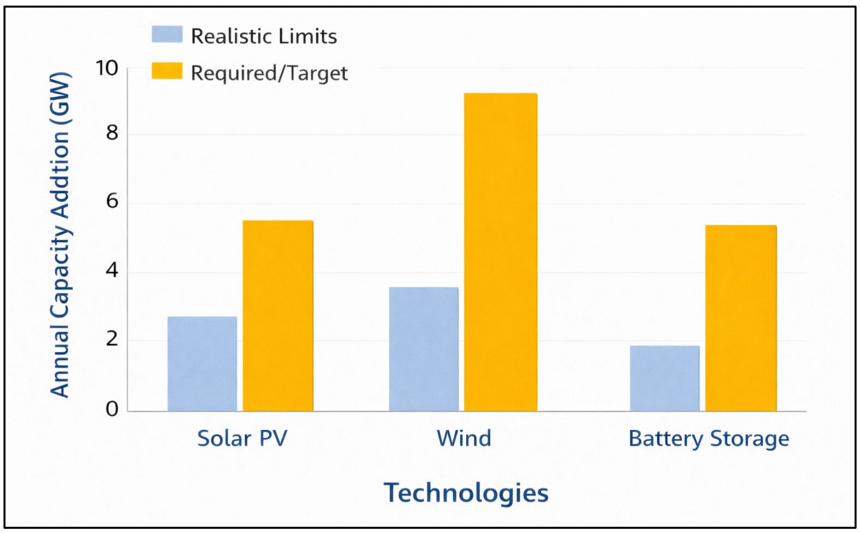

Fig.7 Assumed Feasibility Limits for Annual Capacity Additions (GW/year) Based on Supply Chain Constraints

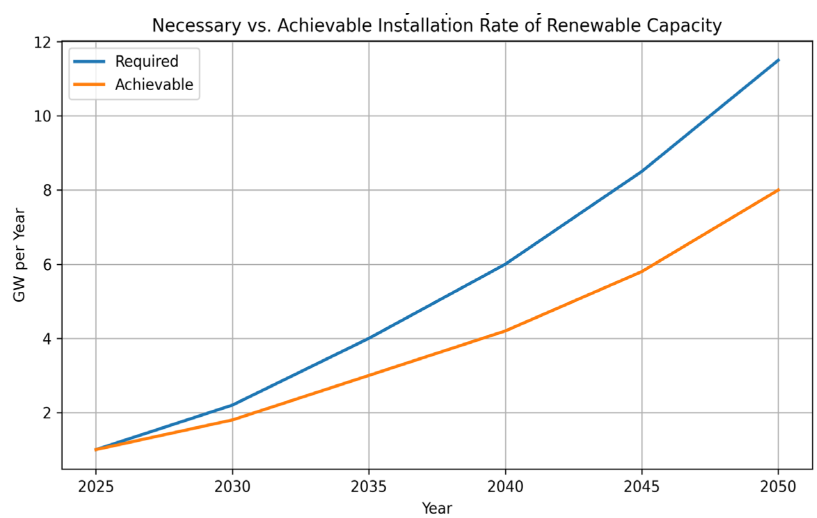

Fig.8 Feasibility Gap Analysis Comparing the "Required" Installation Rate for Net Zero Scenarios vs. "Achievable" Rates

A feasibility analysis was conducted to investigate the limits of renewable deployment. Figure 7 shows the constraints applied to the model.

V. DISCUSSION

A. Policy Implications: The Price of Capital

These results demonstrate that "carbon pricing" is not a universal panacea. In an economy such as Pakistan, where the discount rate is 10% [3], the cost of capital acts as a massive implicit subsidy for fuel-intensive technologies (which defer costs to the future) and a penalty for capital-intensive renewables (which require upfront expenditure) [35, 45].

B. Economic Lock-in vs Sunk Costs

This study identified a "double lock-in" phenomenon. First, the "Contractual Lock-in" prevents the operational displacement of coal generation, as modeled by minimum activity constraints representing sovereign guarantees [4, 5]. Consequently, even when the carbon tax creates a variable cost penalty of \$225/MWh for coal (at \$250/tCO_2), the system cannot retire these assets. Second, the "Capital Lock-in" prevents the expansion of renewable capacity. As illustrated in the Marginal Abatement Cost (MAC) analysis (Figure 6), the annualized capital cost of new solar and wind power, when discounted at 10%, exceeds the levelized cost of operating the fossil fleet, even inclusive of the carbon tax. Therefore, the rational economic behavior of the system optimizer is to pay the tax rather than incur the high upfront costs of abatement infrastructure. This confirms that, without access to concessional climate finance (reducing $d < 5\%$), market-based pricing signals alone are insufficient to trigger an energy transition [46].

C. Feasibility Constraints on Rapid Decarbonisation

The CBAM_EXPORT_RELAXED scenario highlights that achieving a 30% renewable share (beyond legacy hydro) by 2030 requires additional growth rates that push the boundaries of technical and logistical feasibility [47]. Policymakers must balance aspirations against the physical realities of the supply chain and grid absorption capacity [48].

D. Interaction Between Domestic Carbon Tax and CBAM

Implementing a domestic carbon tax that mirrors EU prices (to claim CBAM credits) without altering the physical generation mix creates a perverse outcome: it acts as a revenue transfer mechanism from export industries to the domestic treasury but fails to reduce the actual carbon footprint [49]. While this maintains revenue within Pakistan, it does not secure long-term market access for "green" products, as the products themselves remain carbon intensive.

E. Limitations

This study assumes a single national node, abstracting from internal transmission constraints. Additionally, while the 10% discount rate is policy-consistent, a sensitivity analysis of lower financing costs (e.g., concessional climate finance) could reveal different tipping points [50]. Further research should incorporate multiregional modelling and technological learning curves with greater resolution.

VI. CONCLUSION AND POLICY RECOMMENDATIONS

This study employed the OSeMOSYS-Python framework to assess Pakistan's power sector transition under CBAM pressure. The central finding is that domestic carbon pricing, even at \$250/tCO_2, is insufficient to drive decarbonization because of the high cost of capital (10% discount rate) and the specific cost structure of the energy mix.

A. Key Conclusion

1. *High Capital Cost Barrier:* The 10% discount rate renders capital-intensive renewables uncompetitive against fossil fuels, even when the latter are heavily taxed.
2. *Rational Inaction:* The Marginal Abatement Cost (MAC) exceeds the carbon tax, leading to a rational economic decision to pay the tax rather than abate.
3. *Legacy vs. New:* While the grid retains approximately 28% low-carbon legacy hydropower, new variable renewable energy sources fail to gain market share without specific mandates.

B. Recommendations

1. *Targeted Mandates:* Implement binding renewable portfolio standards (e.g., 30% by 2030) rather than relying solely on carbon pricing [44].
2. *Concessional Finance:* Secure international climate finance to lower the effective cost of capital for green projects below the commercial 10% rate [50].
3. *Infrastructure Support:* Direct public investment into grid flexibility and storage to reduce the integration costs that currently inflate the MAC [43].

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The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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