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RESEARCH REPORT

UNLOCKING SECTOR COUPLING POTENTIAL IN PAKISTAN:

Strategic Pathways for Chinese
B2B Investments in Pakistan

Muhammad Umer, Sarim Zia & Dr Khalid Waleed
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Mailing Address: PO Box 2342, Islamabad, Pakistan.

Telephone: +92 (51) 2278134, 2278136, 2277146, 2270674-76

Fax: +92 (51) 2278135

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Table of Contents

1. Introduction	14
1.1. Paradox of Pakistan's Energy Sector: Capacity Surplus vs. Low Utilization	15
1.2. Objectives.....	18
1.3. Significance	19
2. Methodology.....	22
3. Global Benchmarks: Learning From Success	25
3.1. EU Model: Integrating Intermittent Renewables through Green Hydrogen and EV Grids 25	
3.1.1. Power-to-Gas: Electrolyzers as Dynamic System Buffers.....	26
3.1.2. Power-to-Mobility (PtM): The V2G Ancillary Service Ecosystem	26
3.2. China's Experience with Power-to-Heat for Industrial Clusters	27
3.2.1. Thermodynamic Bottleneck: "Heat-Led" Dispatch and Must-Run Inflexibility ..	27
3.2.2. Technological Decoupling: High-Voltage Electrode Boilers and Thermal Storage	28
3.2.3. Bilateral Market Reforms: Peak-Valley Arbitrage and Direct Purchasing.....	28
4. Assessing the Need for Sector Coupling in Pakistan's Power Sector.....	31
4.1. Uneven Sectoral Distribution of Annual Electricity Consumption	31
4.2. Average Demand Profiling of National Grid Network	33
4.3. Technology-wise Monthly Capacity Utilization Factor (CUF) Analysis	35
4.4. Wind Curtailment and Demand Dynamics: Implications for Sector Coupling	37
5. Proposing Electrification Models for Sector Coupling	41
5.1. Power-to-Transport through Electric Vehicles (PtE)	41
5.1.1. Designing the Base Scenario: High Wind Curtailment Day	41
5.1.2. Estimating EV Demand Profile and Initial Parameters	42
5.1.3. Designing EV Battery Charging Model	44
5.1.4. PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices.....	44
5.1.5. PtE Scenario-2 Results: EV Integration with Fixed Charging Price	46
5.2. Power-to-Industry (PtI)	47
5.2.1. Model Formulation and Operational Constraints	49
5.2.2. Optimization Results and Dynamic Pricing Analysis	51
6. Policy Recommendations and Way Forward	56
6.1. Strengthening Policy and Regulatory Framework for Sector Coupling	56
6.2. Developing Infrastructure and Technological Solutions for Sector Coupling.....	59
6.3. Creating Viable Financial and Market Models for Sector Coupling.....	62
6.4. Building Institutional and Technical Capacity for Sector Coupling	64

7.	Conclusion	67
8.	References	68
9.	ANNEXURE I: GLOBAL SECTOR COUPLING MODELS	71

List of Figures

Figure 1: Sector Coupling: Mechanism, Usage and Economic Architecture.....	15
Figure 2: Net Electricity Generation (GWh) from WPPs in Pakistan (NEPRA, 2025)	16
Figure 3: Net Electricity Generation (GWh) from Solar Plants in Pakistan (NEPRA, 2025).....	17
Figure 4: Overall Methodological Flow of Study	22
Figure 5: EU Power to Gas Sector Coupling Model	26
Figure 6: EU Power to Mobility (PtM) Ecosystem	27
Figure 7: Transformative Outcomes of Chinese Sector Coupling Model	29
Figure 8: Sector-wise average consumption (GWh), FY-2020 to 2025 (NEPRA, 2025)	31
Figure 9: Pakistan's Telecom & IT Services Exports & Imports (Trade Map, 2026)	33
Figure 10: Average Hourly Demand Profile (MW) of National Grid network, FY-2025	34
Figure 11: Average demand profiles for Low, Medium, and High Demand Months, FY-2025....	35
Figure 12: Technology-wise Heat Map (Minimum, Maximum) CUF (%), FY-2025.....	36
Figure 13: Monthly Net Frequency of 0% CUF by Technology, FY-2025	37
Figure 14: Verified Amount on Account of NPMV (NEPRA, 2025)	38
Figure 15: Frequency of Zero Wind Demand Hours vs. Net Wind Demand of 50 MW Wind Project for FY-2025.....	38
Figure 16: 27 th Nov, FY-2025, Wind Demand and Net Demand Excluding Wind (MW) vs. Marginal Price (Rs. /kWh)	39
Figure 17: PtE Base Scenario: 27 th Nov, FY-2025 Marginal Price (Rs. /MWh) vs. Net Demand Profile (MW) (ISMO, 2025)	42
Figure 18: PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices	45
Figure 19: PtE Scenario-2 Results: EV Integration with Fixed Charging Price	46
Figure 20: FY-2025 Monthly Average Profiles of Valley and Non-valley Hours (MW)	48
Figure 21: Average Daily Delta (MW) for 6 th June, FY-2025.....	48
Figure 22: Ptl Scenario-2: 6 th June, FY-2025, Marginal Price (Rs. /MWh) vs. Net Demand Profile (MW) (ISMO, 2025).....	49
Figure 23: Ptl Base Scenario-1 Results: Optimized Industrial Load (MW) vs. Net Grid Demand (MW)	51
Figure 24: Ptl Base Scenario-1 Results: Category-wise distribution of optimized industrial load shares.....	52
Figure 25: Ptl Base Scenario-2 Results: Optimized Industrial Load (MW) vs. Net Grid Demand (MW)	53
Figure 26: Ptl Base Scenario-2 Results: Category-wise distribution of optimized industrial load shares.....	53
Figure 27: Seasonal power demand of neighboring countries of Pakistan (NSB, India, 2022) .	57
Figure 28: Monthly Average Delta (MW) for FY-2025	60
Figure 29: Iran city-wise cooling discharge patterns (kWh) vs. Pakistan's grid demand (MW) on 6 th Jun, FY-2025	61

List of Tables

Table 1: Annual Growth Rate (%) of Electricity Consumption FY-2025 (NEPRA, 2025)	32
Table 2: Charging Availability Factors Estimations	42
Table 3: EV Average Daily Demand and Battery Parameters Calculations.....	43
Table 4: Summary of PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices	45
Table 5: Summary of PtE Scenario-2 Results: EV Integration with Fixed Charging Price	46
Table 6: Input parameters for the optimization process for both Ptl Base Scenarios.....	50
Table 7: Summary of Ptl Base Scenario-1 Results.	52
Table 8: Summary of Ptl Base Scenario-2 Results	53
Table 9: Comparative Analysis of Global Sector Coupling Frameworks	73

List of Abbreviations

ADB	Asian Development Bank
B2B	Business-to-Business
BESS	Battery Energy Storage System
BRI	Belt and Road Initiative
CDB	China Development Bank
CHP	Combined Heat and Power
CMEC	China Machinery Engineering Corporation
CNEEC	China National Electric Equipment Corporation
CNPC	China National Petroleum Corporation
CPEC	China-Pakistan Economic Corridor
CPP	Capacity Purchase Price
CPPA-G	Central Power Purchasing Agency
CTBCM	Competitive Trading Bilateral Contract Market
CUF	Capacity Utilization Factor
DISCOs	Distribution Companies
DoD	Depth of Discharge
DPPAs	Direct Power Purchase Agreements
DRI	Direct Reduced Iron
EDB	Engineering Development Board
EPP	Energy Purchase Price
ERI-NDRC	Energy Research Institute of the National Development and Reform Commission
ESS	Energy Storage Systems
ETS	Emissions Trading System
EU	European Union
EV / EVs	Electric Vehicle / Electric Vehicles
FBR	Federal Board of Revenue
FY	Fiscal Year
GCF	Green Climate Fund
GEF	Global Environment Facility
GENCOs	Generation Companies
GWh	Gigawatt-hour
HVDC	High-Voltage Direct Current
ICBC	Industrial and Commercial Bank of China
IEP	Integrated Energy Plan
IFPs	Independent Flexibility Providers
IGCEP	Indicative Generation Capacity Expansion Plan
IPPs	Independent Power Producers

IRENA	International Renewable Energy Agency
ISMO	Independent System and Market Operator
IT	Information Technology
KE	Karachi Electric
LGCs	Large-scale Generation Certificates
LNG	Liquefied Natural Gas
LSM	Large-Scale Manufacturing
MoCC	Ministry of Climate Change
MoE / MoEP	Ministry of Energy (Power Division)
MoF	Ministry of Finance
MoFA	Ministry of Foreign Affairs
MOFCOM	Ministry of Commerce, Peoples' Republic of China
MoIP	Ministry of Industries and Production
MoPD&SI	Ministry of Planning, Development and Special Initiatives
MW	Megawatt
NDCs	Nationally Determined Contributions
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NEPRA	National Electric Power Regulatory Authority
NGC	National Grid Company
NPMV	Non-Project Missed Volume
OGRA	Oil & Gas Regulatory Authority
$P_{score}(x)$	Performance Score Function for iteration 'x'
PtX	Power-to-X
PEM	Polymer Electrolyte Membrane
PES	Pakistan Economic Survey
PFAN	Private Financing Advisory Network
PPA / PPAs	Power Purchase Agreement / Agreements
PPMC	Power Planning and Monitoring Company
PPPs	Public-Private Partnerships
PSIP	Power Sector Indigenization Plan
PtE	Power-to-EVs
PtG	Power-to-Gas
PtH	Power-to-Heat
PtI	Power-to-Industry
PtM	Power-to-Mobility
PyPSA	Python for Power System Analysis
R&D	Research and Development
RE	Renewable Energy
RED III	Renewable Energy Directive

RFO	Residual Fuel Oil
RGGO	Renewable Gas Guarantees of Origin
RLNG	Re-gasified Liquefied Natural Gas
SBP	State Bank of Pakistan
SGCC	China State Grid Corporation
SCIF	Sector Coupling Investment Facility
SCC	Sector Coupling Cell
SoC	State of Charge
STATCOMs	Static Synchronous Compensators
TES	Thermal Energy Storage
ToU	Time-of-Use
TSEP	Transmission System Expansion Plan
TSOs	Transmission System Operators
UHV	Ultra-High-Voltage
USD	United States Dollar
V2G	Vehicle-to-Grid
VRE	Variable Renewable Energy / Variable Renewable Resources
WB	World Bank
WPPs	Wind Power Plants

Executive Summary

Pakistan's energy sector is currently faced with a structural paradox. With a massive 41-gigawatt (GW) installed generation capacity and a remarkably low national grid utilization rate of approximately 38 per cent, the baseline electricity demand is stagnant that frequently drops below 12 GW during winter months. This oversupply has precipitated a crippling financial crisis driven by rigid "Take-or-Pay" capacity purchase contracts. Under this inflexible legal framework, the government is obligated to pay billions of rupees annually in Capacity Purchase Price (CPP) tariffs for thermal power plants that sit idle for vast portions of the year. Simultaneously, zero-marginal-cost variable renewable energy sources, particularly in the Jhimpir and Gharo southern wind corridors, face forced and frequent curtailment. This immense waste is driven by a convergence of compounding factors: a macroeconomic contraction leading to decreasing overall grid demand, the flight of industrial and residential consumers to off-grid solar alternatives due to exorbitant tariffs, chronic south-to-north transmission bottlenecks, and the recent integration of massive, inflexible coal baseload plants. Since grid dispatchers cannot easily ramp down these newly-added coal units and legacy thermal baseloads without incurring severe operational penalties, the transmission network remains artificially saturated, leaving no capacity to absorb peak nocturnal wind generation.

Consequently, the sector incurs massive financial damages in the form of Non-Project Missed Volume (NPMV), severely threatening the financial viability and return on investment of multi-billion dollar, Chinese-funded wind Independent Power Producers (IPPs) established under the China-Pakistan Economic Corridor (CPEC). To resolve this unsustainable, debt-inducing trajectory, this study introduces sector coupling as a highly pragmatic, demand-side economic intervention. Crucially, this framework provides a direct way forward for stranded Chinese wind plants and other renewable assets, structurally absorbing idle generation and lowering the overall basket price of electricity by escaping the traditional constraints of supply-side grid expansion. To resolve this unsustainable, debt-inducing trajectory, this study introduces sector coupling as a highly pragmatic, demand-side economic intervention. Crucially, this framework provides a direct way forward for stranded Chinese wind plants and other renewable assets, structurally absorbing idle generation and lowering the overall basket price of electricity by escaping the traditional constraints of supply-side grid expansion.

To validate these pathways, the study employs a concise methodology leveraging primary operational data from the National Electric Power Regulatory Authority (NEPRA) and the Independent System and Market Operator (ISMO). Following a comparative benchmarking analysis against the European Union and China, a localized gap analysis was conducted to map seasonal and diurnal demand variations. Linear optimization-based mathematical models were deployed to simulate the grid impacts of Electric Vehicle (EV) integration and industrial load-shifting under various pricing scenarios.

The optimization simulations yielded highly definitive insights into the operational viability of sector coupling, proving mathematically that intelligent demand stimulation can effectively neutralize Pakistan's capacity crisis. Foremost, the Power-to-Transport pathway evaluated the grid-level integration of a national Electric Vehicle (EV) fleet. The empirical results demonstrated unequivocally that highly dynamic, wholesale Time-of-Use (ToU) grid pricing is the absolute prerequisite for sustainable electrification. When exposed to dynamic pricing algorithms, simulated EV charging behaviour flawlessly and automatically shifted towards low-cost, high-supply hours, effectively absorbing surplus generation without requiring new transmission infrastructure. Conversely, the models showed that applying rigid, fixed charging tariffs completely failed to incentivize load shifting. Under fixed pricing, EV charging directly aligned with

traditional evening residential peaks, severely exacerbating existing grid stress, overloading localized distribution networks, and drastically driving up total system generation costs.

Furthermore, the Power-to-Industry simulations identified the transformative macroeconomic potential of shifting continuous, heavy industrial loads to nocturnal valley hours. This intervention was proven to be the most viable structural mechanism for rescuing multi-billion-dollar Chinese wind investments. By actively utilizing curtailed nighttime wind from the southern corridors to power highly energy-intensive, continuous processes specifically the electrolytic production of green ammonia and the generation of industrial steam via electric boilers the grid successfully creates a synthetic, guaranteed demand sink. The models verified that this targeted load shifting directly resolves the Non-Project Missed Volume (NPMV) crisis. It physically absorbs the stranded electrons, dramatically elevates the Capacity Utilization Factors of Chinese Independent Power Producers (IPPs), and translates historically wasted wind into a high-value, exportable industrial commodity. This provides a permanent financial lifeline and a highly profitable, sustainable business model for these stranded assets.

Additionally, the gap analysis and subsequent optimization isolated pronounced daytime demand valleys, particularly during the shoulder and summer months when solar irradiation is at its maximum. The models proved that these midday troughs can be capitalized upon by aligning temperature-flexible commercial loads, such as large-scale cold storage logistics and heavy recycling industries, directly with peak solar feed-in. By shifting these intensive operations to the daytime, the grid effectively captures cheap, abundant solar energy, thereby flattening the "duck curve" and preventing the severe, expensive thermal ramp-up requirements typically experienced during the evening solar drop-off. Ultimately, the interconnected simulation results confirm that by intelligently staggering transport, chemical, and commercial demand across these distinct diurnal valleys, Pakistan can effectively flatten its volatile national load curve, drastically reduce its average generation costs, and establish a technically resilient, 24/7 operational grid.

Transitioning these findings into operational reality requires a profound and immediate overhaul of the country's regulatory, institutional, and financial architecture. The government must first enact a unified sector coupling framework that dismantles bureaucratic silos, aligning the planning cycles of the electricity, industrial, and gas sectors to formalize the integration of clean energy into national economic planning. Unlocking this transition also necessitates empowering "Independent Flexibility Providers" to bid aggregated demand response into a competitive ancillary services market, while legalizing Direct Power Purchase Agreements (DPPAs) to allow stranded renewable generators to sell curtailed power directly to adjacent industrial zones at heavily discounted rates. To address the high upfront capital expenditures required for battery storage and electrolyzers, the study strongly recommends the establishment of a Green Sector Coupling Investment Facility backed by Sovereign Green Sukuk issuances, supplemented by aggressive fiscal incentives such as tax holidays and import duty exemptions. Finally, Pakistan must strategically leverage its bilateral partnerships to move beyond basic generation projects; the next phase of CPEC must focus on the local indigenization of critical smart grid equipment, industrial electric boilers, and energy storage systems to insulate the transition from foreign exchange volatility. By pivoting aggressively away from traditional supply-centric capacity expansion and fully embracing intelligent demand-side optimization, Pakistan can permanently resolve its acute power sector bottlenecks, stabilize its macroeconomic balance of payments, and forge a highly resilient energy economy.

INTRODUCTION



1. Introduction

Sector coupling refers to the strategic interconnection and integration of energy-consuming and producing sectors, predominantly power, heating, cooling, transport, and heavy industry, that operate in silos (Fridgen et al. 2020). For decades, these sectors have been functioning on entirely separate infrastructures and distinct fuel supply chains. The electricity grid primarily relied on dispatchable fossil-fuel generators to match human consumption patterns while transport and industrial sectors relied on the direct, localized combustion of petroleum, coal, and natural gas. At its core, the concept of sector coupling facilitates a profound structural shift in this traditional approach to energy system management. Instead of relying on the conventional load-following paradigm where power generation must constantly and reactively adjust to meet an inflexible baseline demand, sector coupling creates a dynamic, multidirectional network where energy demand can intelligently respond to available supply (Son et al. 2023). This transition is increasingly critical due to the widespread integration of intermittent renewable energy sources, such as solar and wind, which are dependent on weather conditions rather than grid operator dispatch schedules. By breaking down historical infrastructural barriers, energy systems can transform from rigid hierarchies into flexible, responsive ecosystems.

The primary mechanism driving this cross-sectoral integration is the deployment of "Power-to-X" (PtX) technologies. These diverse technological pathways allow surplus electricity, particularly from intermittent renewable sources that might otherwise be wasted during off-peak hours, to be converted and stored in various alternative forms (Brown et al. 2018). By deploying these technologies, the grid effectively captures and utilizes energy that would otherwise be lost to curtailment. This cross-sectoral flow of energy acts as a critical demand-side management tool, maximizing the technical flexibility and overall operational resilience of the broader energy grid (Ramsebner et al. 2021).

Beyond operational flexibility, sector coupling is widely recognized as an essential driver for deep decarbonization and long-term economic efficiency. Though the electricity generation sector has made significant strides in adopting clean energy, the broader climate challenge requires decarbonizing end-use sectors that still rely heavily on direct fossil fuel combustion. By replacing this fossil fuel dependence with clean electricity, sector coupling directly tackles emissions in hard-to-abate industries that are otherwise technologically or economically difficult to electrify through conventional means (Bogdanov et al. 2021). Heavy manufacturing processes, such as steel and cement production, require extremely high-temperature heat that standard electric heaters struggle to provide; however, green hydrogen produced via sector coupling can serve as a viable zero-carbon combustible alternative.

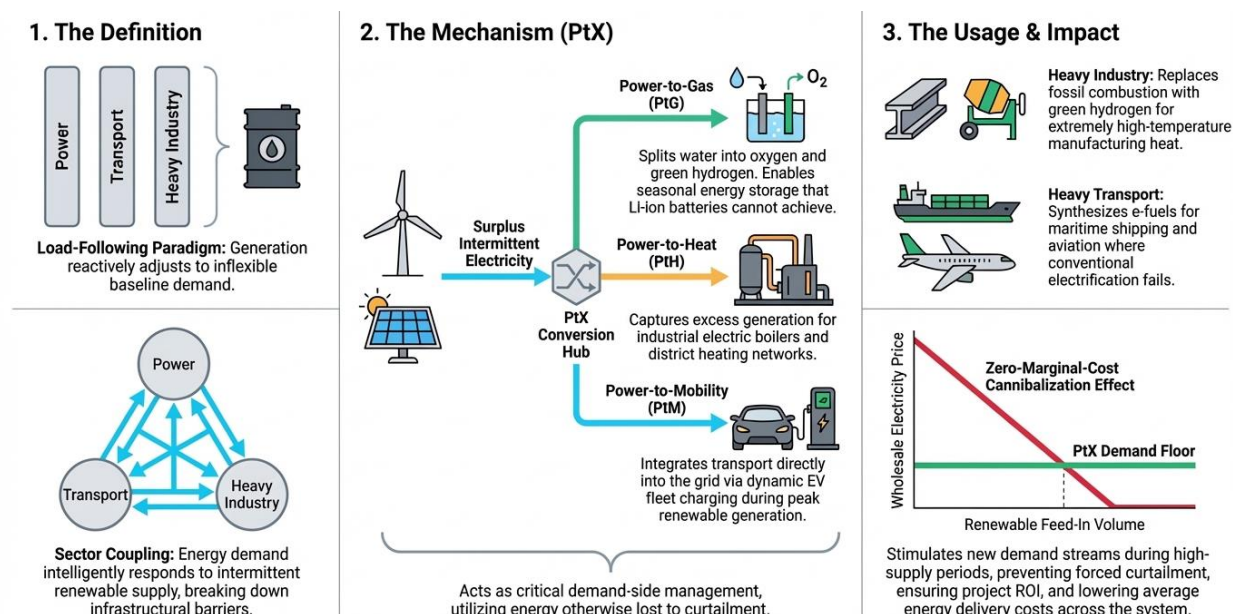


Figure 1: Sector Coupling: Mechanism, Usage and Economic Architecture

Furthermore, establishing these systemic interconnections substantially increases the market value and financial viability of renewable energy installations. In highly saturated renewable energy markets, a phenomenon known as the "cannibalization effect" frequently occurs. When the sun shines brightly or the wind blows strongly across a region, the sudden influx of zero-marginal-cost electricity crashes the wholesale market price, sometimes driving it into negative territory. By actively stimulating new streams of electricity demand during these exact periods of high feed-in and low traditional consumption, sector coupling establishes a critical price floor (Bernath et al. 2021). It effectively prevents the forced curtailment of renewable assets, ensuring that project developers maintain a reliable return on investment and incentivize the further deployment of green infrastructure. Moreover, by spreading the fixed capacity costs of the entire energy system over a much larger volume of consumed units across multiple sectors, the average cost of energy delivery decreases. Ultimately, this comprehensive integration ensures a more cost-efficient transition, reduces reliance on volatile imported fossil fuels, and creates a financially sustainable architecture for future energy landscape.

1.1. Paradox of Pakistan's Energy Sector: Capacity Surplus vs. Low Utilization

While the theoretical framework of sector coupling offers a pathway to optimized grid management, its application is urgently needed in Pakistan. The country's energy sector is currently defined by a severe structural paradox: a massive oversupply of power generation capacity paired with chronically low electricity usage. Today, Pakistan's total installed generation capacity stands at approximately 41 GW, a figure that far outstrips the country's baseline electricity demand. However, this capacity surplus is not a sign of energy security; rather, it has resulted in severe financial distress due to the rigid structure of power purchase agreements (National Electric Power Regulatory Authority [NEPRA] 2025).

The primary driver of this financial burden is the "Take-or-Pay" contract model. Under these agreements, the government is legally obligated to pay Capacity Purchase Price (CPP) tariffs to power producers simply for keeping their plants available, regardless of whether the grid needs or uses their electricity. Since overall demand remains low, these plants sit idle for long periods. During the fiscal year 2024-25, the annual average utilization factor of thermal power plants in the country was a mere 38.19% (NEPRA, 2025). To put this into perspective, as of June 30, 2025, the installed capacity of thermal power plants stood at 26,754 MW, with a dependable

capacity of 24,189 MW (NEPRA, 2025). This reflects a reduction compared to the previous year. On June 30, 2024, the installed and dependable capacities were 32,386 MW and 26,261 MW respectively. the financial damage remains immense because consumers are still paying billions for unutilized thermal power.

This utilization crisis also severely impacts the integration of Renewable Energy (RE). Sources like hydropower, wind, and solar offer the major advantage of zero fuel costs, which lowers the overall Energy Purchase Price (EPP). Since they rely on weather, their power generation is intermittent and uncertain. This natural variability leads to very low operational usage. During FY 2024-25, the actual combined utilization factors for hydropower, wind, and solar power plants were only 39.70%, 23.87%, and 20.13%, respectively (NEPRA, 2025).

Looking closely at wind energy, the total installed capacity stood at 1,838 MW as of June 30, 2025. Despite this substantial footprint, actual generation heavily fluctuates with the weather. For instance, the highest monthly generation from wind plants occurred in June 2025, reaching 522.02 GWh, which accounted for 3.75% of the system's total generation (NEPRA, 2025). In sharp contrast, the lowest generation was recorded in November 2024 at just 98 GWh, making up only 1.20% of total generation (NEPRA, 2025). Overall, the utilization factor for wind remained at 23.87%. Because wind drops unpredictably, the grid must keep expensive thermal plants running as a backup. Consequently, when factoring in the high upfront capital costs, debt servicing, and the cost of maintaining thermal backups, wind power is occasionally supplied to the grid at rates comparable to or even higher than conventional thermal plants (NEPRA, 2025).

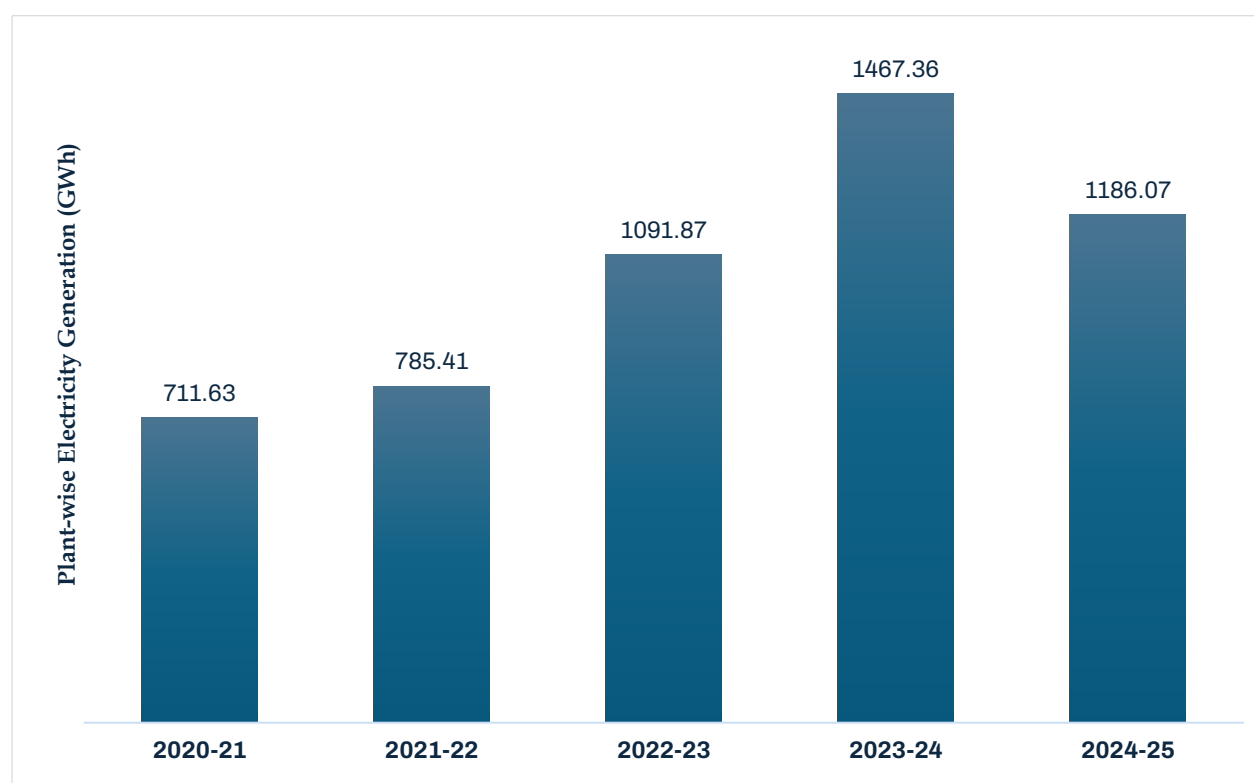


Figure 2: Net Electricity Generation (GWh) from WPPs in Pakistan (NEPRA, 2025)

Solar power faces similar hurdles. As of June 30, 2025, Pakistan had 780 MW of installed solar capacity (NEPRA, 2025). Generation peaked in March 2025 at 140 GWh (contributing 1.39% to the central purchasing agency's portfolio) and hit its lowest in November 2024 at 84 GWh (0.85% of the portfolio) (NEPRA, 2025). Over the entire FY 2024-25, solar power contributed a mere 0.1% to the country's total electricity generation. Notably, some solar Independent Power

Producers (IPPs) are currently supplying electricity to the grid at rates significantly higher than those offered to net-metering household consumers, an inconsistency that complicates policy formulation (NEPRA, 2025).

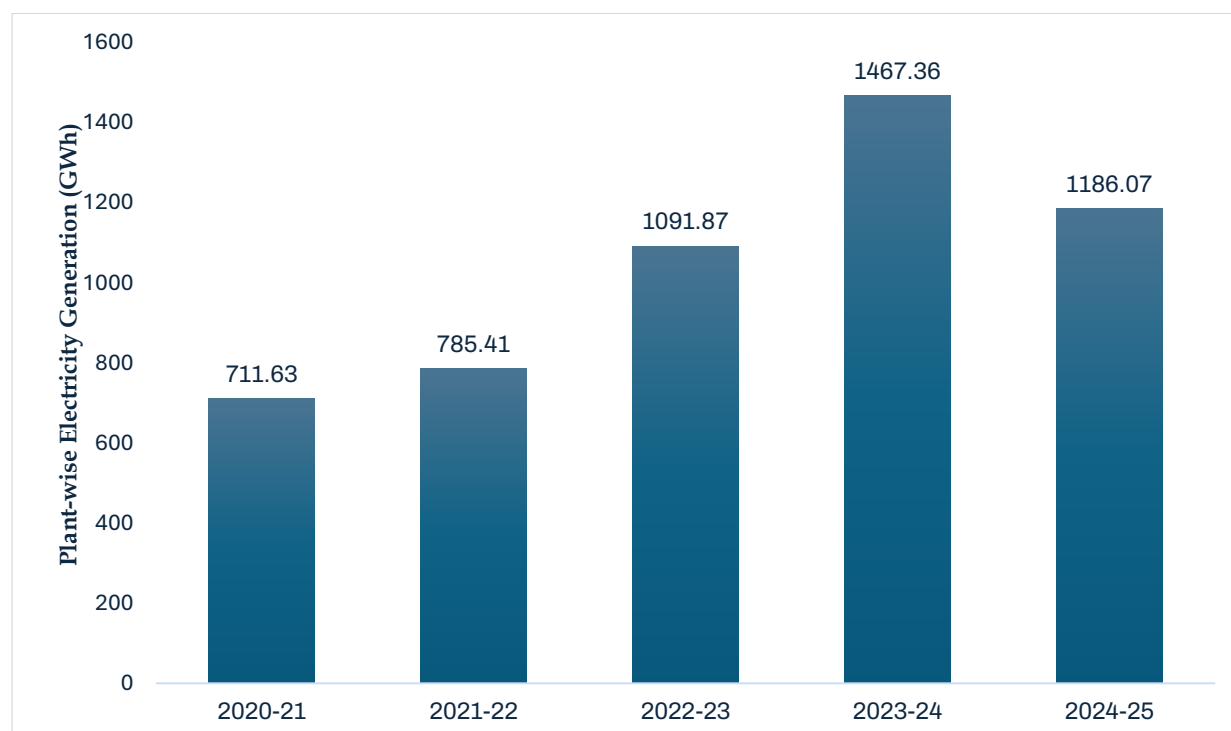
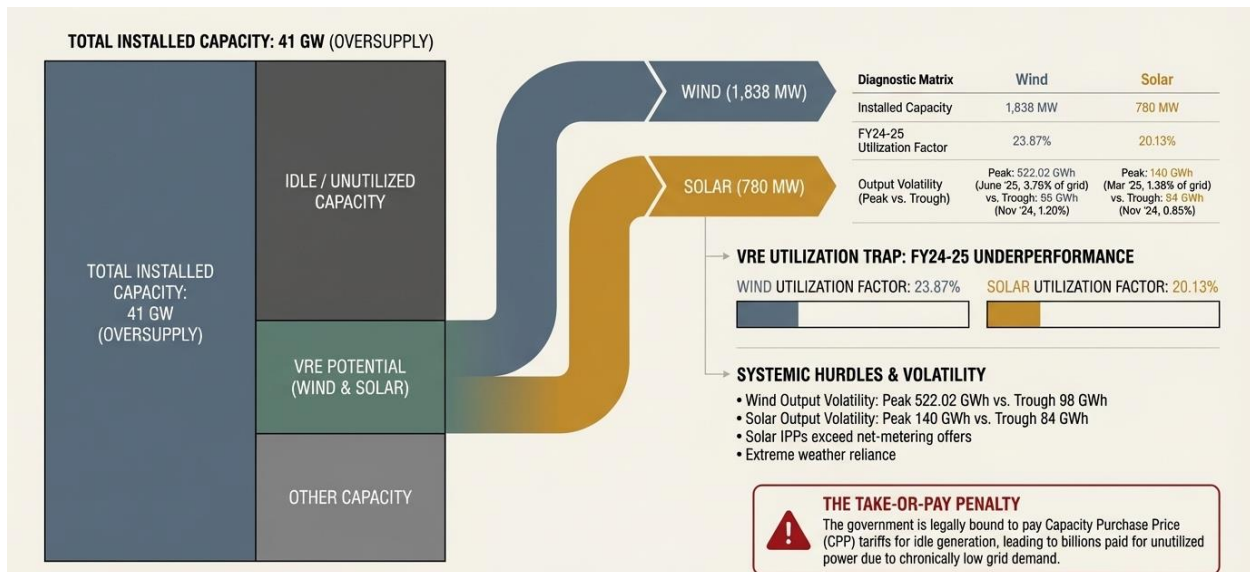


Figure 3: Net Electricity Generation (GWh) from Solar Plants in Pakistan (NEPRA, 2025)

Compounding these generation challenges are severe operational and transmission inefficiencies. Pakistan's transmission network is inadequate and poorly maintained. This physical bottleneck frequently prevents the grid from transporting electricity from the cheapest sources such as Thar coal and nuclear power plants, forcing a reliance on more expensive generation (NEPRA, 2025). Inefficiencies also arise from poor management, such as running combined-cycle power plants in inefficient open-cycle modes, delayed maintenance, and weak fuel supply agreements. While grid management has seen some minor improvements, evidenced by the Non-Project Missed Volume (NPMV) costs dropping from Rs 39.521 billion in FY 2023-24 to Rs 13.285 billion in FY 2024-25, this financial loss remains largely avoidable (NEPRA, 2025). Ultimately, Pakistan's power sector is trapped. It has an overbuilt generation fleet of 41 GW burdened by take-or-pay liabilities, highly variable renewable inputs, and a constrained transmission grid. Resolving this paradox requires a fundamental shift: creating flexible, predictable demand through sector coupling to absorb this idle capacity and lower the overall cost of electricity.



1.2. Objectives

The study primarily aims to present sector coupling not merely as an abstract theoretical concept, but as a highly pragmatic, demand-side economic intervention tailored to Pakistan's specific grid vulnerabilities. By moving away from traditional supply-side additions, this study focuses on creating intelligent, responsive energy demand. Specifically, the proposed sector coupling frameworks are designed to achieve two critical objectives:

- To enhance the Viability of Variable Renewable Energy (VRE) and Reducing Curtailment:
 - **The Challenge:** Intermittent renewable resources in Pakistan, particularly wind and solar, frequently generate power during periods of low baseline electricity demand. Because large-scale grid storage is currently lacking, this temporal mismatch forces operators to curtail zero-marginal-cost clean energy to maintain grid stability (Victoria et al., 2019). Consequently, thousands of megawatt hours are wasted annually. For Chinese-financed wind projects in the Jhimpir-Gharo corridor, this curtailment directly undermines project revenues, capacity utilization factors, and the return on investment under CPEC.
 - **Solution:** By introducing flexible, cross-sectoral demand through "Power-to-X" technologies, surplus VRE generation can be instantly rerouted to charge commercial EV fleets, power industrial electric boilers, or operate agricultural tube wells during off-peak hours (Schill, 2020). Chinese technology providers are well-positioned to supply these solutions, drawing on successful Power-to-Heat interventions in China's northern provinces.
 - **The Outcome:** This dynamic load shifting ensures that every unit of electricity generated by VRE is absorbed and monetized rather than curtailed. For Chinese IPPs and equipment suppliers, this transforms highly variable solar and wind power from unpredictable grid liabilities into highly utilized, profitable assets that reliably power the broader economy, thereby protecting and enhancing the value of CPEC energy investments.
- To reduce "Take-or-Pay" Liabilities and Lowering the Basket Price of Electricity:
 - **The Challenge:** Pakistan's power sector is trapped in a vicious cycle where massive, fixed Capacity Purchase Price (CPP) payments must be made to generation companies for idle power plants. As the total volume of electricity consumed is low, these fixed costs are spread across a small number of billed

units, resulting in exorbitant per-unit tariffs that further discourage consumption (Ruhnau et al. 2020).

- **Solution:** Sector coupling disrupts this cycle by systematically increasing the denominator, the total volume of electricity consumed, without requiring new generation capacity to be built. By electrifying the transportation, industrial heating, and agricultural sectors, the grid can structurally increase both its base load and off-peak load (Gils et al. 2021). For Chinese B2B partners, this creates new market opportunities in EV fleet charging networks, industrial electrification through green ammonia production and cold storage solutions under CPEC 2.0's private-sector focus.
- **The Outcome:** When idle thermal and renewable plants are dispatched to meet this new, coupled demand, the same fixed capacity costs are spread out over a larger volume of utilized energy units. This strategic absorption of idle capacity directly dilutes the per-unit CPP, mathematically lowering the average "basket price" of electricity and providing a roadmap for Chinese investors to improve payment certainty, and a roadmap for restoring the financial solvency of the grid, thereby securing the long-term viability of their energy assets in Pakistan.

1.3. Significance

The primary significance of this study lies in its fundamental departure from conventional, supply-centric energy planning. Historically, Pakistan's response to energy shortages has been to aggressively expand generation capacity, a narrow strategy that has ultimately culminated in an unsustainable 41 GW capacity surplus. This study is highly significant because it shifts the prevailing policy narrative from perpetually financing new supply to intelligently optimizing existing demand. Operationalizing the concept of sector coupling provides a practical, data-driven roadmap for absorbing idle generation capacity rather than building redundant infrastructure. This pivot is especially crucial for energy economies where capital is scarce; instead of abandoning stranded assets, sector coupling maximizes the utility of investments that have already been made, transforming a rigid grid into a flexible ecosystem capable of dynamic load management (Lund et al. 2017).

Economically, the frameworks proposed in this study offer a critical, timely intervention for Pakistan's broader macroeconomic stability. Currently, the continuous reliance on imported petroleum and liquefied natural gas (LNG) for the transportation and industrial heating sectors is depleting the country's already vulnerable foreign exchange reserves. By substituting these imported fossil fuels with domestically generated electricity through Power-to-Mobility and Power-to-Heat pathways, sector coupling inherently enhances national energy security and dramatically improves the balance of payments (Mathiesen et al. 2015). Furthermore, this study presents a mathematical solution to the power sector's impending "death spiral." By demonstrating how to spread crippling fixed capacity costs over a significantly larger volume of newly electrified demand, it offers a tangible mechanism to structurally lower the per-unit electricity tariff. This tariff reduction is essential to prevent vital commercial and industrial consumers from defecting from the national grid to generate their own off-grid thermal power.

From an environmental and strategic perspective, this study is vital for aligning Pakistan with global decarbonization trajectories while simultaneously solving immediate local crises. While adding renewable energy to the power grid is an important first step, achieving meaningful climate mitigation requires addressing the persistent, hard-to-abate emissions located in heavy industry and commercial transport. This report bridges that gap, demonstrating how curtailed, zero-marginal-cost wind and solar generation can be strategically utilized to green these historically fossil-dependent sectors without requiring massive investments (Robinius et al. 2017).

Ultimately, the significance of this study rests in its actionable nature. Rather than presenting sector coupling as a distant, futuristic ideal, it translates complex integration concepts into specific, policy-ready recommendations. By mapping out exactly how regulatory bodies can use dynamic pricing and targeted electrification to overcome immediate financial bottlenecks, the study provides a comprehensive blueprint for transforming Pakistan's energy sector from a fiscal liability into an integrated, sustainable engine for industrial growth.

METHODOLOGY



2. Methodology

To systematically evaluate the potential for sector coupling in Pakistan, this study employs a sequential analytical framework that integrates empirical data analysis with scenario-based linear optimization. The foundation of this study relies on primary operational and regulatory data sourced directly from the National Electric Power Regulatory Authority (NEPRA) and the Independent System and Market Operator (ISMO). This data establishes an accurate baseline of the national energy landscape, capturing historical dispatch metrics, plant-wise utilization factors, and system constraints.

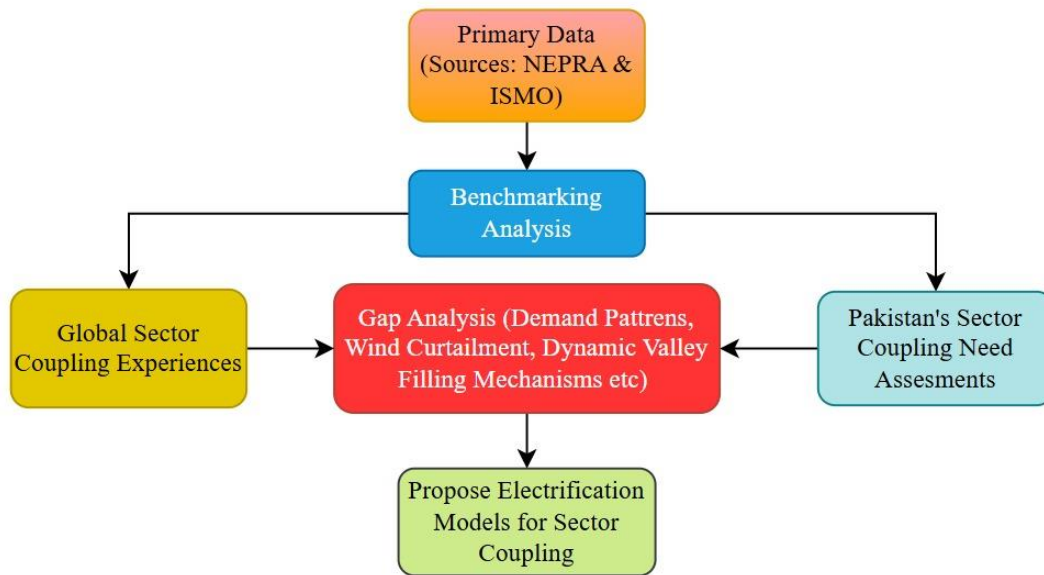


Figure 4: Overall Methodological Flow of Study

Following data acquisition, a comparative benchmarking analysis was conducted to contextualize Pakistan's grid performance. This approach weighed global sector coupling experiences against domestic driven signals, specifically focusing on the curtailment of variable renewable energy and the severe underutilization of generation assets burdened by capacity payments. This benchmarking directly informed a comprehensive gap analysis designed to identify temporal and structural disparities within the grid. Crucially, this gap analysis included an average demand profiling of the national grid to accurately map out seasonal and diurnal variations. Alongside this profiling, the assessment evaluated sectoral energy distribution, monthly unit consumption trends, and technology-wise generation to pinpoint optimal target areas for demand stimulation.

To translate these identified gaps into actionable electrification strategies, the final phase of the methodology utilized **Python for Power System Analysis (PyPSA)** to construct a linear optimization-based model. The primary objective function of this PyPSA model was "valley filling," which aims to strategically increase electricity demand during off-peak periods to flatten the national load curve and absorb excess generation. The optimization framework was executed under various simulated scenarios, specifically focusing on Power-to-Transport. Further, Power-to-Industry pathways were modeled using a linear programming-based optimization framework implemented in Python. This approach enables optimal temporal allocation of flexible industrial loads under demand and price signals to support valley filling and cost minimization. The outcomes of the complex simulations were then visualized utilizing **Gestalt principles** to clearly illustrate the results of load shifting. By evaluating the grid impact of integrating electric vehicle

charging and electrifying industrial heating processes during low-demand hours, the respective models mathematically identify the most efficient load-shifting strategies to improve overall system utilization.

GLOBAL BENCHMARKS: LEARNING FROM SUCCESS



3. Global Benchmarks: Learning From Success

Transitioning a historically rigid, fossil-fuel-dominated power grid into a dynamically coupled energy ecosystem is a formidable structural undertaking. It requires dismantling deeply entrenched regulatory silos, overhauling legacy transmission infrastructures, and fundamentally redesigning market incentives. Over the past decade, several advanced and emerging energy markets have navigated the turbulent intersection of rapid renewable energy integration and inflexible baseload generation. To provide a comprehensive comparative analysis, this section examines two distinct archetypes of successful sector coupling. First, it explores the European Union (EU), which represents the global vanguard in broad, multi-vector energy integration. Driven by aggressive decarbonization mandates, the EU has developed a highly sophisticated regulatory architecture designed to manage massive penetrations of intermittent solar and wind energy across multiple economic sectors. The analysis will specifically focus on the EU's utilization of Power-to-Gas (PtG) pathways and the rapid advancement of Electric Vehicle (EV) grid integration. By demonstrating how transport fleets can be transformed into decentralized, bidirectional battery storage networks, the EU model offers a macro-level blueprint for structurally absorbing excess baseline generation while increasing overall system flexibility.

Conversely, the EU though provides a broad systemic framework, this section will subsequently analyze the People's Republic of China, which offers a highly targeted and pragmatic benchmark for resolving localized grid crises. Specifically, the analysis explores how China successfully mitigated catastrophic wind curtailment rates in its northern provinces, a scenario that is functionally identical to the current bottlenecks suppressing wind generation in Pakistan's southern wind corridors. Faced with rigid, inflexible thermal generation that could not be easily ramped down, China utilized aggressive Power-to-Heat (PtH) technological interventions within concentrated industrial clusters to forcefully decouple thermal demand from localized electricity generation. Ultimately, the objective of evaluating these divergent international case studies is not to suggest a verbatim replication of foreign policies, but to extract actionable, data-driven parameters. By dissecting the specific tariff reforms, dynamic pricing mechanisms, and technological deployments that underpinned both the European and Chinese successes, this section aims to define clear, translatable policy takeaways to guide the National Electric Power Regulatory Authority (NEPRA) and the Central Power Purchasing Agency (CPPA-G) in their regulatory reform efforts.

3.1. EU Model: Integrating Intermittent Renewables through Green Hydrogen and EV Grids

The European Union (EU) currently operates at the absolute global frontier of sector coupling, transitioning the concept from a theoretical engineering framework into binding regional law. Driven by aggressive decarbonization mandates like the "Fit for 55" package and the Renewable Energy Directive (RED III), the EU legally and economically compels the deep integration of its electricity, gas, heating, and transportation networks (Hydrogen Europe, 2024).

As European member states exponentially scale up variable renewable energy (VRE) capacities, they frequently experience periods where localized zero-marginal-cost electricity generation drastically exceeds domestic demand. To prevent the forced curtailment of these renewable assets and avoid the exorbitant capital costs of continuously expanding physical transmission lines, the EU leverages two primary pathways with direct implications for grid management: macro-scale Power-to-Gas (PtG) and decentralized Power-to-Mobility (PtM).

3.1.1. Power-to-Gas: Electrolyzers as Dynamic System Buffers

The cornerstone of the EU's strategy is redirecting curtailed wind and solar electricity to power large-scale industrial electrolyzers (Park et al. 2025). This automated, demand-side response ensures that renewable installations maintain high utilization factors, a dynamic highly analogous to the solution required for Pakistan's southern wind corridors. It directly prevents financial losses from curtailment and preserves project economics.

By converting surplus electricity into electrolytic green hydrogen, the EU provides a structural solution to seasonal energy storage. Furthermore, this hydrogen is routed to aggressively decarbonize hard-to-abate industrial sectors. Driven by the EU Emissions Trading System (ETS), manufacturers are substituting imported fossil fuels with green hydrogen for high-heat processes like steelmaking and agricultural ammonia synthesis (Center Denmark, 2024). This cross-sectoral fuel substitution creates a highly profitable, secondary wholesale market for electricity generation that did not previously exist.

The EU Power-to-Gas Sector Coupling Model

How PEM electrolyzers transform intermittent renewable surpluses into grid stability, seasonal storage, and industrial decarbonization.

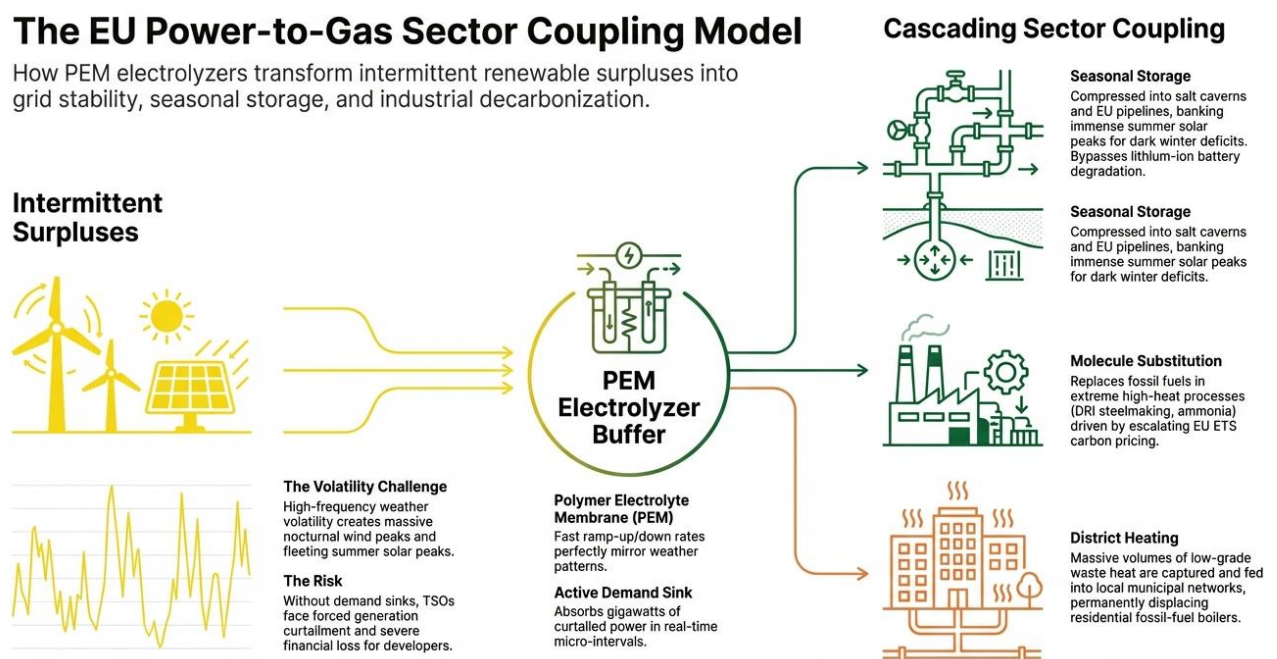


Figure 5: EU Power to Gas Sector Coupling Model

The EU also maximizes systemic thermodynamic efficiency through "cascading" sector coupling. The massive volumes of low-grade waste heat generated as a byproduct by these industrial electrolyzers are not vented into the atmosphere; instead, they are captured and fed into local municipal district heating networks (Interreg CENTRAL EUROPE, 2026). This displaces fossil-fuel-based residential heating boilers, compounding the emissions reductions and radically improving the overall energetic efficiency of the entire grid ecosystem.

3.1.2. Power-to-Mobility (PtM): The V2G Ancillary Service Ecosystem

While green hydrogen addresses heavy industry and macro-seasonal storage, the EU model utilizes the rapidly electrifying transportation sector to manage rapid, daily grid volatility. The widespread proliferation of Electric Vehicles (EVs) initially presented a severe systemic threat to European grid stability. Unmanaged, simultaneous EV charging during peak evening hours risked critically overloading localized, low-voltage distribution networks. However, through aggressive regulatory sector coupling and the standardization of communication protocols, the

EU is actively transforming commercial and residential EV fleets into millions of decentralized, bidirectional battery storage units (Heilmann et al. 2023).

This transformation relies on the widespread rollout of bidirectional smart meters and the implementation of Vehicle-to-Grid (V2G) technologies, fundamentally supported by highly dynamic, Time-of-Use (ToU) wholesale pricing. Since the average passenger vehicle remains parked for over 90% of its lifespan, its battery represents a massive, unutilized grid asset. European consumers are financially incentivized via automated smart-charging software and significantly reduced per-unit electricity rates to plug in their vehicles during hours of peak solar feed-in or high wind generation. This absorbs excess generation, effectively "valley-filling" the national load curve. Conversely, during periods of peak demand when grid supply is constrained and thermal generation is expensive, V2G technology allows these aggregated vehicle batteries to discharge a calculated portion of their stored power back into the grid.

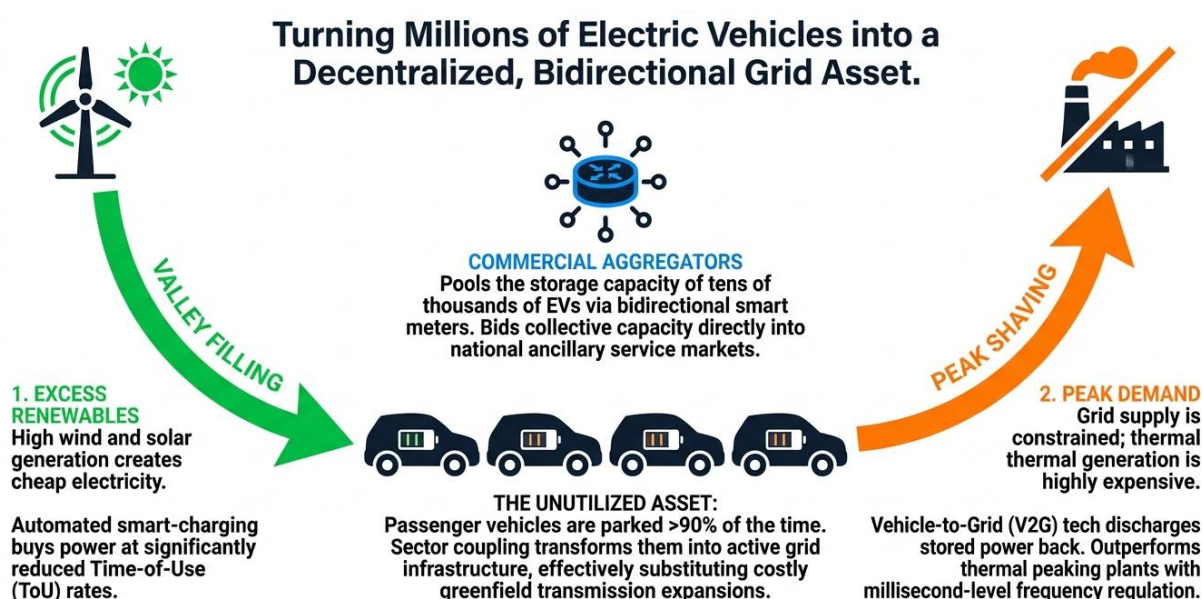


Figure 6: EU Power to Mobility (PtM) Ecosystem

3.2. China's Experience with Power-to-Heat for Industrial Clusters

While the European Union provides a macro-level blueprint for comprehensive, economy-wide sector coupling, the China offers a highly pragmatic, surgical benchmark for resolving acute, localized grid crises. Specifically, China's approach provides empirical data on how to manage catastrophic variable renewable energy (VRE) curtailment caused by the severe inflexibility of legacy thermal power plants. This dynamic serves as an exact parallel to the current gridlock experienced in Pakistan, where the generation output from the Jhimpir and Gharo wind corridors is frequently curtailed due to the inflexibility of thermal baseload plants constrained by "Take-or-Pay" contracts and transmission bottlenecks. By dissecting China's targeted technological and market interventions, policymakers can extract direct, translatable solutions for localized load management.

3.2.1. Thermodynamic Bottleneck: "Heat-Led" Dispatch and Must-Run Inflexibility

During the period between 2010 and 2016, China aggressively scaled up its onshore wind capacity, particularly in the wind rich "Three Norths" (Sanbei) region. However, this rapid supply-

side expansion outpaced the grid's technical ability to absorb power, leading to catastrophic curtailment rates that frequently exceeded 20% of total wind generation (Lu et al. 2022).

The root cause of this massive energy waste was a fundamental thermodynamic conflict within the generation fleet. The northern Chinese grid was heavily dominated by coal-fired Combined Heat and Power (CHP) plants utilizing back-pressure and extraction condensing turbines. During the harsh winter months, grid dispatch was governed by a rigid "heat-led" operational mode (*yi re ding dian*). These CHP plants were legally obligated to provide continuous, high-temperature steam and hot water for municipal district heating networks and localized industrial clusters (Chen et al. 2015). Since the production of electricity and heat was physically locked together in the turbine's thermodynamic cycle, grid operators could not ramp down the coal plants at night, even when baseline electricity demand plummeted. Consequently, when nocturnal wind generation peaked, the transmission grid was already saturated by the must-run coal plants.

3.2.2. Technological Decoupling: High-Voltage Electrode Boilers and Thermal Storage

To resolve this structural gridlock, the Chinese National Energy Administration (NEA) recognized that building massive, long-distance ultra-high-voltage (UHV) transmission lines to export the power would be too slow and capital-intensive. Instead, they focused on creating synthetic, localized demand by initiating aggressive Power-to-Heat (PtH) sector coupling.

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3.2.3. Bilateral Market Reforms: Peak-Valley Arbitrage and Direct Purchasing

Technological deployment alone was insufficient; the Chinese government had to re-engineer the power market to make PtH economically viable. They achieved this through aggressive tariff restructuring and the introduction of direct bilateral trading.

First, regional governments drastically widened the "peak-to-valley" electricity price differential, offering deeply discounted wholesale tariffs during nocturnal off-peak hours when wind generation was at its maximum (Lu et al. 2022). Second, and more importantly in Pakistan's context, China allowed wind farm operators to bypass the central grid purchasing agency and sign Direct Power Purchase Agreements (DPPAs) with industrial heating companies. Wind farms, desperate to avoid generating power that would simply be curtailed and unpaid, agreed to sell their nocturnal electricity to PtH operators at rock-bottom prices.

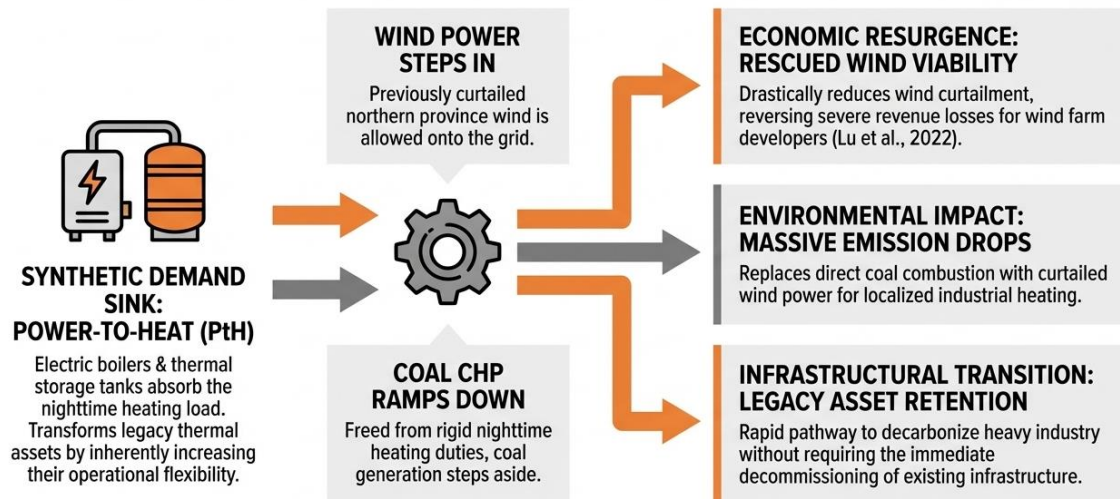


Figure 7: Transformative Outcomes of Chinese Sector Coupling Model

ASSESSING THE NEED FOR SECTOR COUPLING IN PAKISTAN'S POWER SECTOR



4. Assessing the Need for Sector Coupling in Pakistan's Power Sector

The national grid holds sufficient installed capacity to meet peak demand, but gradual demand growth, declining industrial consumption, and operational constraints have limited effective utilization of this capacity. For example, the National Grid Company (NGC) recorded a surplus capacity of 6,697 MW in FY-2024 and 885 MW in FY-2025, while the Karachi Electric (KE) system experienced relatively small deficits during the same period (NEPRA, 2025). These conditions highlight inefficiencies in the current electricity consumption structure and underscore the need to explore mechanisms to absorb surplus electricity while improving system utilization. In this context, sector coupling enables integration of the power sector with other energy-intensive sectors, such as transport, industry, and hydrogen. The following sections examine electricity consumption patterns, demand profiles, technology utilization factors, and wind curtailment trends to identify the underlying rationale and potential opportunities for sector coupling in Pakistan.

4.1. Uneven Sectoral Distribution of Annual Electricity Consumption

The sectoral distribution of electricity consumption identifies the potential sectors for sectoral coupling. In this regard, Figure 8 illustrates the sectoral average electricity consumption in GWh, in which the domestic and industrial sectors remain the dominant consumers of electricity in Pakistan's power system, followed by agriculture and commercial sectors. Over the five years from FY-2020-21 to FY-2024-25, domestic consumption consistently represents the largest share of electricity consumption, reflecting the growing role of residential demand in the overall load composition from 57,856 GWh to 56,304 GWh. Industrial consumption also constitutes a significant portion of demand, although its share fluctuates over the years due to variations in industrial activity and economic conditions. Agricultural sector consumption shows a declining trend from 10,237 GWh to 5,882 GWh from FY-2020-21 to FY-2024-25, while sectors such as public lighting, general services, and others represent relatively small shares of total electricity demand (NEPRA, 2025).

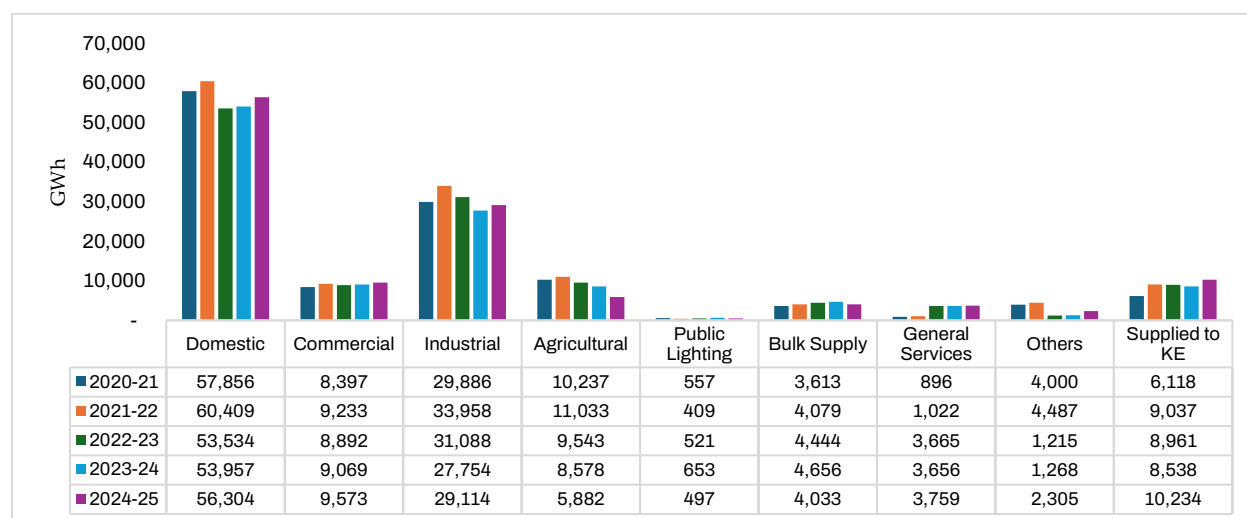


Figure 8: Sector-wise average consumption (GWh), FY-2020 to 2025 (NEPRA, 2025)

The year-on-year average growth trends (Table 3) further highlight structural shifts in electricity consumption across sectors. Domestic and commercial sectors show relatively stable growth in recent years, indicating gradual expansion in residential and commercial electricity use. In

contrast, the industrial sector experienced notable contractions in FY-2022-23 and FY-2023-24, reflecting reduced industrial activity before partially recovering in FY-2024-25. The agricultural sector shows the largest decline in FY-2024-25 (-31.43%), suggesting a significant reduction in electricity consumption for irrigation purposes or related activities. Meanwhile, sectors such as public lighting and general services exhibit high volatility, largely due to their smaller consumption base and administrative or operational changes. Electricity supplied to KE demonstrates strong growth in certain years, particularly in FY-2021-22 and FY-2024-25. Overall, these consumption dynamics indicate **uneven demand growth** across sectors, reinforcing the need to explore potential pathways for sector coupling to utilize available generation capacity better and manage demand variability (NEPRA, 2025).

Table 1: Annual Growth Rate (%) of Electricity Consumption FY-2025 (NEPRA, 2025)

Sectors	2020-21	2021-22	2022-23	2023-24	2024-25
Domestic	4.94%	4.41%	-11.38%	0.79%	4.35%
Commercial	6.63%	9.97%	-3.70%	2.00%	5.56%
Industrial	16.53%	13.62%	-8.45%	-10.73%	4.90%
Agricultural	4.91%	7.77%	-13.50%	-10.11%	-31.43%
Public Lighting	44.70%	-26.58%	27.58%	25.36%	-23.97%
Bulk Supply	-3.85%	12.89%	8.95%	4.78%	-13.39%
General Services	3.31%	14.00%	258.72%	-0.25%	2.81%
Others	9.74%	12.17%	-72.92%	4.34%	81.86%
Supplied to KE	12.75%	47.70%	-0.84%	-4.72%	19.87%

Additionally, within the general services category, the information technology (IT) and telecommunications sectors represent a largely untapped area for future electricity demand growth. Figure 9 provides Pakistan's trade map analysis of the telecom and IT services sector for the last five years from 2020 to 2024. It is observed that the exponential growth of Pakistan's telecom and IT sector services has raised export earnings from USD 1,716 million in 2021 to USD 3,632 million in 2024, indicating a significant national economic success story. However, the imports show a variable trend and are expected to increase in the coming years (*Trade Map*, 2026).

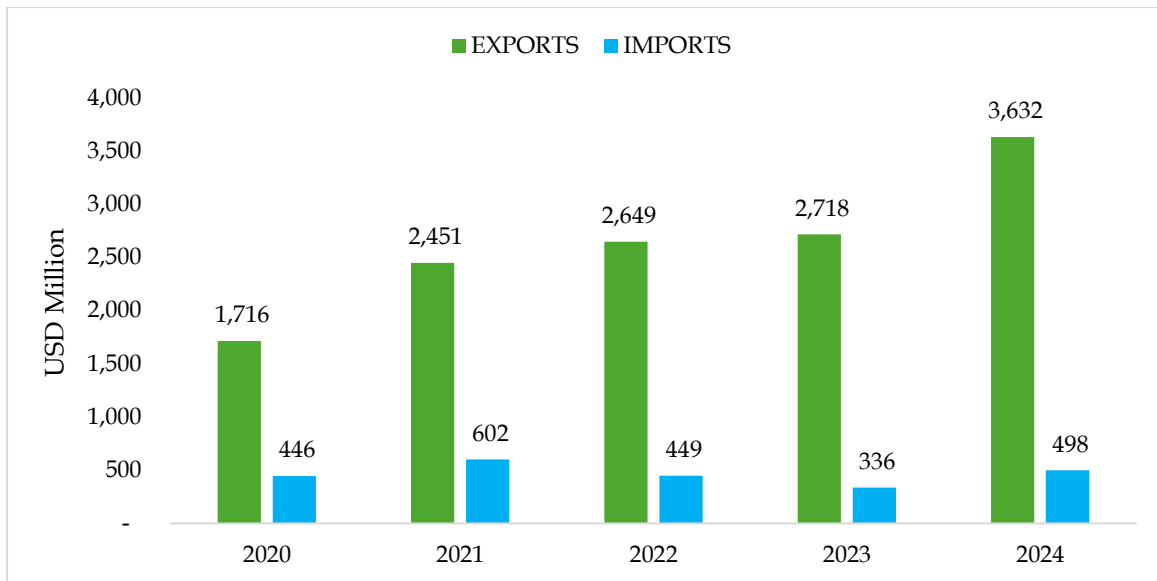


Figure 9: Pakistan's Telecom & IT Services Exports & Imports (Trade Map, 2026)

4.2. Average Demand Profiling of National Grid Network

Building upon the uneven sectoral distribution identified in Section 4.1, a granular analysis of the national grid average hourly demand profile across months examines how these sectoral consumptions aggregate into distinct seasonal and daily load curves to analyze the boundaries for sector coupling. Figure 10 presents the average hourly data across months showing dual asymmetry, including both seasonal and daily demand patterns (ISMO, 2025). The months from May to September exhibit the highest demand levels, with June peaking at 21,261 MW during evening hours and July maintaining consistently high loads above 20,000 MW from late afternoon through midnight, driven primarily by cooling loads in domestic and commercial sectors within sustained industrial activity. This summer peak exhibits a distinctive daily curve, with demand rising from early morning troughs around 16,000-17,000 MW to evening peaks exceeding 21,000 MW, creating a daily ramping requirement that stresses generation flexibility and transmission infrastructure. Conversely, the months from November to March reveal a decline in demand, with December at 7,900 MW in early morning hours and rarely exceeding 12,000 MW even during evening peaks. The winter demand represents the active underutilized baseload generation from coal, nuclear, and hydro plants that cannot be easily ramped down. According to the sectoral trends as represented in Section 4.1, the agricultural sector, having a negative growth rate and volatile industrial demand, indicates critical coupling opportunities. The winter demand valley could absorb massive new loads from electric vehicle charging infrastructure, electric heating adoption in commercial buildings, or green hydrogen production, effectively utilizing generation assets that currently operate at partial load for half the year while creating new revenue streams to utilize the underutilized generation.

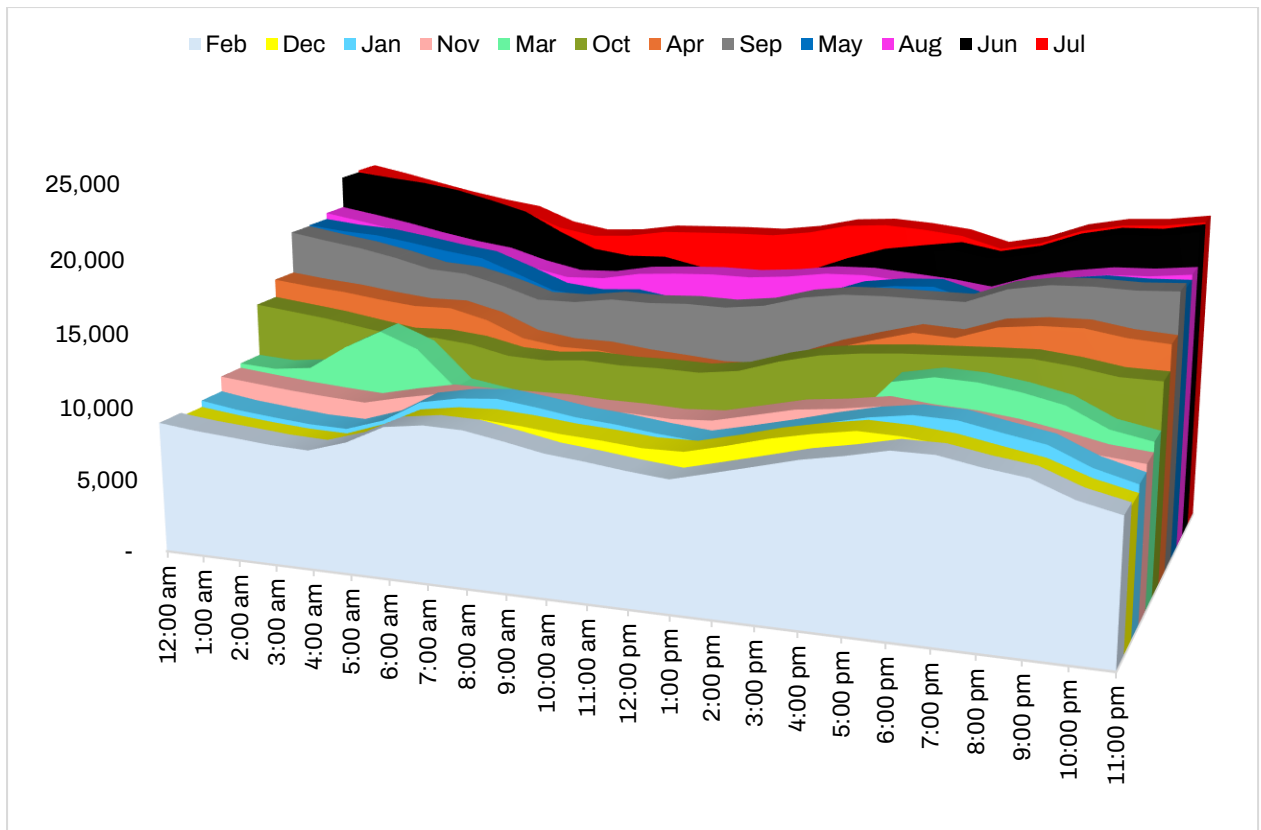


Figure 10: Average Hourly Demand Profile (MW) of National Grid network, FY-2025

Graph is designed by the authors based on the data by (ISMO, 2025).

Moreover, Figure 11 illustrates the average demand profiles and average marginal price of low, medium and high demand months. The high-demand summer months (May to September), despite average loads exceeding 17,700 MW, have an average marginal price of approximately Rs 17,050 /MWh. On the contrary, the medium-demand transitional months of April and October exhibit Rs 20,120/MWh, which is still higher than the low and high demand months. This relationship indicates critical supply-side constraints during shoulder months when the grid ramps up or down quickly while peaking plants remain operational, creating a price spike. This creates a useful three-tiered coupling strategy as follows:

- Winter months (November to March) offer low-cost energy (Rs 17,180 /MWh) ideal for price-sensitive industrial processes, seasonal storage, or Power-to-X (PtX) applications.
- Summer months (May to September) require a demand response strategy for peak shaving to manage the average 21,000 MW evening peaks without expensive new generation.
- April and October, despite their moderate demand and high average marginal price, still justify investments in fast-ramping storage or demand-side flexibility.

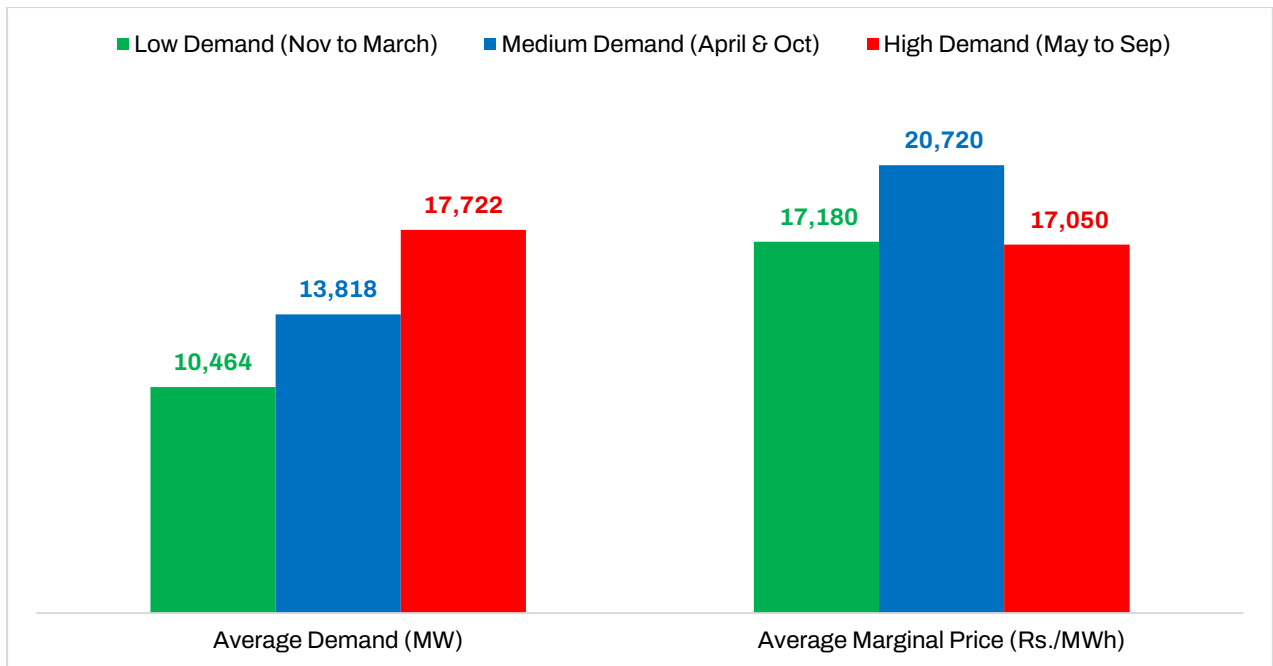


Figure 11: Average demand profiles for Low, Medium, and High Demand Months, FY-2025

Graph is designed by the authors based on the data by (ISMO, 2025).

4.3. Technology-wise Monthly Capacity Utilization Factor (CUF) Analysis

After analysing the seasonal and daily demand variability established in Section 4.2, the technology-wise average monthly utilization factors reveal a deep disconnect between the system's demand profile and the actual operational patterns of generation assets, claiming targeted opportunities for sector coupling interventions. The overall analysis is based on NEPRA's State of Industry Report (2025) (NEPRA, 2025).

The heatmap in Figure 12 presents the monthly minimum and maximum capacity utilization factor (CUF) percentages for each fuel technology. Local coal power plants demonstrate the most consistent operational profile, with minimum values ranging from 5% to a maximum 81% across the year and never falling to zero, indicating that coal-fired plants remain in continuous operation regardless of seasonal demand fluctuations. Nuclear plants, while achieving high maximum values near full capacity. However, a few nuclear plants remain completely shut down for several months, including July, October, May, and June, with minimums dropping to zero due to scheduled refueling or maintenance cycles. Hydel follows a pronounced seasonal pattern, with generation nearly ceasing during the winter months (December through February), with a few hydel plants falling to near-zero, before surging to maximum levels between 89% and 98% during the summer months (April through September), reflecting natural water availability. Bagasse power plants display extreme crop-dependent variability, specifically Fatima Energy Limited, which remains at zero CUF throughout the year. Further, CUF ranges for wind power plants are between 3% in November and 52% in the summer months, while almost all solar plants fall to zero in November and peak at only 30% under optimal conditions.

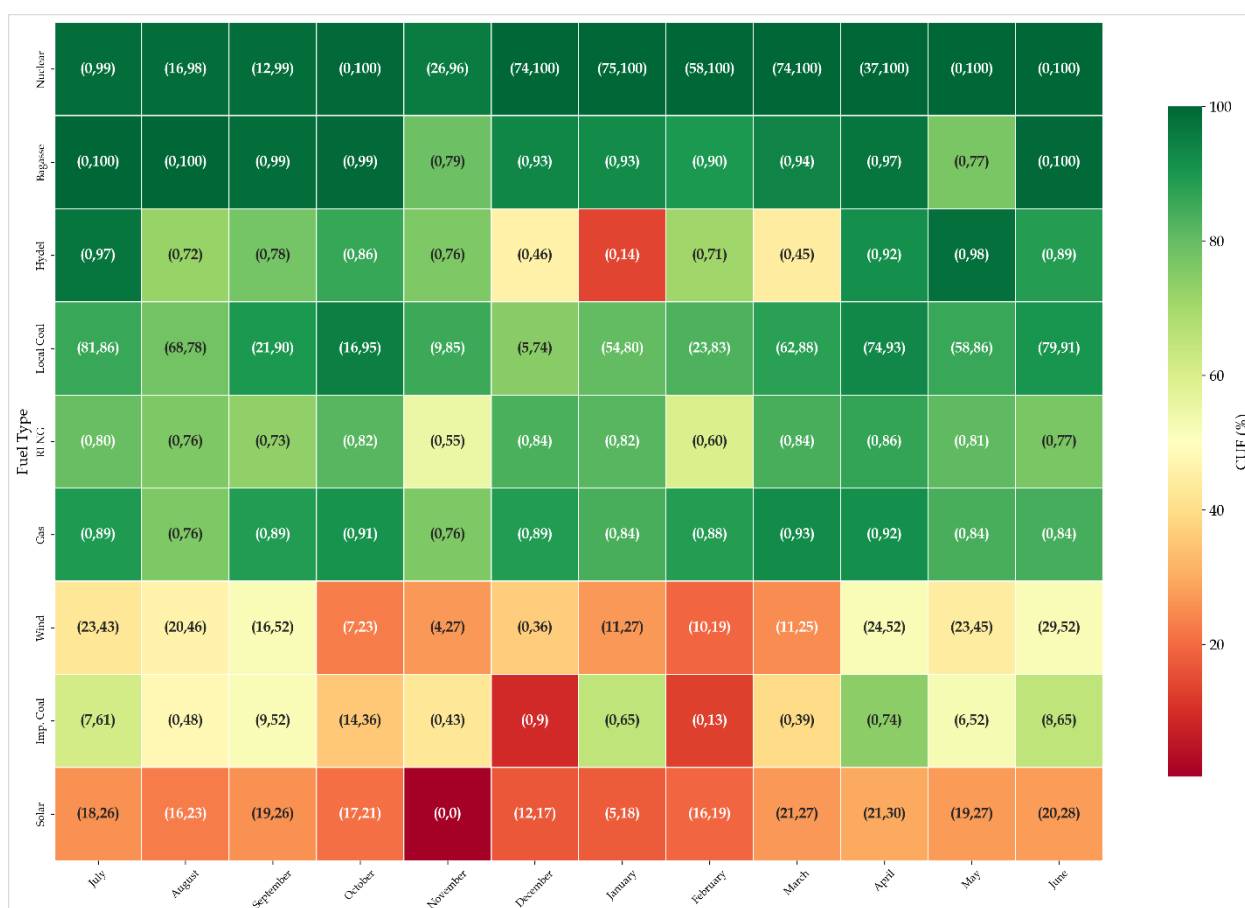


Figure 12: Technology-wise Heat Map (Minimum, Maximum) CUF (%), FY-2025

Graph is designed by the authors based on data from the State of Industry Report, 2025 (NEPRA, 2025)

Moreover, the net frequency analysis (Figure 13) further reinforces this disparity, showing that during FY-2025, hydel and bagasse power plants recorded 53 and 46 instances of no CUF events, respectively. However, both technologies still maintain higher CUFs than solar and wind. Among wind power plants, only the 50 MW Zephyr Power plant showed no CUF event during December. Overall, wind power plants face deliberate curtailment rather than technical unavailability, leading to significant risks for Chinese-funded wind projects due to unpredictable CUFs.

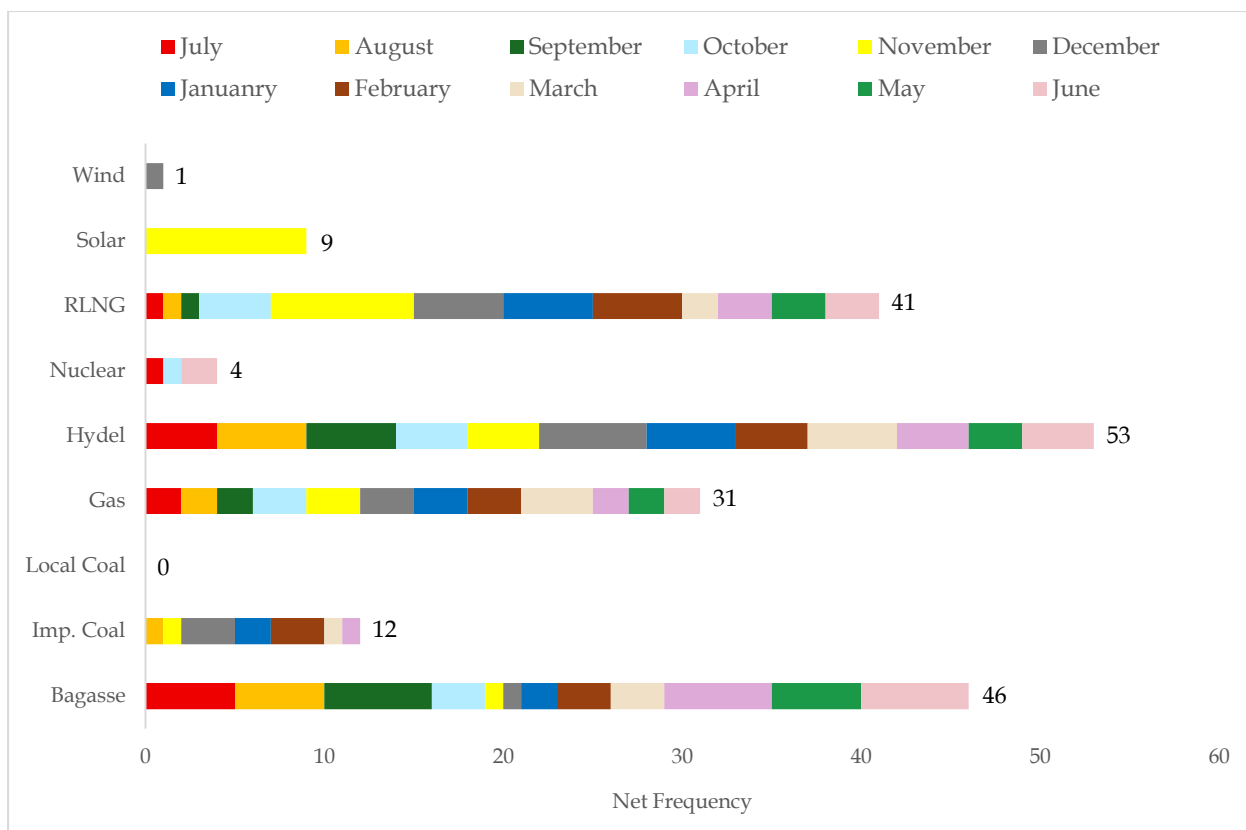


Figure 13: Monthly Net Frequency of 0% CUF by Technology, FY-2025

Graph is designed by the authors based on data from the State of Industry Report, 2025, (NEPRA, 2025).

4.4. Wind Curtailment and Demand Dynamics: Implications for Sector Coupling

Wind power has emerged as a key renewable energy resource in Pakistan, particularly in the Jhimpir–Gharo wind corridor. However, despite significant installed capacity, wind power plants frequently experience curtailment due to transmission constraints, low system demand during certain hours, and operational limitations in the grid dispatch process. Figure 14 illustrates the verified amount on account of non-project missed volume, which represents energy that wind power plants could produce but were unable to dispatch due to system limitations. It is observed that the curtailed wind energy escalated from 99 million kWh in 2020-21 to 1.34 billion kWh in 2023-24, with an approximate 7% increment within three years. This resulted in an incredible financial loss of nearly Rs 39 billion in 2023-24 alone. However, these estimates trickle down to 491 million kWh in 2024-25 but still signal persistent curtailment due to the presence of structural inefficiencies in the electricity market. The issue is further compounded by mismatch between the variability of wind generation and the demand profile of national grid. During periods of low demand, available wind generation may exceed the level that the system operator can absorb without compromising system stability. As a result, wind power plants are often instructed to reduce output, leading to lost generation opportunities and increased inefficiencies in renewable energy utilization (NEPRA, 2025).

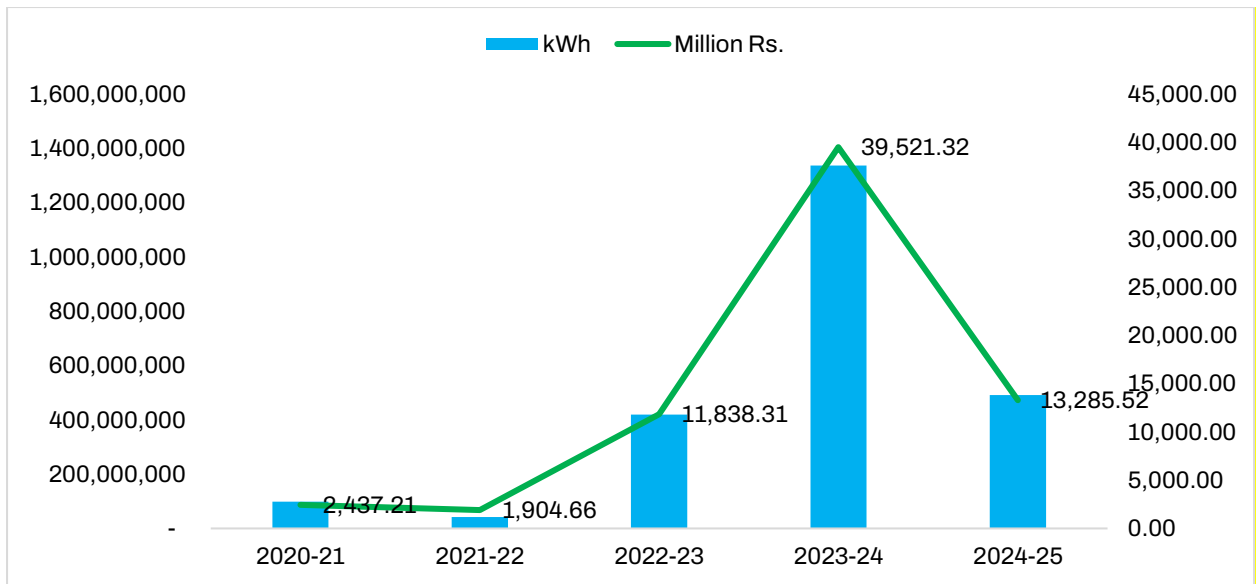


Figure 14: Verified Amount on Account of NPMV (NEPRA, 2025)

The monthly frequency analysis of zero wind demand hours reveals a pronounced seasonal pattern that directly correlates with the winter demand valley identified in Section 4.2. The Figure 15 below presents the typical demand profile of a 50 MW wind project located in Jhimpir for FY-2025. The profile illustrates the variability of wind generation throughout the year. Exploratory data analysis indicates that January, February, October, and November exhibit the highest frequency of zero-generation periods, reflecting declined wind utilization during these months. Among these, November records the lowest average wind demand, with approximately 3,449 MWh, indicating reduced renewable output and higher variability during the winter season.

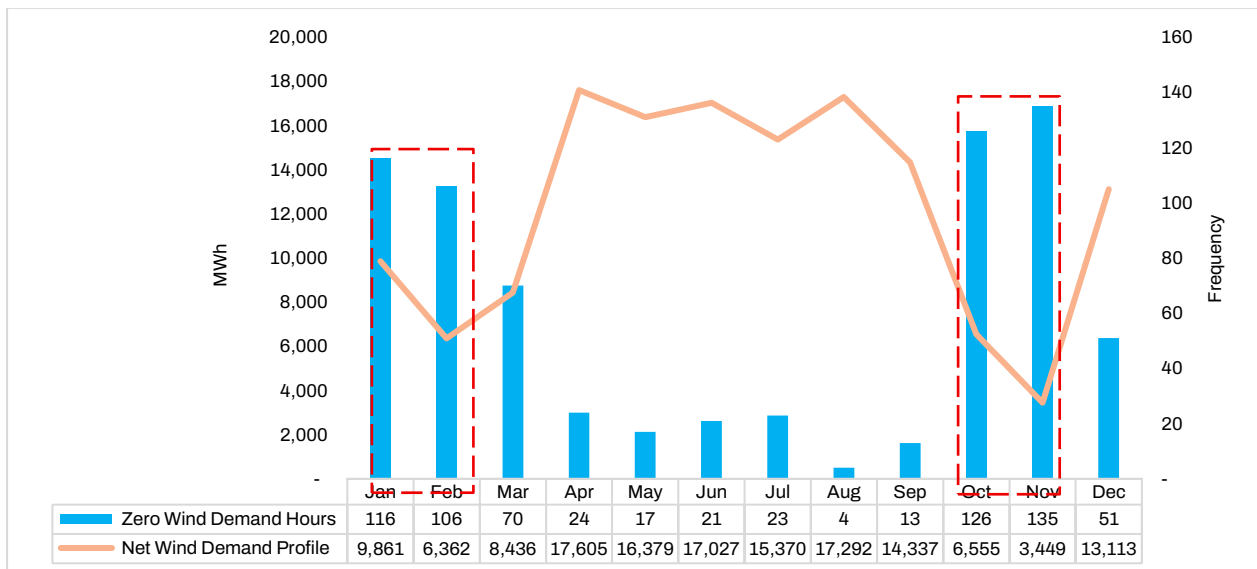


Figure 15: Frequency of Zero Wind Demand Hours vs. Net Wind Demand of 50 MW Wind Project for FY-2025

Table is designed by the authors based on the data by (ISMO, 2025).

The hourly wind demand profile for this representative winter day exposes the magnitude of the sector coupling opportunity at the system's lowest demand point. Further analysis reveals that 27th November represents the lowest net system demand day during FY-2025. This day provides an appropriate test case for evaluating sector coupling strategies under conditions of low

electricity demand and reduced renewable generation. Figure 16 presents a comparison of net demand excluding wind profile, wind demand profile and marginal electricity prices for 27th November. The data shows that system demand remains relatively low during the early morning hours, ranging between approximately 8,000 MW and 9,000 MW. Wind generation during these hours is minimal, frequently approaching zero, reflecting the seasonal variability of wind resources. The marginal price profile also reflects system conditions, with marginal prices split between Rs 15.34 /kWh during morning hours, dropping to Rs 6.18 /kWh in the afternoon before rising to Rs 14.46 /kWh during evening peaks. This price signal, when viewed against the near-zero wind generation, confirms that the system is being served entirely by baseload coal and nuclear plants operating at their minimum technical levels.

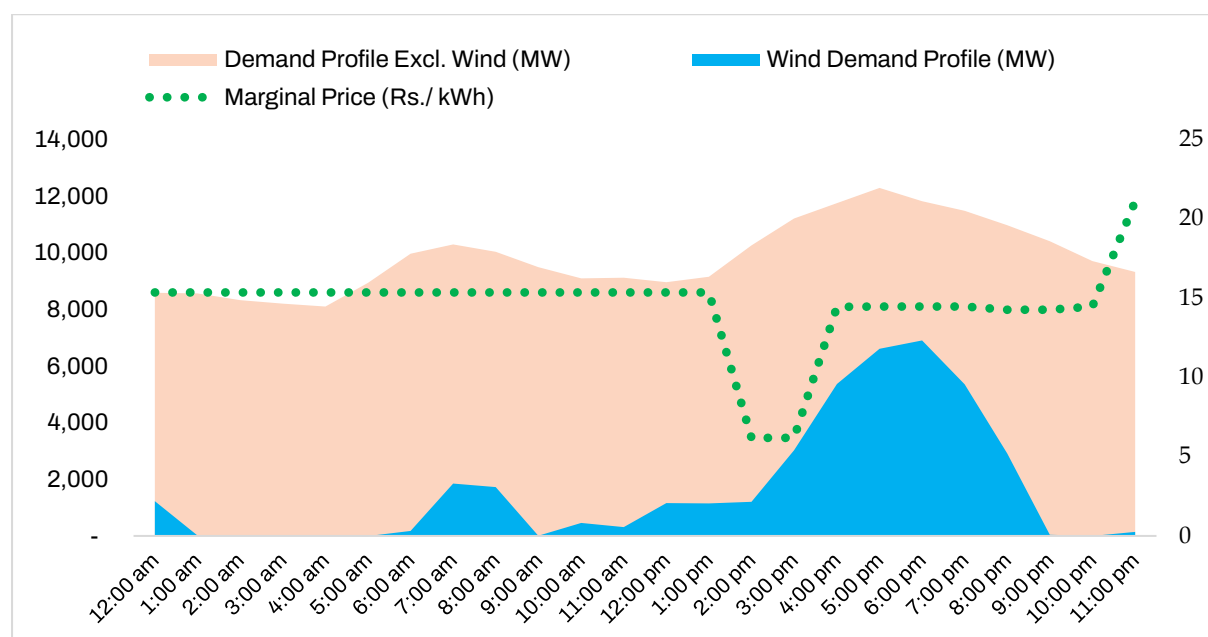


Figure 16: 27th Nov, FY-2025, Wind Demand and Net Demand Excluding Wind (MW) vs. Marginal Price (Rs. /kWh)

Graph is designed by the authors based on the data by (ISMO, 2025)

PROPOSING ELECTRIFICATION MODELS FOR SECTOR COUPLING



5. Proposing Electrification Models for Sector Coupling

To evaluate the feasibility of sector coupling in Pakistan's electricity system, a set of high-level electrification models is developed using a **single-node system** representation. The following two proposed sector coupling pathways are analyzed as test case studies:

- Power-to-Transport through Electric Vehicles (PtE).
- Power-to-Industry (PtI).

The overall analysis of both test case studies utilized only a 24-hour daily profile based on data from (ISMO, 2025). The next sections provide the details of each case study.

5.1. Power-to-Transport through Electric Vehicles (PtE)

This section presents a sector coupling electrification model for the Power-to-EVs (PtE) case, in which a country-wide electric vehicle fleet is assumed as a centralized energy storage system with flexible loads capable of absorbing surplus generation while providing grid services through price-responsive charging. The overall proposed model employs the PyPSA optimization framework to optimally integrate EVs in the electricity market with respect to Pakistan. It includes EVs and two scenarios, including EV integration with hourly wholesale grid prices and EV integration with fixed prices, respectively. To analyze the potential for EVs as sector coupling elements, functional parameters are established to develop the case study.

5.1.1. Designing the Base Scenario: High Wind Curtailment Day

The model considers the existing grid generation capacity of approximately 41 GW as reported by National Electric Power Regulatory Authority (2025). [Click or tap here to enter text.](#) It utilizes a 24-hour demand profile along with price data observed on 27th November of FY-2025 (Figure 17). This selection is intended to represent a low-demand scenario characterized by limited wind energy utilization. This scenario provides a suitable test case for examining how sector coupling technologies can introduce flexible electricity demand and improve system utilization and reduce curtailments. The base case is developed without considering electrification models and ignores transmission limits, allowing for a high-level single-node sector coupling analysis. The details of each proposed electrification model are explained in the next sections to compare their results with the base case.

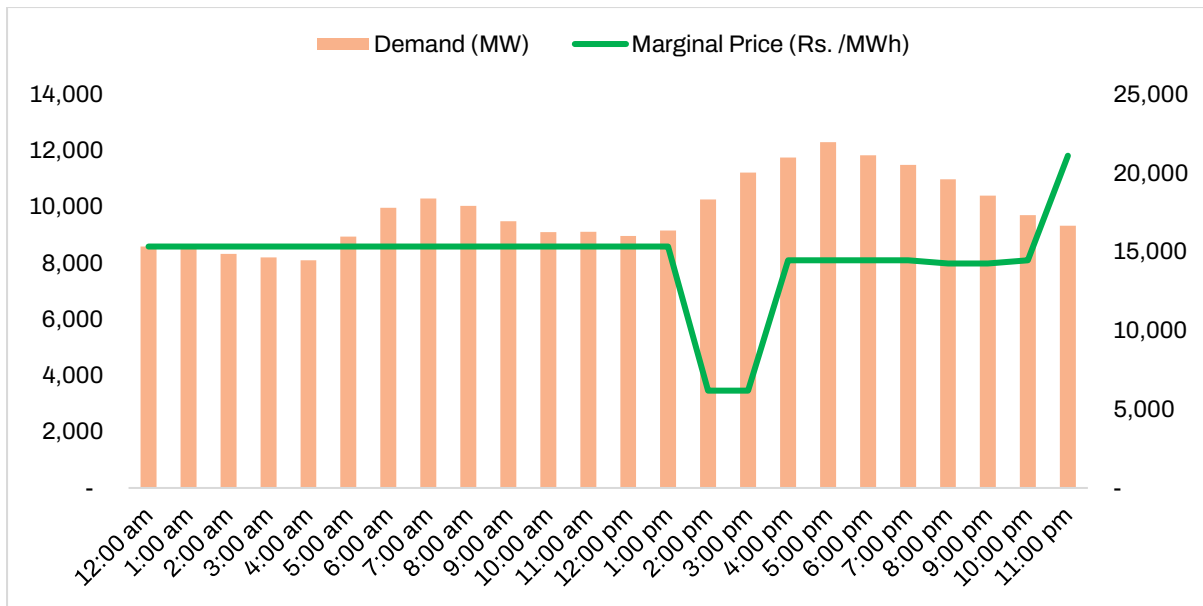


Figure 17: PtE Base Scenario: 27th Nov, FY-2025 Marginal Price (Rs. /MWh) vs. Net Demand Profile (MW) (ISMO, 2025)

5.1.2. Estimating EV Demand Profile and Initial Parameters

To capture the estimated EV demand under the 30% EV penetration scenario for 2030, driving profiles are constructed based on annual energy estimates of 4.7 TWh during daytime (6:00–18:00) and 2.2 TWh during nighttime (18:00–6:00) (Nadeem et al. 2022). This represents 68% of the charging demand during daytime and the remaining 32% during nighttime. Further, Table 2 provides the estimated Charging Availability Factors (scaling from 0.1 to 0.5) that identify the probability of an EV being connected to a grid charger based on daily human activity and driving patterns in Pakistan's context.

Table 2: Charging Availability Factors Estimations

Hour	Charging Availability Factors	Justification
12:00 AM to 05:00 PM	0.1	Very low grid charging activity. Vehicles are typically parked at home or away from charging infrastructure.
05:00 AM to 10:00 PM	0.15	Morning charging is typically quick top-ups and getting ready for office routines.
10:00 AM to 12:00 AM	0.18	Continued low public charger usage. Parked at offices, shopping malls and workplaces, etc.
12:00 PM to 01:00 PM	0.2	Moderate charging.
01:00 PM to 02:00 PM	0.5	Lunch time peak.
02:00 PM to 03:00 PM	0.3	Following the high demand pattern.
03:00 PM to 04:00 PM	0.18	Low charging/ Most of the vehicles get charged.
04:00 PM to 06:00 PM	0.15	Following the low demand pattern.
06:00 PM to 07:00 PM	0.2	Moderate charging during post-office hours.
07:00 PM to 08:00 PM	0.3	Following the high demand pattern (evening entertainment).
08:00 PM to 09:00 PM	0.18	Back to low charging/ Most of the vehicles get charged.

09:00 PM to 10:00 PM	0.15	Low charging, back home.
10:00 PM to 12:00 AM	0.1	Very low grid charging activity. Vehicles are typically parked at home or away from charging infrastructure.

Considering a single-node sector coupling model for a 41 GW generation system with a large battery connected to the grid for the entire EV fleet, the estimations for average daily demand profiles and EV battery parameters are used in this study as a test case and are calculated in Table 3 as follows:

Table 3: EV Average Daily Demand and Battery Parameters Calculations

Parameters	Description/ Calculation	Unit
Average daily daytime driving demand	$\frac{4.7 \times 10^6}{365} = 12,877$	MWh
Average daily night-time driving demand	$\frac{2.2 \times 10^6}{365} = 6,027$	MWh
Total Average daily driving demand	$12,877 + 6,027 = 18,904$	MWh
Charging and Discharging efficiency	90% and 95%	%
Round-trip efficiency	$90\% \times 95\% = 85.5\%$	%
Required daily grid energy after losses	Average Daily Driving demand/ Round Trip Efficiency = $\frac{18,904}{85.5\%} = 22,110$	MWh
Min SoC	20% (Standard Battery protection limit).	%
Max SoC	95% (Standard Battery protection limit).	%
Initial SoC	50%	%
Standing losses	0.5%	
DoD	$\text{DoD} = 1 - \text{Min SoC (\%)} = 80\%$	%
Battery total capacity required	Required grid energy/ DoD = $\frac{22,110}{80\%} = 27,637 \cong 28,000$	MWh
Min SoC	Battery Capacity $\times$ Min SoC (%) = $28,000 \times 20\% = 5,600$	MWh
Max SoC	Battery Capacity $\times$ Max SoC (%) = $28,000 \times 95\% = 26,600$	MWh
Initial SoC	Battery Capacity $\times$ Initial SoC (%) = $28,000 \times 50\% = 14,000$	MWh
Net Battery usable capacity	Battery Capacity $\times$ DoD = $28,000 \times 80\% = 22,400$	MWh
C-rate	Recommended daily cycling = 0.4C	C
Charger rated capacity	Battery Capacity $\times$ C-rate = $28,000 \times 0.40 = 11,200$	MW

From Table 3, charging efficiency is defined as the ratio of energy stored to energy supplied and is assumed to be at a minimum of 90%, while discharging efficiency, the ratio of useful energy delivered to stored energy, is taken as 95% under standard operating conditions. The C-rate, which measures charge/discharge current relative to battery capacity (1C = one hour), typically ranges from 0.2 to 1C in industry practice (BL Energy, n.d.). However, this study adopts a

balanced value of 0.4C to estimate the EV fleet's charger power capacity. A daily standing loss of 0.5% is assumed for the EV fleet battery storage, consistent with the lower bound of the typical 0.5% to 3% daily charge loss reported for most modern EVs when parked with non-essential features disabled (*Recharged Editorial*, 2025). The state of charge (SoC) is constrained between a minimum of 20% and a maximum of 95% as per standard battery protection limits.

5.1.3. Designing EV Battery Charging Model

The Gurobi solver minimizes total system cost subject to energy balance, SoC bounds and charger availability factors. Additionally, Figure 17 provides a 24-hour demand profile along with grid prices. The optimization objective minimizes net grid generation costs, as represented below:

Objective Function:

Minimize (for 24 hours): (Base Load + EV Charging Load) × Marginal Cost

Subject to:

i) SoC Limits:

Min SoC (MWh) = 5,600 MWh (Table 5).

Max SoC (MWh) = 26,600 MWh (Table 5).

ii) SoC Initial Condition:

Initial SoC (MWh) = 14,000 MWh (Table 5).

iii) **SoC Energy Balance:** SoC at each time step evolves based on the previous SoC, accounting for charging, discharging, and standing losses.

iv) **Total Energy Requirement:** Total charging over 24 hours satisfies the daily EV energy demand.

v) **Charger Constraints:** Charging power is non-negative and limited by charging availability factors.

The next section presents scenario-specific results, detailing the EV model's outcomes and comparing them with the base case.

5.1.4. PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices

The results of EV integration with wholesale grid prices are represented in Figure 18. In this scenario, the EV battery charging model optimizes charging decisions based on real-time wholesale electricity prices. The results successfully shifted 22,110 MWh of charging demand, while simultaneously considering both high charging availability factors and lowest-price hours (09 AM to 10 PM) with an average charging price of Rs 12,671/MWh. The day-night distribution shows almost 65% and 35% daytime and nighttime charging, respectively and directly addresses the wind curtailment issues by creating new demand during daytime.

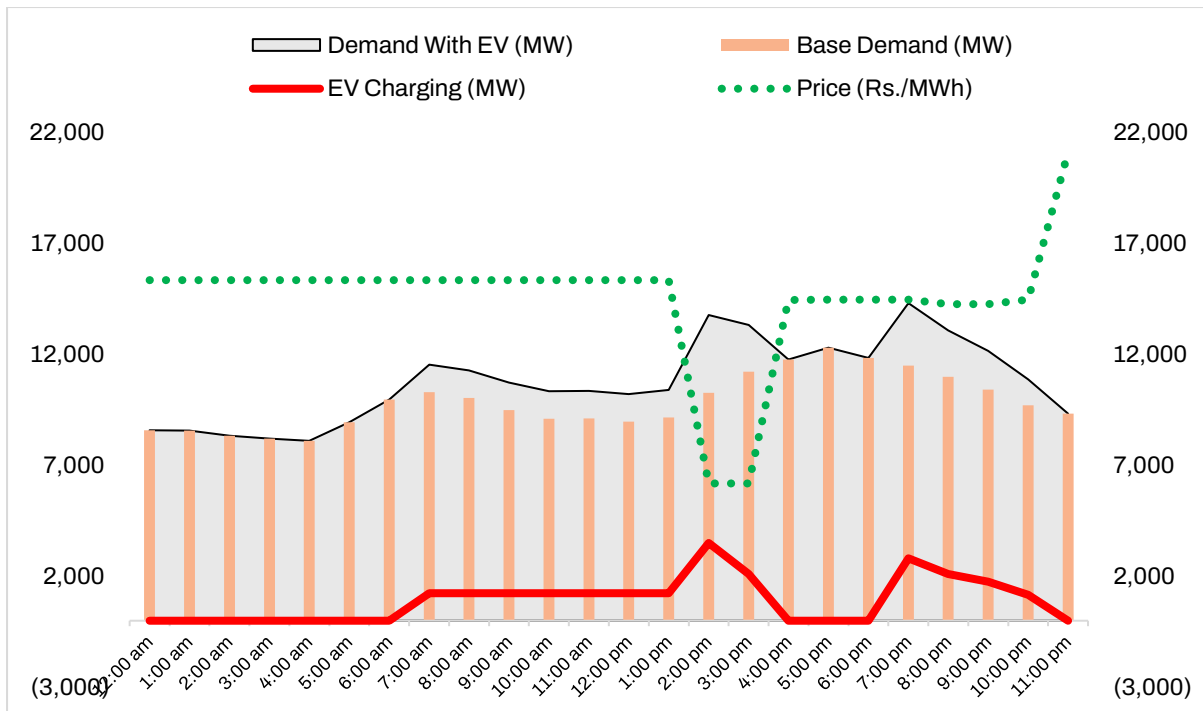


Figure 18: PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices

Moreover, it is also observed that peak demand rises from 12,295 MW at 05:00 PM to 14,301 MW at 07:00 PM, with peak charging reaching 3,500 MW during the evening again at 07:00 PM, perfectly aligning with charging availability factors. The difference of peak hours before and after EV demand integration is 2,006 MW, which strictly highlights the price-based optimization, along with the utilization of surplus generation based on charging availability factors. At the same time, the uncoordinated price signals can create new peaks and require real-time demand response signals to adjust these peaks. Total system cost reaches Rs 3,684 million with EV charging contributing Rs 280 million, representing efficient utilization of wasted generation capacity. Table 4 provides a summary of the overall results of Scenario-1.

Table 4: Summary of PtE Scenario-1 Results: EV Integration with Wholesale Grid Prices

Matrix	Values	
Total System Cost (Million Rs.)	3,684	
Net EV Charging Cost (Million Rs.)	280	
Average Charging Price (Rs. /MWh)	12,671	
Peak Values	Without EV (Base)	With EV
Peak Demand (MW)	12,295 at 05:00 PM	14,301 MW at 07:00 PM
Peak Charging (MW)	-	3,500 at 07:00 PM
Day and Night Distribution	Quantum	Share
Daytime Charging (MWh)	14,281	65%
Nighttime Charging (MWh)	7,829	35%

5.1.5. PtE Scenario-2 Results: EV Integration with Fixed Charging Price

In this scenario, the EV battery charging model optimizes charging decisions under an EV fixed uniform tariff structure of Rs 33.08 /kWh as determined by (NEPRA, 2026), rather than responding to time-varying wholesale prices. From Figure 19, it can be observed that with a flat rate across all hours, the price signal for temporal load shifting is eliminated. In this scenario, the optimization behaviour follows the initial EV demand, which is 68% and 32% of the charging demand during daytime and nighttime and charging availability factors simultaneously. The net EV charging quantum again fulfils the charging demand of 22,110 MWh. At the same time, the EV charging cost escalates significantly to Rs 731 million with a fixed EV tariff. Total system cost rises to Rs 4,135 million despite serving the same EV demand. This leads to an economic inefficiency introduced when price signals are removed, and charging decisions cannot arbitrage low-cost surplus generation periods.

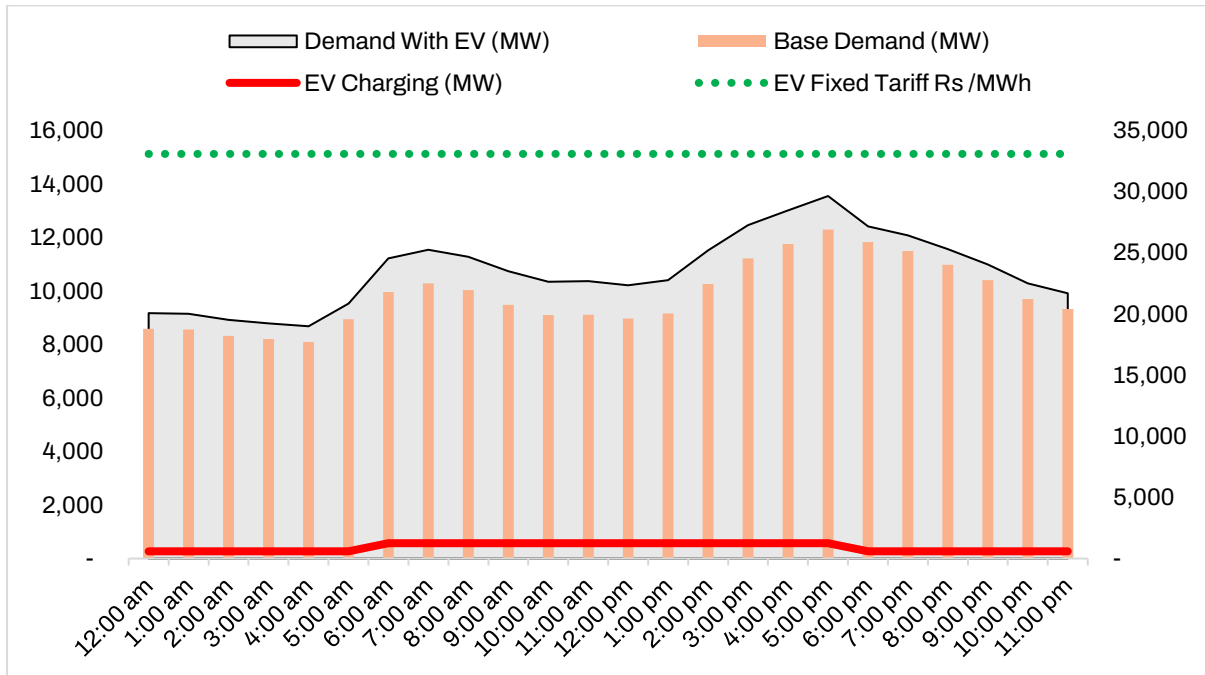


Figure 19: PtE Scenario-2 Results: EV Integration with Fixed Charging Price

Additionally, in Scenario-2, peak demand with EV increases to 13,548 MW at 05:00 PM, while charging reaches a constant 1,253 MW from 05:00 PM to 06:00 PM. However, the flattened pattern reduces distribution stress and avoids new system peaks and **fails** to capture sector coupling benefits due to the fixed EV tariff. Table 5 provides a summary of the overall results of Scenario 2.

Table 5: Summary of PtE Scenario-2 Results: EV Integration with Fixed Charging Price

Matrix	Values	
Total System Cost (Million Rs.)	4,135	
Net EV Charging Cost (Million Rs.)	731	
Average Charging Price (Rs. /MWh)	33,086	
Peak Values	Without EV (Base)	With EV
Peak Demand (MW)	12,295 at 05:00 PM	13,548 at 05:00 PM

Peak Charging (MW)	-	1,253 at 05:00 PM
Day and Night Distribution	Quantum	Share
Daytime Charging (MWh)	15,035	68%
Nighttime Charging (MWh)	7,075	32%

In conclusion, dynamic pricing mechanisms provide flexibility for both EV owners and grid operators when coupled with real-time demand response programmes for valley filling. The net system cost in Scenario 2 (Rs 4,135 million) is higher than in Scenario 1 (Rs 3,684 million), resulting in a net profit of Rs 451 million for EV owners. Additionally, the average charging cost of Scenario-1 is 2.6 times less than that of Scenario-2. This translates to net EV charging being more efficient under dynamic pricing, demonstrating that time-varying tariffs enable cost-efficient utilization of surplus generation capacity while supporting grid stabilization objectives.

5.2. Power-to-Industry (Ptl)

Industrial electrification provides another pathway for sector coupling by introducing flexible electricity demand within energy-intensive industries through Power-to-Industry (Ptl). The industrial sector is a backbone of Pakistan's economy and serves as a vital engine for economic growth and employment. In FY-2025, the sector recorded a growth of 4.77%, recovering from previous contractions (Pakistan Economic Survey 2025). This growth, however, masks underlying challenges, particularly in large-scale manufacturing (LSM), which constitutes 67.5% of overall manufacturing activity (*PES [Manufacturing & Mining]*, 2025). The high input costs and structural bottlenecks have led to continued contractions. The performance of key industries such as textiles, automobiles, pharmaceuticals, and chemicals remains mixed, which highlights the sector's vulnerability to energy price volatility and fluctuating demand.

Ptl offers a significant opportunity for sector coupling by introducing flexible electricity demand within energy-intensive industries. Unlike traditional baseload operation, dynamic valley filling takes advantage of the inherent flexibility of industrial processes to increase electricity consumption during periods of low grid demand or high renewable generation. This approach helps stabilize the grid by absorbing excess power, thereby reducing curtailment and improving overall system efficiency. However, successful implementation requires careful consideration of process constraints, operational safety, and economic viability across different manufacturing sectors, ensuring that demand-side flexibility is harnessed without compromising product quality or production targets. To maintain this competitive edge and manage the increased production demands of expanding markets, the industry is adopting advanced operational strategies to optimize energy consumption. The following are the two base scenarios that are implemented as test case studies for efficient dynamic valley filling for overall industrial demand:

- Base Scenario-1: High Wind Curtailed Day.
- Base Scenario-2: Targeted Valley Filling Day.

Base Scenario-1: High Wind Curtailed Day

In this scenario, the demand profile is taken from Section 5.1, corresponding to 27th November, 2025. This day is selected to represent a low-demand system condition characterized by significant wind curtailment and underutilization of available renewable energy.

Base Scenario-2: Targeted Valley Filling Day

In this scenario, a targeted valley-filling approach is adopted to identify and analyze days with significant load imbalances. From the system operator's perspective, the hours between 05:00 PM and 03:00 PM are mostly considered critical for valley filling, while the remaining hours (04:00 AM to 04:00 PM) are treated as non-valley periods. To determine the most suitable period for intervention, monthly averages of both valley and non-valley demands are evaluated, and the corresponding minimum valley months are identified as represented in Figure 20.

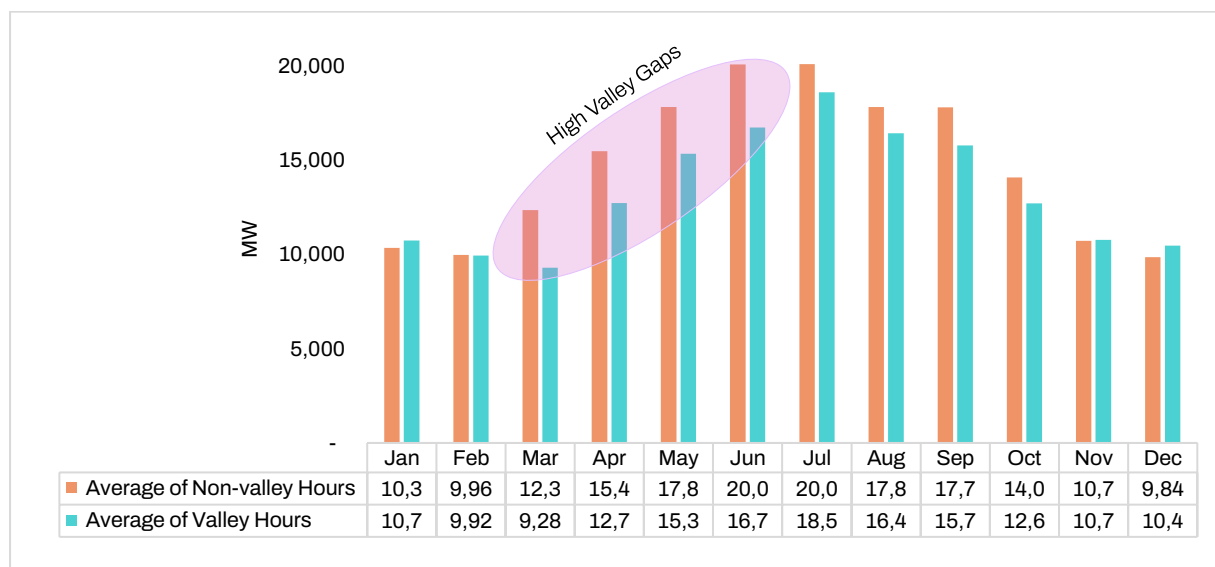


Figure 20: FY-2025 Monthly Average Profiles of Valley and Non-valley Hours (MW)

Graph is designed by the authors based on the data by (ISMO, 2025).

Based on this analysis, as observed in Figure 20, June is selected for detailed assessment, as it exhibits the highest gap between valley and non-valley demand profiles. Further detailed examination is carried out to determine the highest valley day in June. For that purpose, an average daily delta is calculated as follows:

$$\text{Avg. Daily Delta (MW)} = \text{Avg. of Daily Non-valley Hours (MW)} - \text{Avg. of Daily Valley Hours (MW)}$$

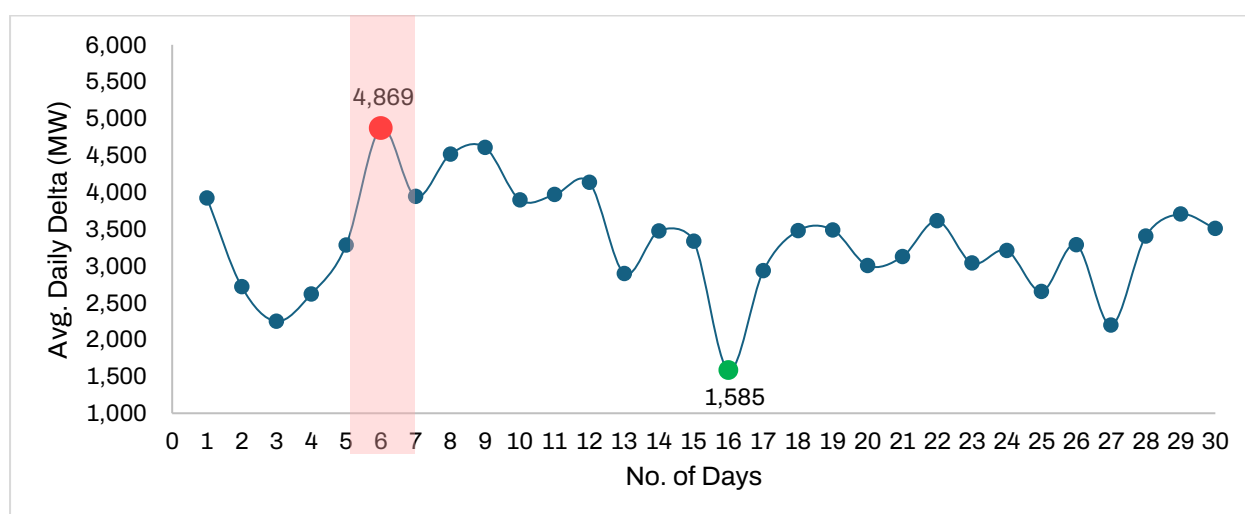


Figure 21: Average Daily Delta (MW) for 6th June, FY-2025

Graph is designed by the authors based on the data by (ISMO, 2025).

The calculated results (Figure 21) of Average Daily Delta reveal that on 6th June, FY-2025, it reaches a maximum of 4,868 MW, indicating a significant opportunity for additional industrial demand. Therefore, this day is selected as the representative base case for implementing and evaluating the targeted industrial load flexibility under Base Scenario-2. The real-time demand and price data observed on 6th June, FY-2025 is represented in Figure 22.

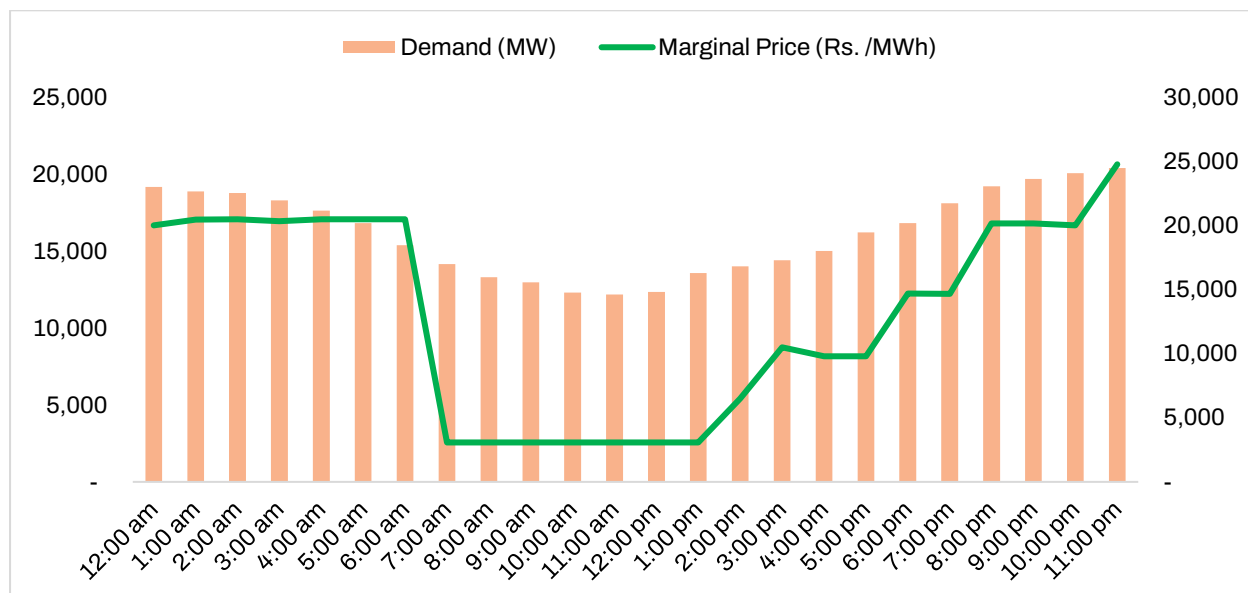


Figure 22: Ptl Scenario-2: 6th June, FY-2025, Marginal Price (Rs. /MWh) vs. Net Demand Profile (MW) (ISMO, 2025)

To assess the impact of industrial electrification and sector coupling, a dynamic valley-filling model is designed for both scenarios to evaluate the potential of the sector coupling strategy. The next section will provide the overall model structure along with operational constraints.

5.2.1. Model Formulation and Operational Constraints

Designing Linear Optimization Framework

To evaluate the role of industrial demand flexibility in sector coupling, a price-responsive linear Gourbi's optimization framework is used for this study. The optimization model operates by systematically exploring a range of possible configurations for flexible industrial load. In each iteration, a specific combination of two parameters is selected, which includes the maximum allowable industrial demand and the total daily energy that must be consumed by the industrial sector. For each such combination, the model uses linear programming to distribute the flexible load across the 24 hours of the day, respecting physical constraints such as hourly demand bounds and a ramping limit. The objective in each iteration is not to minimize the actual electricity cost directly, but rather to minimize a composite index formed by the total grid demand at each hour multiplied by a weighted average of two normalized values. These values represent the base demand profile (prioritize load following) and the other represents the electricity price (prioritize price-responsive shifting). These coefficients allow system planners, market participants, and grid operators to work under border objectives and deliver the solution toward a trade-off between flattening the grid load and manipulating cheaper price periods. The overall optimization process is discussed below:

Objective Function:

Minimize (for 24 hours): Base Grid Demand $\times$ (Demand Coefficient $\times$ Normalized Industrial Demand + Price Coefficient $\times$ Normalized Grid Prices)

Subject to:

i) **Load Balance:** The total grid load at each hour equals the sum of base electricity demand and the flexible industrial load.

ii) **Daily Energy Requirement:** Total industrial consumption over 24 hours meets the required energy target within specified limits.

iii) **Industrial Demand Bounds:** Industrial load remains within minimum and maximum limits (MW).

iv) **Ramp Rate Limit:** A limit is applied for the change in industrial load between consecutive hours for smooth operations (15% of maximum daily demand for hybrid technology).

v) **Demand Target Range:** Daily industrial energy consumption satisfies minimum required levels (MWh).

vi) **Weight Normalization Coefficients:** Demand Coefficient + Price Coefficient = 1 with both demand and price coefficients must be ≥ 0 .

Further, the following Table 6 provides the initial inputs for the optimization process.

Table 6: Input parameters for the optimization process for both Ptl Base Scenarios

Parameters	Values
Minimum Industrial Load (MW)	501
Maximum Industrial Load (MW)	100,000
Minimum Daily Energy Requirement (MWh)	12,000
Maximum Daily Energy Capacity (MWh)	6,000,000
Minimum Flexible Demand (MW)	500
Demand Coefficient	0.75 (higher priority to demand)
Grid Price Coefficient	0.25 (lower priority to price)

Performance Score Model

After the optimization solves an iteration, several performance metrics are calculated from the resulting load schedule, most notably the total electricity cost and the variance of hourly load. A performance score is assessed using a normalized composite score function that combines cost and load variance, derived from the optimized total grid demand. This process repeats every combination of parameters and iterations, generating a complete set of feasible solutions. For each metric, the iteration with the best minimum value obtained from the performance score function, having minimum system cost and low variance, is considered as the optimal iteration result to select the maximum allowable industrial demand along with grid stability. The resulting performance metrics guide the selection of the optimal solution for dynamic valley filling, as discussed below.

Performance Metrics:

i) **Total Electricity Cost:** Total cost based on real-time electricity prices.

ii) **Average Load:** Average system demand over the entire 24 hours.

iii) **Load Variance:** Variance of load, indicating the degree of flattening.

vi) **Performance Score Function (Multi-objective Trade-off):** The iteration 'x' with the lowest performance score function represents the optimal trade-off and is represented as:

Minimize: $P_{score}(x) = \text{Normalized Value of Total System Cost (x)} + \text{Normalized Value of Load Variance (x)}$

v) **Peak, Shoulder, and Valley Demand Categories:** These categories represent the highest and lowest load levels, capturing peak stress and valley utilization. Valley hours are the nine hours with the lowest demand, peak hours are the six hours with the highest demand, and the remaining nine hours are classified as shoulder.

5.2.2. Optimization Results and Dynamic Pricing Analysis

The optimization process effectively redistributes additional industrial electricity demand over 24 hours, increasing consumption during low-demand periods and limiting it during peak hours. To achieve a balance among low-demand targets, operational flexibility, and economic efficiency, the optimizer has tested the optimal configuration in both base scenarios.

Ptl Base Scenario-1 Results: Figure 23 presents the optimized load profile for Scenario-1, where a constant 3000 MW industrial load is scheduled during the early morning valley hours (12:00 AM to 5:00 AM). The base demand during these hours ranges from approximately 8,500 MW at midnight down to 8,900 MW by 5:00 AM, providing a deep valley that can absorb additional flexible load without stressing the grid. By concentrating the added industrial demand in this period, the optimizer effectively fills the overnight trough while considering ramp-rate limits and demand-price priorities, resulting in a significantly smoother total load shape compared to the original base profile.

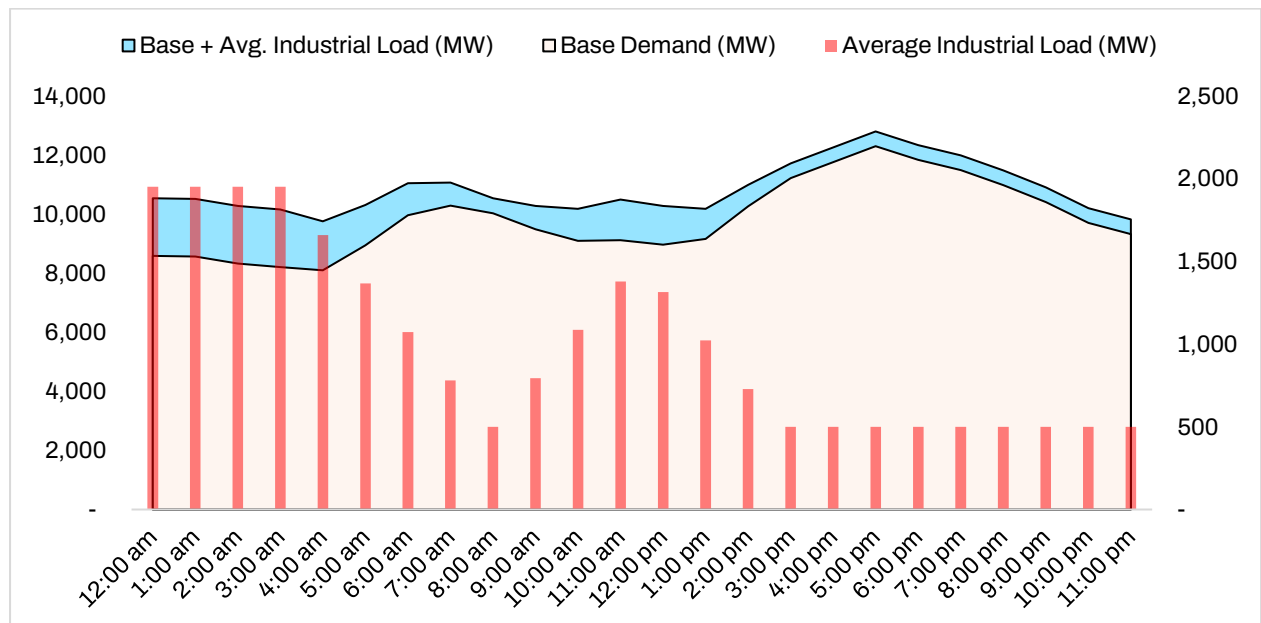


Figure 23: Ptl Base Scenario-1 Results: Optimized Industrial Load (MW) vs. Net Grid Demand (MW)

Table 7 summarizes the optimal configuration for Scenario 1. As per constraints, the flexible industrial load is allowed to vary between 500 MW and 1,951 MW, delivering a total daily energy of 24,000 MWh under a ramp limit of 293 MW/hour. The additional system cost is Rs 3,760 million and the performance score of 0.0516 confirms an excellent trade-off between cost minimization and load flattening. The optimization process effectively redistributed consumption to align with system conditions, resulting in 42% of total demand incurred during daytime hours

and 58% during nighttime hours. Further, Figure 24 represents the optimized scheduling successfully shifts load into valley hours, which constitute 61% of total hours, reflecting effective valley filling. Shoulder hours account for 27%, indicating moderate load levels, while peak hours are minimized to just 13%, demonstrating significant peak reduction. This distribution confirms that the flexibility strategy achieves a well-balanced, flatter load profile, enhancing grid stability and operational efficiency.

Table 7: Summary of Ptl Base Scenario-1 Results.

Parameters	Values
Industrial Load Range (MW)	500 to 1,951
Total System Demand (MWh)	24,000
$P_{score}(x)$	0.051588
Ramp Rate Limit (MW/hour)	293
Total System Cost (Million Rs.)	3,760
Load Share Distribution (%)	Day: 42% Night: 58%

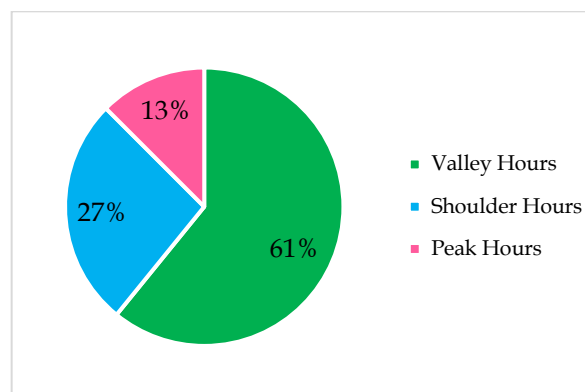


Figure 24: Ptl Base Scenario-1 Results: Category-wise distribution of optimized industrial load shares

It is worth noting that the annual curtailed wind energy in FY-2025 is 491,892 MWh (on an average of 1,348 MWh per day), the additional industrial demand emerges as the most suitable candidate for sector coupling with wind power. The fertilizer industry, particularly green ammonia production via electrolysis, is highly suitable for coupling with wind power. Its continuous but flexible Electrolyzer operation can utilize curtailed wind energy to produce ammonia, effectively storing renewable energy in chemical form while decarbonizing both the power and industrial sectors.

Ptl Base Scenario-2 Results: Figure 25 illustrates the optimized load distribution for Scenario-2, where approximately 67% of the total additional industrial energy is concentrated during the daytime hours from 7:00 AM to 1:00 PM. This period coincides with exceptionally low real-time grid electricity prices, which remain fixed at Rs 3,076 /MWh, and significantly lower grid demand levels ranging between 12,000 and 14,000 MW. By aligning the flexible load with both price signals and existing grid troughs, the optimizer achieves an efficient valley-filling pattern that utilizes the daytime demand at its maximum level without intensifying peak stress.

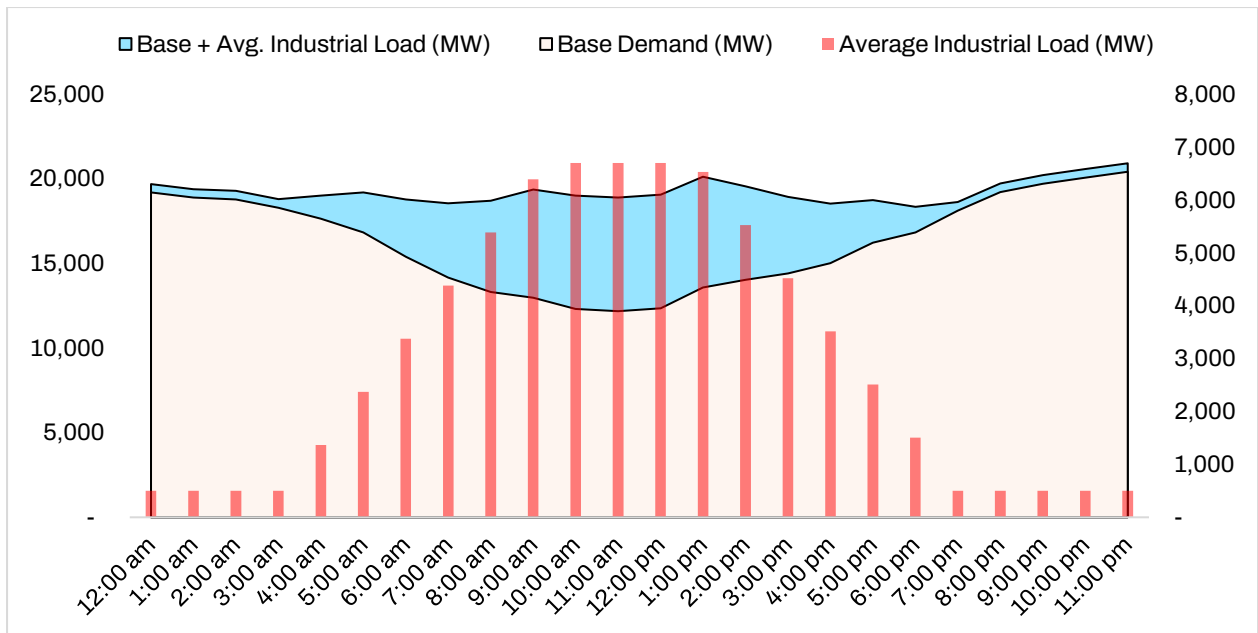


Figure 25: Ptl Base Scenario-2 Results: Optimized Industrial Load (MW) vs. Net Grid Demand (MW)

Further, Table 8 presents the optimal configuration parameters for this scenario. The industrial load is allowed to vary between 500 and 6,701 MW, delivering 72,000 MWh of daily energy under a ramp limit of 1,005 MW/hour. The resulting system cost is Rs 6,120 million with a performance score of 0.0778, and the load is heavily skewed toward daytime (86% day and 14% night). The optimized daytime load shape creates an incentive to allocate additional grid capacity for cold storage and recycling industries, enabling them to expand operations during periods of low demand and low prices without stressing the overall grid system. This form of sector coupling unlocks valuable flexible space for industrial growth, turning daytime troughs into opportunities for productive energy use. Additionally, Figure 26 describes the optimized scheduling results in valley hours comprising 73% of the total hours, indicating an additional load into low-demand periods. Shoulder hours account for 22%, while peak hours are reduced to 4%, demonstrating a significant flattening of the overall load profile. This distribution confirms that the flexibility strategy effectively balances grid demand, enhancing stability and operational efficiency.

Table 8: Summary of Ptl Base Scenario-2 Results

Parameters	Values
Industrial Load Range (MW)	500 to 6,701
Total System Demand (MWh)	72,000
$P_{score}(x)$	0.077845
Ramp Rate Limit (MW/hour)	1,005
Total System Cost (Million Rs.)	6,120
Load Share Distribution (%)	Day: 86% Night: 14%

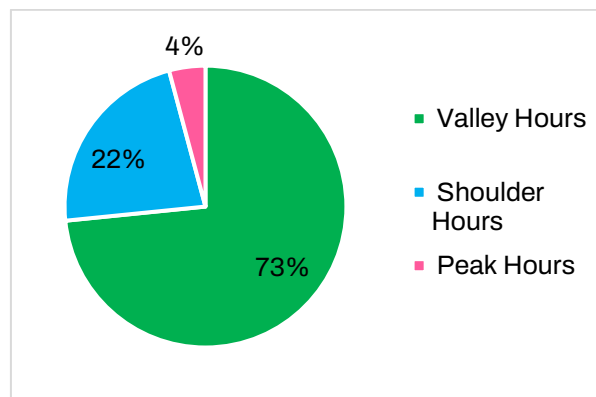


Figure 26: Ptl Base Scenario-2 Results: Category-wise distribution of optimized industrial load shares

In the comparison of two base scenarios, these results demonstrated that sector coupling can be a viable option in both nighttime and daytime grid conditions. Scenario-1 offering a cost-efficient, wind-curtailed, focused solution to secure Chinese investments in wind power projects. Scenario-2 provides a more aggressive load-shaping strategy suited for industrial sectors like

cold storage and the recycling industry that favor daytime operation. Both scenarios confirm that flexible industrial demand can effectively absorb surplus energy while improving grid stability. The next section presents detailed policy recommendations and a way forward utilizing these sector-coupling strategies.

POLICY RECOMMENDATIONS AND WAY FORWARD



6. Policy Recommendations and Way Forward

Building on the quantitative evidence from sector coupling analyses in transport and industry, this section presents a comprehensive set of policy recommendations to unlock Pakistan's sector coupling potential. The assessment of electricity consumption patterns, demand profiles, technology utilization, and wind curtailment trends highlights key structural barriers as well as emerging opportunities within the energy system. The recommendations are organized around four thematic pillars:

- (i) Policy and regulatory framework.
- (ii) Infrastructure and technological development.
- (iii) Financial and market development.
- (iv) Capacity building and training.

Each pillar outlines the core challenges, followed by targeted policy actions and a structured implementation approach to guide effective execution.

6.1. Strengthening Policy and Regulatory Framework for Sector Coupling

Issue 1: Absence of a Cross-Sectoral Policy Framework for Sector Coupling

Pakistan's energy sectors operate in institutional silos, governed by separate regulators (NEPRA for power, OGRA for oil and gas) and guided by policies that lack coordination. The National Electricity Policy 2021, National Electricity Plan 2023-27, Indicative Generation Capacity Expansion Plan (IGCEP), and Transmission System Expansion Plan (TSEP) do not contain provisions for sector coupling pathways. This results in planning documents that ignore the full potential of flexible industrial loads, EV-grid integration, and power-to-hydrogen to reduce curtailment and enhance grid flexibility. Consequently, investors face uncertainty when considering cross-sector projects that could utilize curtailed wind energy for productive purposes such as green ammonia production or valley-filling industrial operations.

Issue 2: Lack of Regulatory Framework for Flexible Loads and Ancillary Services

The optimization results (Section 5.2) demonstrated that flexible industrial loads can effectively shift 24,000-72,000 MWh of daily energy to valley hours, reducing peak demand shift and improving grid stability over a period of 24-hours. However, no regulatory mechanism exists to value or compensate for such flexibility. The existing tariff structure does not incentivize demand response, and there is no market for ancillary services (frequency regulation, voltage support) that sector-coupled assets could provide. Furthermore, the absence of a certification system for renewable gases (green hydrogen, biomethane) prevents the creation of a transparent, tradable market and blocks access to export opportunities.

Issue 3: Geopolitical and Technical Barriers to Cross-Border Energy Trade

Geopolitical tensions and historical mistrust between neighbouring countries create barriers to negotiating long-term energy trade agreements and collaborative infrastructure projects. From a technical perspective, differences in grid codes, operational standards, and voltage levels require substantial investment in synchronization technologies, such as back-to-back HVDC systems, to ensure compatibility and reliability. Strengthening cross-border interconnections with India, Tajikistan, Bangladesh and Iran to balance VRE fluctuations faces significant challenges, limiting Pakistan's ability to export surplus renewable energy or import balancing power during peak demand. As illustrated in the regional power demand heat map (Figure 27), India-West exhibits High Demand only from January to March, followed by Low Demand from June to December,

presenting nine months of opportunity for Pakistan to export solar power if technical and political barriers are resolved. Furthermore, the map reveals that Bangladesh and India-East share nearly identical peak demand patterns (March–June and August–September), while Nepal and Bhutan peak in winter (January–February and November–December), meaning no single bilateral agreement can address all balancing needs. Pakistan requires a portfolio of differentiated season-specific trade agreements with multiple neighbours.



Figure 27: Seasonal power demand of neighboring countries of Pakistan (NSB, India, 2022)

Recommendations

- The government should mandate the inclusion of **PtX projects** in future iterations of the IGCEP and TSEP. This will ensure that infrastructure planning accounts for the load and generation profiles of EV charging networks, industrial electrolyzers, and renewable heating systems. NEPRA should develop a regulatory category for **Independent Flexibility Providers (IFPs)**, allowing aggregators to bundle demand response from industrial units and Vehicle-to-Grid mechanisms and sell flexibility as an ancillary service to the ISMO.
- Pursuant to Section 5.8.1 of the National Electricity (NE) Policy, the Government of Pakistan, through the Integrated Energy Plan (IEP) Secretariat (Ministry of Energy, Power Division) as the focal entity for integrated energy planning, should establish a dedicated **Sector Coupling Cell (SCC)** with representation from NEPRA, OGRA, ISMO, NGC, Ministry of Climate Change and the CPEC Authority to oversee cross-sectoral integration for a unified decarbonization roadmap.
- Chinese stakeholders, including **China State Grid Corporation (SGCC)**, **China National Petroleum Corporation (CNPC)**, and **China Machinery Engineering Corporation (CMEC)**, should engage with Pakistan's federal and provincial authorities to align CPEC energy projects with emission reduction and energy resilience targets. This could involve integrating clean energy goals into grid expansion projects, with a focus on decarbonizing the energy mix through investments in hybrid VRE solutions (solar, wind) and energy storage technologies, specifically targeting the wind curtailment issue at the Jhimpir-Gharo corridor.
- The Government of Pakistan, through the Ministry of Climate Change, should extend the **policy guidelines for trading in carbon markets** and establish a **National Carbon Credit Monetization Framework** for EV adoption and commercial charging infrastructure. Following Thailand's model, where Thai Smile Bus trades carbon credits with Switzerland's Klik Foundation, with over 27% of Bangkok's buses electric as of

September 2024 (Laoonual, 2024), Pakistan should prioritize electrifying two- and three-wheelers and mandate solar-integrated charging infrastructure in office buildings and malls. The framework must include simplified Monitoring, Reporting and Verification (MRV) protocols for distributed EV assets, enabling aggregators to sell verified credits to international buyers (e.g. Klik Foundation, South Korea's ETS). Revenues can subsidize EV upfront costs and accelerate smart charging deployment, directly supporting the valley-filling flexibility.

- The government should prioritize the development of a **smart grid infrastructure** that incorporates advanced metering, real-time monitoring, and two-way communication systems to enhance grid management, operational efficiency, and renewable energy integration. This will enable better demand-side management, reduce losses, and improve grid stability, directly supporting the dynamic valley-filling strategies validated in Section 5.2.
- In extension to the sector coupling approach analyzed, future avenues may include the Renewable Gases such as Biogas, Green Hydrogen, Green Ammonia and Biomethane. NEPRA, in consultation with the private sector, should establish a transparent national **Renewable Gas Guarantee of Origin (RGGO) system**, based on international models (e.g. the European Union's Guarantees of Origin). This certification system will track the renewable origin and carbon intensity of gases like biomethane, biogas, and renewable hydrogen, enabling the coupling of gas and electricity sectors. It allows renewable gas attributes to be independently verified and traded alongside large-scale generation certificates (LGCs) under the Greenpower framework (GPRGC Rules, 2024). This RGGO framework is particularly relevant for green ammonia production using curtailed wind energy.

Term	Role	Key Action Items
Short-term	MoPE, MoPD&SI, NEPRA, OGRA, CPEC Authority, PPMC & MoCC	Develop a comprehensive sector coupling framework under IEP with defined targets and regulatory mandates. Initiate stakeholder consultations for RGGO system design along with international partners. Extend the policy guidelines for trading in carbon markets and establish a National Carbon Credit Monetization Framework for EV adoption and commercial charging infrastructure.
	SGCC, CNPC, CMEC, Chinese private sector	Align CPEC energy projects with emission reduction and energy resilience targets. Propose pilot PtX projects under CPEC and Chinese B2B investments.
Medium term	NEPRA, OGRA, ISMO, PPMC	Finalize and enforce regulations for IFPs and the ancillary services market. Operationalize the RGGO certification system.
	MoEP, NEPRA, DISCOs	Mandate time-of-use tariffs for all public EV charging stations and large industrial consumers (at least initially 500 kW).
Long-term	MoEP, NEPRA, ISMO, PPMC, MoFA.	Fully integrate sector coupling provisions into IGCEP and TSEP planning cycles. Establish cross-border energy trading mechanisms with neighbouring countries using synchronized grid codes.

6.2. Developing Infrastructure and Technological Solutions for Sector Coupling

Issue 1: Inadequate Grid Infrastructure for Variable Renewable Energy Integration

The existing grid infrastructure and operational models lack the granularity required to accurately simulate and predict voltage recovery dynamics under varying dynamic loads like air-conditioning, thermal heating, and cooling loads. This limitation is further impaired by the absence of sufficient real-time load data and advanced measurement systems across different regions in transmission planning. It is revealed in Section 4.4 that wind curtailment escalated from 99 million kWh in 2020-21 to 1.34 billion kWh in 2023-24, with a financial loss of nearly Rs 39 billion in 2023-24 alone. While curtailment reduced to 491 million kWh in 2024-25 with persistent structural inefficiencies indicate an urgent need for infrastructure upgrades and flexibility solutions.

Issue 2: Limited Infrastructure Support for Urban and Rural Microgrids for Sector Coupling Initiatives

The development of urban and rural microgrids faces significant challenges due to inadequate policy frameworks, insufficient financial incentives, and limited grid infrastructure readiness for sector coupling integration infrastructure. Decentralized solar microgrids could provide reliable power to areas where traditional grid expansion is prohibitively expensive and logistically challenging. Moreover, the absence of smart grid technologies capable of managing two-way energy flows hinders the strategic sector coupling initiatives.

Issue 3: Limited Industrial Capacity for Local Manufacturing of Grid Equipment

The local manufacturing of critical grid equipment (e.g. STATCOMs, shunt capacitors, electrolyzers, battery storage systems) faces challenges due to Pakistan's limited industrial capacity and technological expertise. The lack of infrastructure for high-precision manufacturing and quality assurance processes could impact on the reliability and competitiveness of locally produced equipment. This dependency on imports increases costs, delays project implementation, and limits the scalability of sector coupling solutions.

Issue 4: Untapped Opportunity for Large Energy Storage Systems (ESS) during High and Low Valley Gap Months

As illustrated in Figure 28, the months of March, April, May, and June exhibit the highest valley-filling gaps, with June peaking at 3,354 MW, followed by March (3,058 MW), April (2,753 MW), and May (2,481 MW). These low and high-delta months represent a prime opportunity for large Energy Storage Systems (ESS) to capture curtailed renewable energy by charging in low and high valley months to high demand months (July, August and September). It is worth noting that annual curtailed wind energy in FY-2025 stands at 491,892 MWh (averaging 1,348 MWh per day). The fertilizer industry, particularly green ammonia production via electrolysis, is highly suitable for coupling with wind power. Its continuous but flexible Electrolyzer operation can utilize curtailed wind energy to produce ammonia, effectively storing renewable energy in chemical form while decarbonizing both the power and industrial sectors.

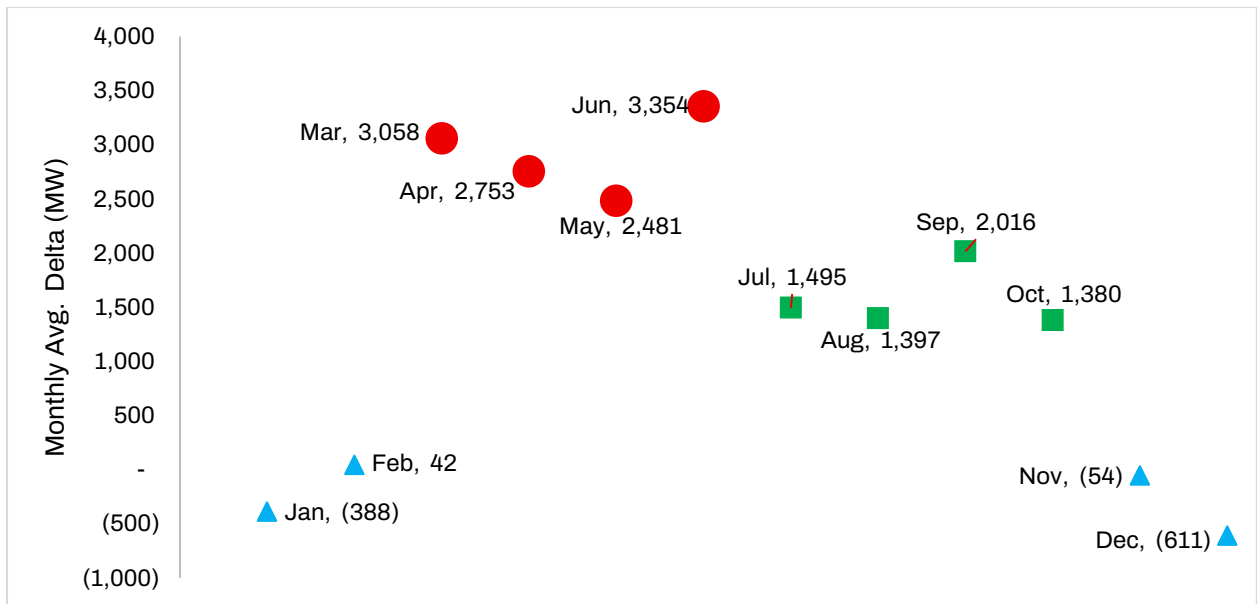


Figure 28: Monthly Average Delta (MW) for FY-2025

Graph is designed by the authors based on the data by (ISMO, 2025).

Issue 5: Neglecting High-Impact Opportunity for Cold Storage and Recycling Industries During Daytime Valley Hours

Figure 29 presents cooling discharge patterns for four Iranian cities (Arak, Esfahan, Bandar Abbas, Yazd) alongside Pakistan's grid demand on June 6th, FY-2025 (Base Scenario-2). Bandar Abbas climate is similar to Karachi's, sustaining cooling discharge from 7:00 AM to 8:00 PM, aligning with Pakistan's daytime valley period. Arak and Esfahan peak between 11:00 AM and 5:00 PM, while Yazd concentrates demand in the early afternoon. All profiles confirm that cold storage naturally shifts electricity consumption to daytime valley hours when prices drop to Rs 3,076 /MWh (from 07:AM to 01:00 PM) as per Pakistan's grid demand on June 6th, FY-2025. Further, the analysis of Base Scenario-2 results with 72,000 MWh average daily consumption with 86% daytime share confirms that cold storage and recycling industries are ideally suited for this aggressive load-shaping strategy. However, Pakistan is still neglecting this high-impact opportunity, which can effectively absorb surplus energy while improving grid stability.

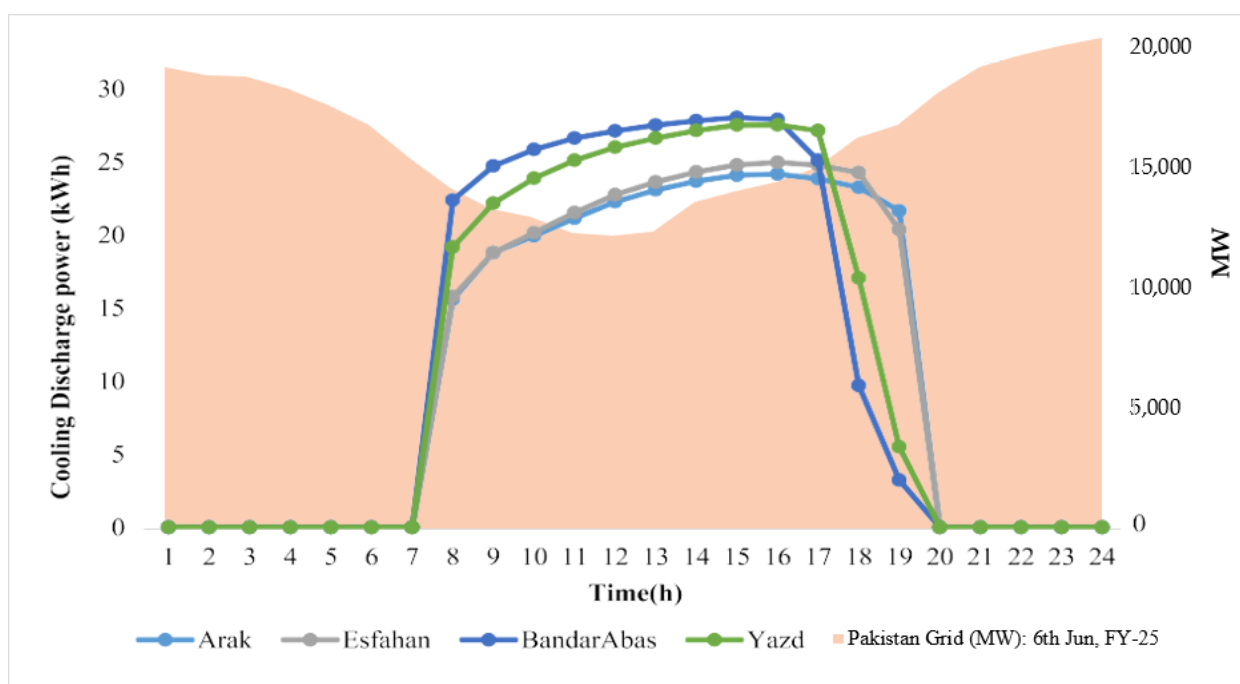


Figure 29: Iran city-wise cooling discharge patterns (kWh) vs. Pakistan's grid demand (MW) on 6th Jun, FY-25

Graph is designed by the authors based on the data sources by (ISMO, 2025; Mehdipour et al., 2025)

Recommendations

- The Ministry of Energy (Power Division) (MoEP) must take steps for the inclusion of sector coupling-specific equipment in Tier 2 and Tier 3 programmes under the **Power Sector Indigenization Plan (PSIP) 2026–2035**, led by the Engineering Development Board (EDB) and the Power Planning and Monitoring Company (PPMC). It is essential to strengthen the localization of advanced energy systems in Pakistan. By prioritizing components such as electric vehicle charging infrastructure, industrial electrification technologies, thermal storage systems, electrolyzers for hydrogen production, and smart grid interfaces, the initiative can accelerate the integration of power, transport, and industrial sectors. This will not only reduce reliance on imported technologies but also foster domestic manufacturing capabilities, enhance supply chain resilience, and support innovation in emerging clean energy domains. Ultimately, embedding sector coupling technologies within PSIP will drive indigenization, improve energy efficiency, enable flexible demand management, and position Pakistan to transition towards a more integrated, sustainable, and self-reliant energy ecosystem.
- **Chinese technology providers** like SGCC, ZTE, Huawei, and **China National Electric Equipment Corporation (CNEEC)** should assist in developing and deploying advanced short-circuit management tools, real-time fault detection technologies, automated diagnostic tools, and smart grid solutions. Chinese stakeholders could also support the NTDC in training personnel to use these tools effectively for grid management. Specific focus should be placed on **Chinese-made smart grid solutions** (e.g. from Huawei, ZTE) to improve real-time monitoring and load data collection.
- Prioritize utility-scale ESS deployment at Jhimpir-Gharo wind corridor during high-delta months (March-June) to capture curtailed wind energy. Facilitate 10-year PPAs between wind farm operators and fertilizer producers (Fauji Fertilizer, Engro) for green ammonia offtake.
- Establish a "Daytime Valley-Filling Industrial Tariff" for cold storage and recycling facilities committing 70%+ consumption during 7:00 AM–4:00 PM. It will further allow them to participate in the ancillary services market as Independent Flexibility Providers (IFPs).

- The Ministry of Energy (Power Division), in coordination with the National Electric Power Regulatory Authority (NEPRA), National Grid Company (NGC), Central Power Purchasing Agency (CPPA-G), and distribution companies (DISCOs), should establish a robust grid price forecasting framework to enable dynamic pricing and improve demand-side flexibility. This should include the deployment of AI-enabled load forecasting models, renewable generation forecasting tools, weather-linked demand projections, and short-term market analytics to predict hourly and day-ahead electricity prices. Accurate price signals would allow industrial, commercial, and large residential consumers to shift consumption to low-cost periods, support time-of-use and real-time tariff reforms and incentivize participation in ancillary services and demand response programmes. Such a system would improve grid efficiency, reduce peak demand stress, lower system costs, and enhance the integration of variable renewable energy into Pakistan's power system.

Term	Role	Key Action Items
Short-term	MoEP, NGC, ISMO, PPMC	Develop a comprehensive short-circuit management roadmap, focusing on critical substations. Initiate feasibility studies for a 100 MW large ESS and BESS at the Jhimpir wind corridor.
	Chinese technology providers (Huawei, ZTE, SGCC, CNEEC)	Deploy advanced real-time monitoring and fault detection systems at pilot substations. Provide technical training for NGC engineers.
	MoEP, MoIP, NEPRA, DISCOs	Approve Daytime Valley-Filling Tariff. Launch pilot programmes in Karachi, Faisalabad, and Lahore.
Medium term	Chinese ESS firms, Fauji Fertilizer, and Chinese partners.	Conduct feasibility for a 100 MW large ESS + 50 MW BESS integrated project for Green Ammonia production.
	MoIP, CPEC Authority, and Chinese recycling firms.	Conduct a feasibility study for cold storage units and establish the first pilot projects for cold storage, integrated with the recycling industry, at the Faisalabad Industrial Estate with a 100 MW grid capacity.
	MoEP, EDB, PPMC, NGC Chinese private partners	Initiate Tier 2 and Tier 3 programmes under PSIP for the indigenization of the sector coupling ecosystem.
Long-term	MoEP, NGC, EDB, Chinese private partners	Complete the development of energy storage hubs under the CPEC framework. Establish a fully functional local manufacturing ecosystem for electrolyzers, BESS, and smart grid equipment, charging infrastructure, reducing reliance on imports by 50%. Execute 10-year PPA to commission pilot by the end of 2036.

6.3. Creating Viable Financial and Market Models for Sector Coupling

Issue 1: High Upfront Capital Costs and Lack of Concessional Financing

High upfront capital costs for PtX technologies (e.g. a 240 kW fast charger costs between Rs 18.2 million to 18.5 million) and a lack of dedicated, concessional financing mechanisms make projects financially unviable. For this reason, investors are currently facing significant exchange

rate volatility and tariff unpredictability. The existing circular debt crisis, which exceeded Rs 1.6 trillion in September 2025, further disrupts private investor confidence. However, under Scenario-1 dynamic pricing, EV owners achieve a net profit of Rs 451 million within 24 hours. This 24-hour analysis can be extended on an annual basis to capture a sustained positive margin. The gap is that despite this demonstrated annual profit potential, no policy or regulatory mechanism exists to convert the projected annual earnings into a bankable assurance that de-risks upfront capital investment, leaving investors unable to access concessional financing.

Issue 2: Absence of Revenue Models for Sector-Coupled Assets

Currently, no revenue models exist for sector-coupled projects. Without long-term offtake agreements for green hydrogen or a transparent market for grid flexibility services, private investment cannot be justified. The existing tax structure treats key sector coupling technologies with high tariffs, taxes, and levies that destroy their economic case. For example, imported electrolyzers face customs duties of 10-20% plus additional taxes, adding 30-40% to project costs. Similarly, battery storage systems are classified as "end-consumers" rather than "energy storage assets," subjecting them to electricity taxes and levies that reduce their operational viability.

Issue 3: Financial and Operational Constraints in Debt Recovery and Market Reforms

In the current situation, enforcing debt recovery in high-default areas and implementing performance-based tariffs are hindered by significant financial and operational constraints. High-default regions often have socioeconomic challenges where consumers cannot pay due to low-income levels, and targeted recovery campaigns may face resistance without addressing underlying affordability issues. The circular debt crisis directly impacts DISCOs' ability to pay independent power producers (IPPs), including Chinese-owned wind and solar projects, undermining investor confidence in Pakistan's power sector.

Recommendations

- The government should facilitate **bankable business models** for sector coupling. This includes:
 - Facilitating EV charging infrastructure (Levels 1, 2, and 3) and battery swapping stations through public-sector entities (e.g. PPIB and provincial transport authorities) to capture the mass two- and three-wheeler market, with priority deployment at office buildings, shopping malls, public parking zones, and high-density urban corridors to enable carbon credit monetization under the proposed framework.
 - Utilizing **Public-Private Partnerships (PPPs)** to co-finance large-scale, integrated renewable hubs (solar/wind + storage).
 - Directing NEPRA to create an **ancillary services market** where BESS and aggregated flexible loads can bid for frequency regulation, voltage support, and black-start services, creating a new revenue stream for sector-coupled assets.
- The Government of Pakistan should establish a **Sector Coupling Investment Facility (SCIF)** under the State Bank of Pakistan to channel concessional loans, blended finance, and credit guarantees specifically for sector-coupled projects. This facility should expand SBP's existing RE financing scheme to include PtX projects (electrolyzers, BESS, EV charging infrastructure, smart grid upgrades).
- The government should provide **targeted tax and tariff incentives** for sector coupling components. Grant investment tax credits (up to 30% of project cost), import duty exemptions (0% customs duty), and a 5-year tax holiday for critical equipment such as EV charging infrastructure, BESS, and heat pumps etc.
- The government should issue sovereign and corporate **Sukuk Bonds** specifically assigned for sector coupling infrastructure (ESS, electrolyzers, EV charging networks,

etc.) to mobilize domestic institutional investors (pension funds, Islamic banks) and tap into global sustainable finance.

Term	Role	Key Action Items
Short-term	MoE, MoF, SBP, NEPRA	Establish SCIF framework and approve first tranche of concessional financing (Rs. 50 billion). Issue first sector coupling specific Sukuk (target initially with USD 500 million).
	Chinese banks (CDB, ICBC), Chinese investors	Participate in SCIF as co-financiers. Anchor the first Green Sukuk issuance.
Medium term	MoE, MoF, NEPRA, CPPA-G, ISMO	Operationalize the ancillary services market for frequency regulation and voltage support. Approve performance-based tariffs for DISCOs.
	MoE, SBP, Chinese private partners	Mobilize initially at least USD 2 billion in private investment (Chinese and domestic) for sector coupling projects through SCIF credit enhancements.
	FBR, EDB, MoIP, MoEP	Reduce taxes and duties under different phases of the sector coupling specific products.
Long-term	MoE, MoF, NEPRA, DISCOs	Mandate flexible load participation (industrial demand response, EV aggregators) and storage integration (utility batteries, hybrid solutions). Achieve 50% reduction in circular debt through improved DISCO performance (loss reduction, billing efficiency) and new revenue streams from ancillary services fees, carbon credit sales (EVs, buildings), and wheeling charges for power-to-hydrogen projects.

6.4. Building Institutional and Technical Capacity for Sector Coupling

Issue 1: Fragmented Institutional Governance for Cross-Sectoral Integration

Institutional governance for energy and climate is critically fragmented. No single entity has the mandate or authority to oversee cross-sectoral integration, leading to a fundamental disconnect between national climate ambitions and on-the-ground energy policy. The transformative potential of sector coupling to achieve decarbonization targets remains systematically overlooked and untapped in Pakistan's core climate action plans, including the Nationally Determined Contributions (NDCs). The recently established ISMO is a positive step, but it currently lacks the technical capacity, market systems, and regulatory mandate to value and procure flexibility from sector-coupled assets.

Issue 2: Significant Skills Gap in Emerging Technologies

A significant skills gap exists in regulatory bodies (NEPRA, OGRA), financial institutions (SBP, commercial banks), and industry regarding PtX technologies, smart grid systems, and sector coupling project financing. This impedes effective regulation, due diligence, and project implementation. Many existing project managers in power planning in the public sector lack

exposure to modern planning tools, agile principles, and integrated energy system modeling. The absence of experienced trainers and collaboration with international entities complicates the development of personalized training modules.

Issue 3: Limited Data Transparency and Digitalization

The absence of a national energy data-sharing platform that provides integrated data on VRE generation forecasts, grid congestion, transmission constraints, and gas pipeline flows hinder investor site selection and business planning. The NGC and ISMO currently operate with limited real-time data sharing, and historical curtailment data is not systematically published. This lack of transparency increases investment risk and prevents the optimization of sector-coupled assets.

Recommendations

- The Government of Pakistan should mainstream sector coupling in climate commitments by integrating sector coupling pathways and targets into Pakistan's updated NDCs. This will align with and attract international climate finance, including the Green Climate Fund (GCF) and the Global Environment Facility (GEF).
- The government should launch a **National Capacity Building Programme** for sector coupling. This programme should:
 - Develop partnerships with international agencies (IRENA, World Bank, ADB), Chinese institutes (Tsinghua University, NDRC's Energy Research Institute), and private sector firms to train regulators, bankers, and engineers on sector coupling technologies, risk mitigation strategies, and project finance.
 - Establish a **Pakistan-China Center of Excellence for Sector Coupling** at a leading university to lead R&D, standardization efforts, and workforce development. The center should offer certification programmes for system operators, energy managers, and grid planners.
 - Organize capacity-building workshops and training to train project managers in modern execution methodologies (e.g., agile frameworks, PyPSA modeling, Gurobi optimization). The government should engage private entities (Chinese firms) to co-finance and expedite delayed projects through hands-on training.
- The government, in partnership with ISMO and NGC, should develop a **National Energy Data Sharing Platform** that provides integrated data on:
 - Hourly VRE generation forecasts (wind, solar) at the plant level.
 - Real-time grid congestion and transmission constraints.
 - Historical curtailment data (wind, solar) by location and cause.
 - Gas pipeline capacity and flow data.
 - This platform will assist investors in site selection, business planning, and risk assessment. Chinese technology partners (e.g., **Huawei, ZTE, Alibaba Cloud**) can provide the digital infrastructure and data analytics capabilities for this platform.
- The government should enhance ISMO's development with specific functionality to:
 - Procure ancillary services (frequency regulation, voltage support, black start) from aggregated flexible loads and BESS.
 - Manage capacity obligations and settlement of energy imbalances for PtX facilities.
 - Enable compliance monitoring for all market participants, including IFPs and virtual power plant operators.
- Chinese-led infrastructure projects under CPEC offer an excellent opportunity for **knowledge and technology transfer** in areas such as smart grid development, energy-efficient appliances, Electrolyzer manufacturing, and capacity-building workshops. By aligning these investments with local workforce training, both sides can work towards creating a sustainable and energy-efficient environment. **Chinese firms (SGCC, Huawei, Longi)** should establish training partnerships with Pakistani universities and technical institutes to provide hands-on training in agile

methodologies, modern tools, and software for power planning, using real-world case studies from CPEC projects.

Term	Role	Key Action Items
Short-term	MoE (Power Division), MoPD&SI, NEPRA, OGRA, ISMO, CPEC Authority	Establish the SCC under IEP. Initiate consultations for NDCs integration. Launch the National Capacity Building Programme with Chinese partners.
	Chinese institutes (Tsinghua University and ERI-NDRC), Chinese firms (Huawei, ZTE, SGCC)	Sign MOUs for Pakistan-China Center of Excellence. Deploy a pilot energy data sharing platform for the Jhimpir-Gharo wind corridor.
Medium term	MoE, ISMO, NGC, NEPRA, Chinese technology partners	Operationalize ISMO with ancillary services procurement. Fully launch the National Energy Data Sharing Platform with real-time data feeds.
	Pakistani universities, Chinese private partners	Establish the Pakistan-China Center of Excellence for Sector Coupling with degree programmes and certification courses. Train 500+ energy professionals.
Long-term	MoE, NEPRA, OGRA, ISMO	Fully integrate sector coupling into NDCs and national climate reporting. Achieve recognition as a regional hub for sector coupling expertise, attracting investment from the Middle East and Central Asia.

7. Conclusion

Pakistan's energy sector is trapped in a structural paradox: a 41 GW capacity surplus burdened by crippling "Take-or-Pay" capacity payments, coexisting with forced curtailment of zero-marginal-cost renewable energy. This study demonstrates that sector coupling offers a pragmatic, data-driven escape by shifting the policy paradigm from perpetual supply-side expansion to intelligent demand-side optimization. The empirical analysis validates that dynamic pricing mechanisms are an absolute prerequisite for sustainable EV integration, with optimization models proving that price-responsive charging automatically shifts load to low-cost, high-supply hours, absorbing surplus generation and reducing system costs by Rs 451 million within a single day. Similarly, Power-to-Industry simulations confirm that shifting flexible industrial loads to valley hours can absorb 24,000–72,000 MWh of daily curtailed energy, directly rescuing stranded Chinese wind investments in the Jhimpir-Gharo corridor while simultaneously reducing peak demand stress and flattening the national load curve.

The significance of these findings extends beyond technical feasibility. Economically, sector coupling offers a mechanism to break Pakistan's power sector "death spiral" by spreading fixed capacity costs over a larger volume of utilized energy units, mathematically lowering the per-unit basket price of electricity. Strategically, substituting imported fossil fuels with domestically generated electricity through PtX pathways enhances national energy security and improves the balance of payments. Environmentally, the frameworks enable decarbonization of hard-to-abate industrial and transport sectors without requiring massive new investments, aligning Pakistan with global climate trajectories while solving immediate local crises. However, realizing such potential demands profound regulatory restructuring, institutionalizing the dynamic Time-of-Use tariffs, authorizing Direct Power Purchase Agreements, creating markets for Independent Flexibility Providers, and establishing concessional financing vehicles like the Sector Coupling Investment Facility supported by Sovereign Green Sukuk issuance.

Future research must address critical gaps that this study could not fully explore. Multi-node grid modeling incorporating actual transmission constraints is essential to identify optimal investment locations and quantify reinforcement requirements. A detailed techno-economic assessment of Power-to-Gas pathways, particularly green hydrogen production, storage economics, and export potential to regional markets and remains urgently needed. Vehicle-to-Grid integration modeling, including battery degradation costs and ancillary service revenue streams, would unlock additional grid flexibility. Cross-border energy trade analysis with neighboring countries, socio-economic impact assessments, and behavioral studies of industrial consumer response to dynamic pricing would provide the granular evidence required for phased implementation. By addressing these research priorities, Pakistan can transform sector coupling from a proven concept into a fully operational framework, positioning itself as a regional leader in integrated energy systems and attracting the international climate finance essential for a just, sustainable transition.

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9. ANNEXURE I: GLOBAL SECTOR COUPLING MODELS

Power-to-Gas and Industrial Integration

To manage the systemic bottlenecks caused by massive renewable energy deployments across Europe, Transmission System Operators are actively redirecting curtailed electricity to power large-scale industrial electrolyzers. The EU has strategically prioritized Polymer Electrolyte Membrane (PEM) electrolyzers due to their exceptionally fast ramp-up and ramp-down capabilities, allowing them to rapidly absorb excess gigawatts and perfectly mirror the high-frequency volatility of wind and solar generation. This Power-to-Gas (PtG) pathway fundamentally solves the seasonal storage dilemma; while conventional lithium-ion batteries suffer from degradation over long periods, electrolytic green hydrogen can be heavily compressed and stored in underground salt caverns or blended into natural gas pipelines for use during winter energy deficits. The economic viability of this coupling is guaranteed by the EU Emissions Trading System (ETS), which financially compels manufacturers to substitute fossil fuels with green hydrogen for extreme high-heat processes like steelmaking and agricultural ammonia synthesis. Furthermore, the EU maximizes systemic efficiency through thermodynamic cascading, capturing the massive volumes of low-grade waste heat generated during electrolysis and feeding it directly into municipal district heating networks to displace residential fossil-fuel boilers.

Power-to-Mobility and Vehicle-to-Grid Ecosystems

While the rapid proliferation of Electric Vehicles (EVs) initially threatened to overload localized low-voltage distribution networks during peak evening charging hours, the EU has aggressively mitigated this by transforming these fleets into millions of decentralized, bidirectional battery storage units. This Power-to-Mobility (PtM) transition relies entirely on widespread bidirectional smart meters, Vehicle-to-Grid (V2G) hardware, and highly dynamic Time-of-Use (ToU) wholesale pricing. Because passenger vehicles are parked for over 90% of their lifespans, automated smart-charging software financially incentivizes consumers to charge during peak renewable generation, effectively valley-filling the load curve. Conversely, during peak grid demand, V2G technology allows these batteries to discharge a calculated portion of their stored power back into the network. In advanced pilot programmes, commercial "Aggregators" pool the storage capacity of tens of thousands of EVs and bid it directly into national ancillary service markets. Utilizing digital inverters, these aggregated EV fleets provide millisecond-level frequency regulation and peak shaving, vastly outperforming the mechanical ramp rates of traditional thermal peaking plants and stabilizing the grid without the need for expensive fossil-fueled backup generation or greenfield transmission expansions.

China's Experience with Sector Coupling

Overcoming the Thermodynamic Bottleneck via Decoupling

The massive curtailment of wind in China's "Three Norths" (Sanbei) region was fundamentally driven by the thermodynamic configuration of the generation fleet, which was heavily dominated

by coal-fired Combined Heat and Power (CHP) plants utilizing back-pressure and extraction condensing turbines. During the winter, dispatch was governed by a rigid "heat-led" operational mode known as *yi re ding dian* (Chen et al., 2015). Because the production of electricity and high-temperature steam were physically locked together within the thermodynamic cycle of these specific turbines, the plants could not be ramped down when baseline electricity demand plummeted at night, resulting in total transmission saturation. To break this physical link, the primary technological intervention involved deploying utility-scale, high-voltage electrode boilers, often exceeding 50 MW capacities with exceptional 99% energy conversion efficiencies, directly adjacent to existing CHP infrastructure (IRENA, 2019). Crucially, these electric boilers were physically paired with massive sensible thermal energy storage (TES) systems. By utilizing heavily insulated, stratified water tanks capable of holding thousands of cubic meters of thermal fluid, these systems act as a massive buffer for the generated heat, completely decoupling the heating obligation from the thermal power plant.

Operational Flow and Peak-Valley Arbitrage

This decoupled infrastructure enables a highly efficient peak-valley arbitrage cycle designed to structurally absorb curtailed renewable energy. The cycle begins with nocturnal charging; when nighttime wind speeds spike, deeply discounted tariffs trigger the industrial electric boilers to turn on. The grid operator seamlessly reroutes the excess zero-marginal-cost wind power directly into these boilers, and the generated heat is safely banked in the massive stratified thermal storage tanks rather than being immediately consumed (Chen et al., 2015). Conversely, the system switches to daytime discharging when electricity demand peaks and wind speeds typically fall. During this period, the electric boilers are entirely shut down, and the industrial facilities simply draw the stored thermal energy from the tanks to meet their continuous heating requirements. This operational flow perfectly valley-fills the electrical load curve by monetizing trapped nighttime wind, all without adding any additional stress to the daytime grid peak.

Table below shows the comparative analysis of global sector coupling models and their relevance for Pakistan

Table 9: Comparative Analysis of Global Sector Coupling Frameworks

Feature	The European Union (EU) Model	The Chinese Model (Northern Provinces)
Primary Objective	Macro-level decarbonization and deep, economy-wide integration of electricity, gas, heat, and transport networks.	Surgical resolution of acute grid bottlenecks, specifically mitigating massive variable renewable energy (VRE) curtailment.
Core Technologies	Polymer Electrolyte Membrane (PEM) Electrolyzers; Vehicle-to-Grid (V2G) bidirectional EV chargers.	High-Voltage Industrial Electrode Boilers; Sensible Thermal Energy Storage (TES) tanks.
Target Sectors	Heavy industry (steel, chemicals), long-haul and passenger transportation, and municipal district heating.	Concentrated, energy-intensive industrial parks and existing municipal district heating networks.
Primary Grid Function	Providing macro-scale flexibility, millisecond frequency regulation (via EVs), and long-term seasonal energy storage (via hydrogen).	Localized "valley-filling" to absorb nocturnal off-peak wind generation and physically decouple heat production from legacy coal turbines.
Market Mechanisms	Highly dynamic Time-of-Use (ToU) tariffs; EU Emissions Trading System (ETS) carbon pricing; Ancillary service bidding for EV aggregators.	Extreme "Peak-to-Valley" wholesale tariff arbitrage; Direct Power Purchase Agreements (DPPAs) between wind farms and heating companies.
Relevance to Pakistan	Provides a long-term blueprint for utilizing EV fleets as grid assets and structuring ToU tariffs to incentivize intelligent demand.	Provides an immediate, direct parallel for resolving localized wind curtailment and overcoming the "must-run" inflexibility of thermal baseload plants in the southern corridors.