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From Structural Indices to Behavioral Benchmarks: A Comprehensive Assessment of Market Power in Pakistan's Evolving Electricity Market Considering Transmission Constraints

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ABSTRACT

This study evaluates market power in Pakistan's evolving electricity market, considering underlying transmission network constraints, using 10 structural and behavioral indices—a significant expansion beyond the single existing study that examined only four structural indices. Anticipating a shift toward day-ahead auctions, we combine capacity-based structural analysis with bid-based behavioral modeling. Structural indices generally show low concentration, though the Herfindahl–Hirschman Index indicates moderate levels. Our behavioral Lerner Index (LI) assessment, a first for Pakistan, reveals competitive conditions ($LI = 0.39$) under cost-based generation, but a substantial 62% increase to 0.63 under strategic bidding scenarios. Critically, temporal disaggregation exposes intraday volatility masked by daily averages: LI rises from 0.17 during off-peak hours (h02–h07) to 0.53 at peak (h12–h17), and reaches an extreme of 0.80 at the maximum-price hour (h15). This granularity confirms that market power risks are pronounced during high-price periods, whereas aggregate averages significantly dilute these acute risks. The study demonstrates that bid-based modeling uncovers risks missed by structural analysis alone, offering vital guidance for regulators preparing for competitive market implementation. Finally, our framework provides a replicable template for monitoring liberalizing electricity markets, particularly in transitional economies where strategic bidding behaviors may emerge alongside structural reforms.

1 | Introduction

Electricity is one of the basic needs of a country, and it plays a crucial role in a country's economy and of electricity. In the case

of Pakistan, generation, transmission, and distribution functions are performed by separate companies, but the National Electric Power Regulatory Authority (NEPRA) still regulates the power market. This type of centralized market offers stability but may

Abbreviations: α , alpha coefficient; β , beta coefficient; AMES, agent-based modeling of electricity systems; EC, Entropy Coefficient; FERC, Federal Energy Regulatory Commission; GenCos, generators; HHI, Herfindahl–Hirschman Index; ISO, Independent System Operator; LI, Lerner Index; LMP, locational marginal price; LSE, Load Serving Entity; MC, marginal cost; NEPRA, National Electric Power Regulatory Authority; NTDC, National Transmission & Despatch Company; OPF, optimal power flow; RSI, Residual Supplier Index; SMA, Supply Margin Assessment; WPMP, wholesale power market platform.

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lack efficiency. In the longer run, Pakistan aims to shift from a regulated power market to a deregulated power market. A deregulated market, adopted mainly by developed countries, promotes competition by unbundling the power sector. Competition in the deregulated power markets generally leads to lower electricity prices and enhanced efficiency. However, deregulated power markets need strong regulation to curb market power, volatility, and reliability issues. Recent empirical evidence shows that market-based electricity reforms can improve dispatch efficiency, but imperfectly competitive wholesale markets may still increase markups and consumer prices, which makes market-power monitoring essential in deregulated electricity systems [1]. This concern is particularly relevant because many contemporary reforms advance through transitional or hybrid arrangements rather than through an immediate move from regulated monopoly to a fully liberalized wholesale pool. In such settings, market power should be assessed by examining the interaction between centralized and decentralized trading arrangements [2]. Sequential bidding evidence further shows that bidding formats and mitigation rules can alter both strategic behavior and market outcomes [3].

International experience reinforces this concern by showing that formal restructuring alone does not eliminate market-power risk when market design, network constraints, or ownership structures remain imperfect. In Colombia, market power persists because generation and retail activities remain integrated in parts of the electricity sector [4]. Brazil's wholesale market literature similarly argues that market rules require modernization as generation mixes, contracting arrangements, and operating requirements evolve [5]. Nigeria's 2023 market-competition assessment likewise evaluates competition within a staged transition toward deeper wholesale competition in the Nigerian Electricity Supply Industry [6].

Consumers are affected by the market power in various forms. Companies with price control can raise prices for consumers due to unfair competition. When a few companies dominate, customers have fewer options. Dominant companies create a barrier to new companies entering the market. Efficiency declines significantly as consumers end up paying more for less value for their money. Knowing market power indices before a deregulated power market in Pakistan rolls out is crucial for several reasons. Market power indices assess market power concentration, predict potential risks of market manipulation, and help ensure fair competition in the power market. In a newly deregulated power market, there could be a risk of the emergence of monopolistic or oligopolistic groups; market power indices can help identify these risks and enable regulators to avoid manipulation. Analysis of market power would help establish an appropriate regulatory framework for a deregulated power market. Understanding market power early on in Pakistan can help ensure that the electricity market is competitive, transparent, and beneficial to consumers. These international studies are relevant to Pakistan because competitive bilateral contracting and future short-term trading are emerging within a system still shaped by regulated procurement, legacy contracts, capacity-payment obligations, and network constraints. Pakistan-specific congestion-management evidence shows that dispatch procedures that overlook transmission-line loading constraints can increase the risk of overload, reinforcing the need to incorporate network constraints into market

monitoring and dispatch design [7]. Pakistan-specific reform literature also argues that competitive power-market development requires institutional arrangements that support sustainable competition [8]. Recent review evidence further emphasizes that market-power mitigation mechanisms should be embedded in market design before strategic behavior becomes fully established [9]. Three primary contributions of this paper are described as follows:

This study establishes new standards in market power assessment by evaluating all 10 major indices, representing the most comprehensive analysis conducted for any electricity market to date. Our work significantly surpasses previous studies that examined at most 7 indices for developed economies, while also advancing comparative market analysis through an extensive benchmarking of Pakistan's Herfindahl–Hirschman Index (HHI) against 38 country scenarios. This expansion beyond existing literature, where only two prior studies compared against 20+ countries, is complemented by our systematic compilation of 14 foundational studies, which provides researchers with the first consolidated reference framework for cross-country market power comparisons.

Our research breaks new ground in South Asian energy economics through multiple pioneering achievements. We present the inaugural behavioral Lerner Index (LI) calculation for Pakistan, revealing a significant disparity between cost-based and bid-based scenarios. This work also constitutes the first bid-wise market simulation using actual 2018 network constraints and simultaneously applies the most extensive set of market power indices (10 vs. the previous 4) to Pakistan's electricity market. The 2018-based analysis maintains its relevance as Pakistan's wholesale market retains its fundamental structure, with no substantial changes in either the generator portfolio or bidding behaviors that would fundamentally alter our baseline findings, despite ongoing reforms.

The study pioneers an innovative modeling framework that successfully bridges structural and behavioral analysis through AMES simulations. By anticipating future market designs, our approach simulates day-ahead auction dynamics and quantitatively demonstrates how strategic bidding inflates prices and amplifies market power. This work represents the first agent-based model capable of assessing both current bilateral contract dynamics and future competitive market scenarios in Pakistan, providing regulators with a unique decision-support tool to navigate market design transitions. The methodology's forward-looking capabilities offer particular value as Pakistan progresses toward more liberalized market structures.

The remainder of the paper is structured as follows: Section 2 presents a comprehensive literature review. Section 3 examines all significant market power indices. Section 4 details the research methodology. Section 5 provides results and discussions. Section 6 concludes and offers future insights.

2 | Literature Review of Market Power

The literature on market power in electricity markets is primarily organized into three main areas: market power fundamentals,

measurement methodologies, and modeling approaches. These areas provide a foundation for understanding, evaluating, and analyzing market power across various electricity market contexts. Recent literature also strengthens this framing by treating market power as a design-dependent issue rather than a purely structural outcome. Centralized and decentralized market arrangements differ in dispatch, transmission management, and participant autonomy [2]. Research on local and short-term electricity markets further shows that additional price-formation layers can create localized or time-varying market power [10].

2.1 | Market Power Fundamentals

This section discusses the concept of market power, detailing its definition, manifestations in electricity markets, and regulatory measures to prevent abuse. It aims to establish a fundamental understanding of how suppliers influence prices and how this conduct is monitored and regulated.

2.1.1 | Definition

Market power generally refers to a supplier's ability to raise spot prices above competitive levels to earn profits [11]. It results in financial benefits for the supplier(s) guilty of market power abuse. This market power abuse usually occurs when certain suppliers hold overwhelming market share and hence the power to influence or manipulate prices in their favor. Abuse of market power could result in unfair competition, price changes, market concentration, and transmission constraints.

2.1.2 | Manifestation Mechanism

Literature highlights the main methods of exercising market power: physical (quantity) withholding, economic (financial) withholding, and transmission congestion [11]. Physical withholding occurs when a supplier intentionally reduces its generation below its full capacity. By withholding its capacity, the supplier can create an artificial shortage in the generation. Consequently, prices increase in the market, and the supplier gets higher profits. Economic withholding means a supplier sets its price much higher than its actual production cost instead of offering a fair and competitive price. In this scenario, the supplier strategically offers to operate its generators to earn higher profits. Market power can also be exerted by a strategic supplier that owns transmission rights and uses them to create transmission congestion.

2.1.3 | Regulatory Implications

These forms of market power can be curbed by implementing mitigating measures such as monitoring participants and their behavior, which may lead to withholding strategies. Establishing and enforcing rules that prevent market manipulation in any form and ensure fair trading and transmission opportunities for participants is necessary to control market power. Market power must be carefully evaluated to curb its exercise and ensure that the market remains efficient and transparent. This regulatory

concern becomes more complex in hybrid electricity-market structures where bilateral contracts, regulated procurement, centralized dispatch, and short-term competitive trading coexist. In such settings, market power may arise not only from ownership concentration but also from transmission bottlenecks, contract positions, and pivotal capacity during peak hours [2]. Sequential market stages and bidding formats can also influence strategic behavior and market outcomes [3]. For Pakistan, this framing is more appropriate than assuming a fully deregulated pool market because the sector is still moving from a single-buyer structure toward competitive bilateral contracting and possible day-ahead trading [8]. Many methods and tools for identifying and measuring market power have been reported in the literature across different countries.

2.2 | Measurement Methodologies

This section outlines different methodologies for evaluating market power in electricity markets, including ex-ante (structural), post-ante (behavioral) indices, and other specialized indices introduced in recent studies to better capture subtle aspects of market influence and competition.

2.2.1 | Structural Indices for Basic Analysis

Structural indices remain essential for initial market power screening due to their computational efficiency and regulatory adoption, despite limitations in detecting strategic behavior [12]. HHI dominates structural analyses, with Rhoades demonstrating its superiority over simple concentration ratios [13]. While Borenstein [12] demonstrated limitations of HHI in predicting strategic withholding in California, Hellmer and Wårell [14] successfully applied HHI to Nordic market coupling. FERC revised its previous guidelines in 2010 by increasing the HHI thresholds used to establish competitive benchmarks [15]. Complementary measures serve distinct functions: Concentration Ratios (CR_n) effectively screen emerging markets (Turkey's CR₈ = 65.2% (2006) [16], Iran's CR₈ = 76.67% (2010) [17]), whereas the Residual Supplier Index (RSI) detects pivotal suppliers across diverse systems—from California [18] to Poland [19]. Modified versions of Concentration Ratios and HHI were tested in India to estimate market power [20]. At the same time, HHI and Entropy coefficient were assessed for the potential abuse in power markets [21]. However, three fundamental constraints of HHI persist: HHI's inability to capture dynamic strategic behavior [22]; network blindness ignores congestion effects [23]; and demand inelasticity assumptions often fail [12]. These shortcomings are particularly acute in transitional markets like Pakistan's, where must-run plants may create unique physical withholding risks despite moderate HHI/CR₈ values. Although structural indices provide necessary first-order screening, their inability to capture strategic behavior necessitates supplemental analysis, especially in markets undergoing liberalization where participants' incentives are evolving. Regulatory frameworks increasingly recognize this, maintaining structural thresholds [15] through encouraging more sophisticated behavioral and simulation approaches for comprehensive monitoring. Latest evidence from the Polish market confirms the continued relevance of HHI, RSI, and related structural measures for tracking evolving concentration

[19]. Recent review evidence further indicates that structural screening indicators are more useful when paired with mitigation mechanisms and behavioral monitoring in practical market design [9].

2.2.2 | Behavioral Indices for Comprehensive Insight

Behavioral indices have become indispensable for assessing exercised market power, overcoming the limitations of structural indices by analyzing actual market outcomes. During the California crisis, no single supplier held more than 20% of the market share, and the HHI value was 664; therefore, we cannot rely solely on structural indices for a comprehensive assessment of market power [17]. This paper also emphasizes how strategic bidding behavior can significantly alter market dynamics and considers that the LI is the same as Price–Cost Markup.

Wolfram established the foundation for behavioral analysis [22], whose Price–Cost Markup (PCM) study of the British spot market demonstrated the critical relationship between bidding behavior and marginal costs. This approach has since been validated across diverse markets, from Singapore's competitive pool (PCM (2005) 0.03–0.18) [24] to India's more concentrated wholesale market (PCM (2007–08) 0.74) [25]. Kamiński's longitudinal study of liberalization in Poland [26] further confirmed the sensitivity of behavioral indices to market design changes, showing changes in LI values following the 2008 reforms.

The behavioral paradigm extends beyond basic markup analysis to sophisticated withholding detection. Behavioral indices offer three key advantages: they capture actual rather than potential abuse [22], identify time-varying strategies [27], and incorporate network constraints [28]. However, implementation challenges persist, particularly regarding marginal cost estimation in regulated markets [29] and bid data availability issues [25]. For Pakistan's evolving market, behavioral indices provide essential tools to monitor post-reform strategic bidding and emerging congestion risks due to competing bilateral trading requests—gaps that structural indices alone cannot address. Transmission-congestion-aware analysis further shows that a zonal LI can distinguish unilateral market power from congestion rents and identify generators that exercise market power only in specific congested zones [30]. Recent two-stage market studies extend this logic by showing that mitigation rules can alter strategic incentives across day-ahead and real-time settlements [3]. Mitigation-aware bidding analysis further demonstrates that bidders may explicitly account for regulatory procedures when forming their offers [31]. Pakistan-specific reform literature supports the need for market-power assessment during the transition toward a competitive electricity market, and the present study extends this evidence by applying bid-wise behavioral assessment before market arrangements become fully mature [8].

2.2.3 | Specialized Indices for Subtle Aspects

The evolving complexity of electricity markets has spurred the development of specialized indices that address nuanced dimensions of market power beyond conventional structural and behavioral measures. Among these, network-constrained indices have

proven particularly valuable for identifying localized market power. Gan and Bourcier [23] pioneered the Must Run Ratio to quantify the extent to which a generator is pivotal in both zonal and nodal systems. Furthermore, Wang advanced this concept through Nodal Must Run Share indices that account for transmission bottlenecks using proportional tree methodologies [28]. These approaches have been further refined to assess influence in the reactive power market [32]. The Price offset Index and wealth transfer effects are taken into account in bilateral markets [33], demonstrating their adaptability to diverse market architectures.

Recent methodological innovations have produced indices tailored to emerging market challenges. The Return on Withholding Capacity (RWC) index, tested in the German-Austrian market [34], offers a dynamic alternative to the traditional RSI by quantifying the profitability of capacity-withholding strategies. Social network analysis has also entered the field through centrality indices [35], which evaluate market power by grid topology in contrast to conventional generation share metrics. Particularly relevant for developing countries are hybrid indices such as the Contribution Congestion Factor Matrix and the Location Privilege Surplus Deviation Index [36], which simultaneously address market concentration and infrastructure constraints but require deregulated market and bid-wise data.

The Must-Use Quantity and Must-Cut Quantity indices [37] could effectively monitor demand-side market power in emerging pool-based markets. Similarly, the Structure-Conduct-Performance Framework [38] provides a holistic assessment tool for transitional markets undergoing liberalization. However, implementation barriers persist, including data requirements for nodal indices [39] and computational complexity of network-aware metrics [32]. Recent research on local electricity markets shows that market power can extend beyond conventional generator concentration, as local trading, distributed resources, demand response, and flexible assets add further layers to price formation [10]. These developments reinforce the need for regulators in emerging markets to build monitoring frameworks before market complexity increases [9]. Even though these specialized indices have not yet been applied to Pakistan's market, several show particular promise for developing economies. For Pakistan's evolving power sector, these advanced indices represent valuable directions for future research following the implementation of a deregulated market structure, particularly as the system evolves toward more sophisticated market designs where conventional indices may prove inadequate.

2.3 | Modeling Approaches for Market Power Analysis

To effectively analyze market power in electricity markets, various modeling approaches have been employed, each offering distinct strengths in capturing strategic behavior and market dynamics. These approaches range from analytical game-theoretic models to simulation-based methods, such as agent-based and hybrid models. This section provides a comprehensive overview of these methodologies, highlighting their application in assessing market power across different market structures and conditions.

2.3.1 | Game-Theoretic Models

Game theory provides essential frameworks for analyzing strategic behavior in electricity markets, with the Cournot model proving particularly influential. Borenstein [12] demonstrated its effectiveness in explaining California's market power crisis, while subsequent refinements addressed real-world complexities. Gan and Bourcier [23] incorporated security constraints through quasi-equilibrium concepts. Ahn and Niemeyer tailored Cournot models for Korea's developing market, highlighting strategic behaviors related to transmission [40]. The field then expanded with Barroso [41] modeling competitive bidding in bid-based hydrothermal systems via static and dynamic Cournot-Nash frameworks. Recent advances like Bansal et al. [3] investigation of market power in two-stage electricity markets, through analysis of supply function bidding and quantity bidding mechanisms, provide policymakers with empirical selection criteria. Latest mitigation-aware bidding research further shows that generators may anticipate regulatory procedures when forming offers [31]. This insight is relevant to Pakistan because a future day-ahead or short-term market may combine competitive bids with regulatory safeguards rather than operate as an unconstrained pool [8].

However, game theory's reliance on centralized optimization and complete information limits its ability to capture crucial complexities of the real world: asymmetric information and autonomous decision-making. These limitations have spurred the development of agent-based modeling, which simulates decentralized interactions while preserving proprietary data and strategic autonomy. Such an agent-based approach is particularly valuable for Pakistan's evolving market, where regulatory visibility into participant behavior remains limited. While game theory continues to offer valuable theoretical insights, its practical application requires supplementation with more flexible approaches to address the nuanced realities of modern electricity markets.

2.3.2 | Agent-Based Models

Agent-based simulation has revolutionized market power analysis by modeling decentralized decision-making under realistic information constraints, overcoming limitations of game theory. FERC-conforming AMES demonstrates unique capabilities for simulating strategic interactions while maintaining private cost data, and it has been tested on a five-node grid [42]. AMES validation in Germany [43] confirmed its ability to replicate real congestion patterns and bidding behaviors that theoretical models miss. The field has diversified to include platforms like PowerACE, which is used in the German electricity market. PowerACE combines agent-based modeling with LI measurements to monitor changes in market power [44]. Recently, an agent-based simulation model called ElecSim, along with a learning algorithm, has been used to develop bidding strategies and evaluate market power in a uniformly priced electricity market [45].

The ability of AMES to project generator learning curves offers particular value for Pakistan's transitioning market. These approaches nevertheless represent a significant advance over traditional methods, enabling regulators to anticipate market power

issues in complex, evolving systems where conventional models fall short. Their adaptability makes them especially valuable for emerging markets facing unique constraints and data limitations.

2.3.3 | Hybrid Models

Recent developments in market power analysis are increasingly utilizing hybrid modeling approaches. These methods prove especially valuable for transitional systems where conventional models fail to capture evolving participant behaviors and regulatory interactions. Wu [31] demonstrated value of bilevel optimization for transitional markets by simultaneously evaluating strategic bidding and regulatory mitigation. Modern bidding strategy analysis integrates computational intelligence with traditional optimization. Although methods like Mixed-Integer Programming remain prevalent for discrete strategy modeling, emerging hybrid approaches combine machine learning and metaheuristics to address complex market dynamics [46]. Market-design literature supports hybrid assessment frameworks that combine transparent screening indices with behavioral and simulation-based tools because market-power risks can shift across trading arrangements and network-constrained dispatch conditions [2]. Market-power mitigation reviews also support combining screening indicators with behavioral monitoring for transitional electricity markets [9]. Co-optimization of energy and reserve capacity considering renewable energy unit with uncertainty has been studied in [47], which concludes more economical system operation.

Game-theoretic hybrids integrating non-cooperative models (e.g., Cournot, Supply Function Equilibrium) with multi-agent simulation are recognized as transformative for market power mitigation. Computational tools like Genetic Algorithms refine equilibria, while machine learning enables dynamic adaptation to bidding behaviors. Cooperative frameworks, including transferable utility games, extend these approaches but face persistent computational complexity challenges [9]. Hybrid models in the modern era combine traditional analytical methods with advanced computational techniques to better capture the complexity of real-world systems. These models offer improved adaptability, scalability, and predictive accuracy, making them especially valuable in dynamic and data-rich environments.

2.4 | Summary of Literature Review

This systematic review synthesizes market power assessment methodologies across 34 key studies, as catalogued in Tables 1 and 2. Three principal methodological paradigms emerge: structural (ex-ante) indices, behavioral (post-ante) indices, and computational modeling approaches. For consistency, this paper treats conceptually similar metrics as equivalents—specifically considering the LI and Price–Cost Markup as interchangeable, and the Supply Margin Assessment (SMA) and Pivotal Supplier Index as analogous measures.

Structural indices dominate the literature, with the HHI being the most widely applied metric across diverse markets—from Texas's early deregulation [48] to Poland's recent market concentration

TABLE 1 | Market power indices evaluated in research articles.

Country/region	Year ^b	CS1	CS3	CS4	CS8	HHI	RSI	EC	NR5	SMA	LI	Paper
Texas	1998					✓						[48]
Britain	1999										✓	[22]
Multiple Countries	2001					✓ ₂ ^a						[49]
California	2002						✓					[18]
Singapore	2007			✓		✓ ₂ ^a	✓			✓	✓ ₁ ^a	[24]
Iran	2010			✓	✓	✓ ₄ ^a		✓				[17]
India	2011			✓	✓	✓ ₂ ^a	✓			✓	✓ ₂ ^a	[25]
Poland	2012	✓	✓			✓ ₂₂ ^a	✓	✓	✓	✓	✓	[26]
Turkey	2014			✓	✓							[16]
Spain	2016	✓	✓			✓ ₁₀ ^a	✓	✓	✓ ₁₀ ^a	✓		[11]
Pakistan	2017	✓			✓	✓	✓					[8]
Turkey	2019	✓		✓		✓						[50]
India	2021			✓		✓						[20]
Poland	2023	✓	✓			✓	✓	✓	✓		✓	[19]
Pakistan	2025	✓ ₅ ^a	✓ ₃ ^a	✓ ₆ ^a	✓ ₃ ^a	✓ ₃₈ ^a	✓ ₇ ^a	✓ ₄ ^a	✓ ₁₃ ^a	✓ ₃ ^a	✓ ₅ ^a	This paper

^aComparison with the number of index values calculated for other countries/scenarios.^bThe year of publication of the research.**TABLE 2** | Market power indices covered in review articles.

Year ^a	CS1	CS3	CS4	CS8	HHI	RSI	EC	NR5	SMA	LI	Paper
1996					✓					✓	[12]
2000					✓					✓	[51]
2001						✓				✓	[52]
2001					✓		✓			✓	[29]
2003					✓	✓					[53]
2003					✓						[54]
2004					✓					✓	[39]
2005	✓				✓	✓			✓	✓	[27]
2008					✓					✓	[32]
2009	✓				✓					✓	[14]
2009	✓	✓				✓				✓	[44]
2011					✓						[15]
2013					✓					✓	[36]
2013					✓						[55]
2016			✓	✓	✓						[56]
2018			✓	✓	✓	✓			✓	✓	[46]
2021					✓	✓	✓				[35]
2021					✓	✓				✓	[38]
2022					✓	✓				✓	[9]
2022					✓		✓				[21]

^aThe year of publication of the research.

studies [19]. Our analysis reveals that the majority of research articles (Table 1) and review papers (Table 2) incorporate HHI, though its static nature increasingly prompts supplementation with dynamic measures. Concentration Ratios (CRn) remain

prevalent in emerging markets, particularly for initial screening in Turkey [16] and India [25], whereas the RSI has become the gold standard for detecting pivotal suppliers in complex markets like California [18] and Spain [11].

Behavioral analysis shows greater methodological evolution, with LI emerging as the primary post-ante metric. While Wolfram's [22] seminal British study exclusively used behavioral indices initially, recent work demonstrates a growing number of studies in Table 1 now combine structural and behavioral approaches. Our research extends this trend by calculating LI for Pakistan alongside structural metrics, providing the first comprehensive dual-perspective assessment.

Computational methods have evolved from abstract game theory models [29] to practical tools for market analysis. Modern approaches prioritize realism through agent-based simulations (AMES [42], PowerACE [44]) that model decentralized decision-making, hybrid systems combining optimization with machine learning [46] to detect strategic behavior, and network-aware indices [35] addressing congestion effects. This progression reflects a shift from theoretical constructs to operational frameworks for analyzing complex, real-world market dynamics while preserving critical features such as participant autonomy and physical grid constraints.

As demonstrated in Table 1's Pakistan row (2025), this study advances the field by:

- Evaluating all 10 major indices (vs. prior maximum of 7).
- Providing the first LI calculation for Pakistan.
- Benchmarking HHI against 38 countries.
- Introducing bid-based behavioral analysis via AMES.

These contributions address critical gaps identified in the literature while establishing replicable methodologies for emerging markets undergoing liberalization.

3 | Major Market Power Indices

3.1 | Concentration Ratio

Concentration ratio indicates the proportion of market share held by the leading companies, expressed as a percentage. Market share is analyzed for both long-term trends and near real-time insights. Over extended periods, it helps track market share fluctuations, while in real-time studies, it observes immediate market changes and competitive dynamics. There are two primary methods for calculating a company's market share: one method uses production capacity, measured by daily, monthly, or annual net generation, whereas the other is predicated on the installed capacity of the generators. Suppliers' capacity market share remains stable, influenced by total capacity, maintenance plans, and market structure, unless there are significant changes to the market structure.

In contrast, the generation market share fluctuates based on bidding strategies and transmission constraints. Meanwhile, market share based on generation varies dynamically depending on bidding strategies and constraints related to transmission networks [17]. However, Kirschen and Strbac suggest defining market shares based on installed capacity rather than energy production for better assessment [57]. It is noted that most researchers,

in a country-based study, have gone with a combination of the concentration ratio of the top 4 companies (CS4) and the concentration ratio of the top 8 companies (CS8). In comparison, countries such as Spain and Poland have gone with a combination of the concentration ratio of the largest company (CS1) and the concentration ratio of the top 3 companies (CS3). Consequently, this paper separately presents the concentration ratio for both combinations.

CS1 is the market share of the largest company in the market. CS3, CS4, and CS8 refer to the total market share held by the three, four, and eight largest companies in the market.

$$CS_x = \sum_{i=1}^x S_i$$

where S_i is the market share of the firm i . According to FERC, if the market share of a firm(s) exceeds 20%, then the firm(s) may exert market power [27].

3.2 | NR5

In contrast to the concentration ratio, NR5 indicates the count of suppliers holding at least a 5% market share. An increased number of suppliers with this level of market share implies reduced potential for market power and a more competitive market environment [26].

3.3 | HHI

A constraint of the concentration ratio is that it overlooks the market shares of all the companies involved [25]. Another limitation is that a supplier with a 20% market share may have different abilities to exert market power depending on the market's structure. In a non-concentrated market, this supplier could be the most significant player, whereas in a concentrated market, they might be the second or third largest. HHI determines the share of each participant and highlights the disproportion in market shares [13]. HHI is a concentration ratio widely used in market power analysis. It is described as:

$$HHI = \sum_{i=1}^n (S_i)^2$$

S_i is the firm's market share. FERC modified the 1992 guidelines into the 2010 guidelines, which raised the threshold for HHI. The market is regarded as unconcentrated when the HHI is below 1500. It is deemed moderately concentrated when HHI falls within the range of 1500 to 2500, and it is classified as highly concentrated when HHI surpasses 2500 [15]. The inverse of HHI indicates the effective number of competitors with equal market shares [17].

3.4 | Entropy Coefficient

Entropy coefficient is an alternative way of measuring the concentration in the market. It represents the market share weighted according to the logarithm of the market share [29]. It is determined as:

$$EC = \sum_{i=1}^n S_i \log_2 \left(\frac{1}{S_i} \right)$$

where n represents the overall count of participants and S_i represents the market share of each participant. Range of S_i is between 0 and 1. The entropy coefficient decreases as market concentration increases, ranging from zero to infinity. A value of zero indicates a monopoly, while infinity represents perfect competition, unlike HHI, which is capped at 10,000. As the entropy coefficient rises, the likelihood of exerting market power diminishes. A market with 10 equally-sized competitors has a benchmark entropy coefficient of 3.32, and for 5 equally-sized competitors, it's 2.32. Markets with an entropy coefficient above 3.32 are considered unconcentrated [17].

3.5 | SMA

SMA determines if peak demand in a market can be met without depending on a particular supplier's capacity. If the specific supplier's capacity is necessary to meet that demand, the supplier becomes pivotal and holds market power. It is given as:

$$SMA_i = \left(D_p - \sum_i S_{-i} \right)$$

or

$$SMA_i = \text{Peak Day Demand} - (\text{Total Capacity} - \text{Supplier } i\text{'s Capacity})$$

where SMA_i is the SMA for the particular supplier i . D_p represents peak demand. $\sum_i S_{-i}$ represents the total capacity minus the specific supplier's capacity. If SMA_i is positive, the particular supplier becomes pivotal [25].

3.6 | RSI

Market share indices are criticized for their static nature and for considering only the supply side. Power market dynamics continually evolve due to variations in demand, generation disruptions, and transmission problems, rendering these indices inadequate. Recognizing these limitations and other constraints has led to a more dynamic index [17]. RSI monitors the market's dependence on its suppliers' generation capacity [53]. It is determined as:

$$RSI_i = \frac{(\text{Total Capacity} - \text{Supplier } i\text{'s Capacity})}{\text{Total Demand}}$$

If a supplier's RSI is less than 1, it is considered pivotal. Market power potential increases if RSI decreases [17]. California Independent System Operator (CAISO) states that a market is competitive when the RSI of a unit i rises above 1.2. If RSI of unit i falls below 1, it suggests that the unit has the potential to exert market power [38].

Pakistan's RSI was computed under three demand scenarios: RSI,max, RSI,avg., and RSI,min. Here, RSI,max pertains to the low-demand situation, yielding the highest RSI value. In contrast, RSI,min indicates the high-demand condition, producing the lowest RSI value. RSI,avg. represents the average demand,

offering a middle-ground RSI value. These distinctions illustrate the shifts in market power as demand varies under different operational circumstances.

3.7 | LI

Structural indices only consider market power potential and do not measure the exercise of market power. A supplier can exert market power by limiting its capacity or offering bids above its marginal cost. Measuring market power abuse is crucial to assessing how much the price deviates from its marginal cost. For that purpose, behavioral indices are used [25]. The LI is determined by subtracting the marginal cost from the price and then dividing that result by the price. Its mathematical formula is given below:

$$L_x = \frac{(P - MC)}{P}$$

P denotes the price cleared by the market, while MC represents the marginal cost [24]. In a perfectly competitive market, the LI equals zero and rises with increasing market power. LI is one when a firm can exercise market power. For simplicity, this paper treats the LI and Price Cost Mark-up as equivalent.

4 | Methodology

4.1 | Data Collection and Formatting

In this paper, NTDC data for the year 2018 were used as the base system dataset. Initially, the network data were reduced using the E4ST software [58]. After the reduction, the dataset was organized into Excel sheets and divided into bus data, generator data, transmission-line branch data, demand data, and generator learning parameters. The flowchart of the proposed methodology is presented in Figure 1.

The reduced Pakistan power-system model contains 114 buses, 235 generation units, and 175 transmission branches. The bus data define the electrical nodes and their interconnections, including the links between generators and buses. The generator data identify each generating unit by technology, including hydro, wind, nuclear, solar, biomass, and thermal generation. The branch data define the starting bus (fbus), destination bus (tbus), line reactance, and thermal rating of each transmission branch. The demand data use the July 2018 hourly load profile, covering 24 h per day for the complete month. Among the available AMES demand formats, fixed demand was selected for all LSEs to isolate generator-side bidding behavior and transmission-network effects. In AMES, one Load Serving Entity (LSE) is connected to one node in the transmission grid; therefore, the reduced model represents demand through 100 LSEs/grids/distributing entities distributed across the network.

The study uses AMES software as an agent-based simulation platform for the wholesale electricity market. After formatting the reduced 114-bus Pakistan power system to meet AMES requirements, the simulations were performed using direct current optimal power flow (DC OPF). The strategic behavior is represented through reinforcement-learning-based bid updates by the GenCo agents in AMES and LI calculations using nodal price outputs

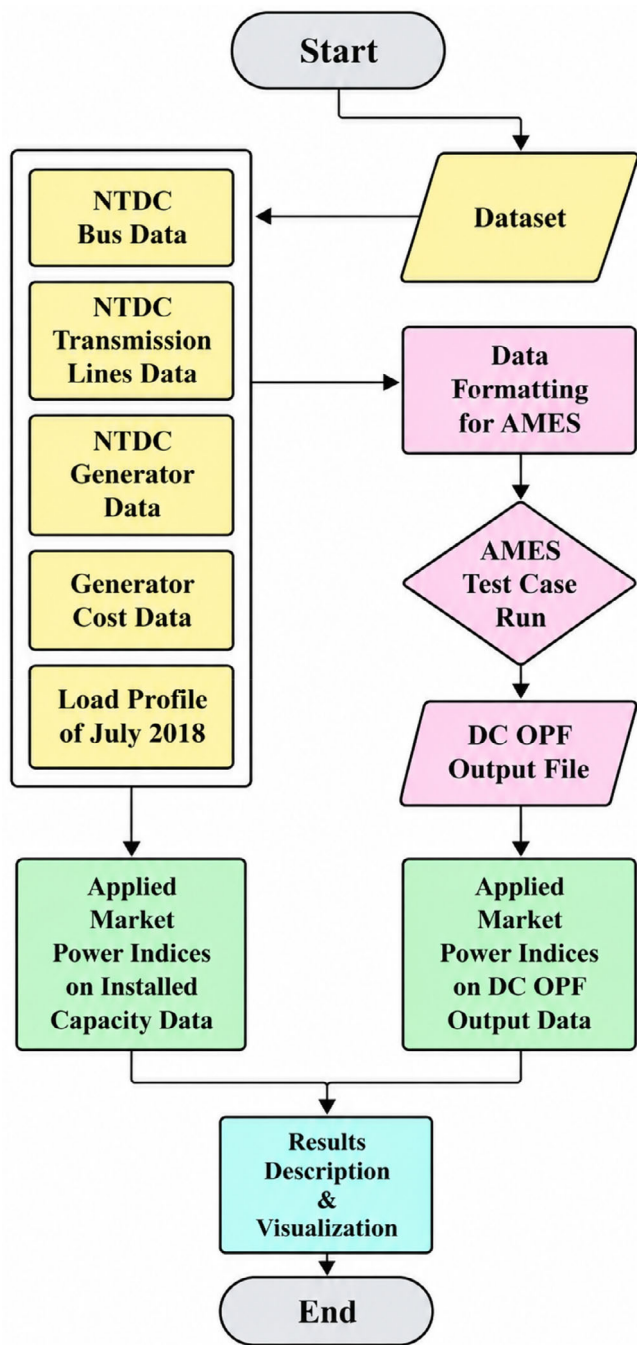


FIGURE 1 | Flowchart of proposed methodology.

of DC OPF. Day 0 represents dispatch based on submitted cost data, whereas Day 4 represents the converged bid-wise simulation after generators learn profit-oriented bidding behavior. It is pertinent to note that the proposed research does not deploy any game-theoretic approach, like the Cournot model, for behavioral aspects.

After data organization, the dataset was formatted according to AMES version 2.06 requirements. The base voltage was set to 500 kV, and the base apparent power to 100 MVA. The penalty weight was selected as 0.050 and kept consistent with the AMES test cases. For the branch dataset, all 175 branches were entered with the corresponding from-bus number, to-bus

number, maximum branch capacity, and reactance. For the generator dataset, all 235 GenCos were entered with their connected bus numbers, fixed cost, cost coefficients, and operating limits. Fixed cost was set at 0\$/h. The cost coefficient α (\$/MWh) for each generator technology was obtained from NEPRA tariffs for the year 2018 [59]. Since the available tariff values were expressed in Rs/kWh, they were converted into \$/MWh to satisfy AMES input requirements. The cost coefficient α for Hydel, Wind, Nuclear, Solar, and Bagasse technologies was fixed at the technology-specific values presented in Figure 2, whereas it varies across thermal GenCos. The coefficient β (\$/MW²h) was taken in the range of 0.0050–0.0080\$/MW²h, consistent with the AMES test cases. The minimum and maximum generation capacities of each GenCo were obtained from the NTDC dataset.

In AMES, the term “GenCo” refers to a generation unit. All power plants (suppliers) are considered separate entities. A single power plant (supplier), regardless of how many GenCos/units it owns, is considered a single entity. Accordingly, units belonging to the same physical power plant are aggregated at the plant/supplier level for market-power assessment, whereas ownership aggregation across different power plants under the same holding company or state entity is not applied.

The locked and contestable capacities of power generation in Pakistan are presented in Table 3. This distinction is included because the assessment of market power is meaningful over the capacity that can participate in the proposed competitive market, whereas contracted or locked capacity is not treated as freely contestable.

Physical grid constraints are explicitly modeled as the reactance values and thermal limits of transmission lines in the DC OPF formulation of AMES. Furthermore, the Locational Marginal Price (LMP) outputs from the simulation of the reduced 114-bus network in the AMES framework are subsequently used for calculating the behavioral index LI. Therefore, the presented research fully incorporates transmission congestion and its effects on nodal prices and, consequently, market power.

For the behavioral simulation, AMES generator learning parameters were kept consistent with the AMES test-case settings to maintain comparability with the validated AMES framework. The developers of AMES software have validated their use of reinforcement learning for behavioral modeling [42]. Thus, the proposed bid-wise behavioral assessment uses the established AMES reinforcement-learning structure while applying Pakistan-specific 2018 generation, load, and network data.

Finally, the market-power indices were calculated using a combination of structural indices, and the behavioral LI enables the study to evaluate both ex-ante market concentration and post-ante strategic bidding outcomes within the same physically constrained Pakistan network model.

4.2 | Market Simulations by AMES

This section provides an overview of AMES and its mathematical formulation. AMES is an open-source computational platform. It is used to study wholesale power markets that are grid-supported

Sr. #	Bus No	Name	Technology Type	α (\$/MWh)	β (\$/MW ² h)	cap _L (MW)	cap _U (MW)
1	35	Tarbela	Hydro	0.2	0.0060	60	210
2	43	Mangla	Hydro	0.2	0.0059	50	112
3	97	Jamshoro	Wind	0.08	0.0062	10	50
4	106	Jhimpir-1	Wind	0.08	0.0077	9	30
5	29	C-3/C-4	Nuclear	0.32	0.0068	250	325
6	30	C-1/C-2	Nuclear	0.32	0.0061	250	325
7	79	Kapco220	Solar	1	0.0065	10	22
8	99	Hala Road	Solar	1	0.0056	1	10
9	68	Jaranwala Road	Biomass	6.71	0.0053	10	31.2
10	81	Bahawalpur220	Biomass	6.71	0.0071	20	42
11	79	Kapco220	Thermal	11.43	0.0065	40	100
12	87	Guddo220	Thermal	13.31	0.0056	60	150

FIGURE 2 | GenCos technology-wise cost.

TABLE 3 | Locked and contestable generation capacity in Pakistan.

Total capacity (MW)	Contestable capacity (MW)	Locked capacity (MW)
27834.122 (100%)	22164.122 (79.63%)	5670 (20.37%)

and centrally managed. It is designed for research, teaching, and training purposes. Key aspects of the FERC-proposed WPMP have been included in its default configuration. It is built in Java/Python to have an extendable modular structure. It allows users to modify the FERC-proposed WPMP Design and conduct performance tests through systematic computational experiments. Core features of WPMP incorporated in AMES are:

- Operation for 24 consecutive hours for a maximum number of continuous days on an AC transmission grid.
- Entails the involvement of an Independent System Operator (ISO) functioning as a regulatory entity, in conjunction with Load-Serving Entities (LSEs) and Generators distributed throughout a given region.
- The ISO manages daily operations within a dual-settlement framework featuring a Real-Time Market and a Day-Ahead Market. These markets operate independently and use Locational Marginal Pricing (LMP) for settlement.

- Every afternoon, the ISO establishes power commitments and LMPs for the Day-Ahead Market. These calculations are performed utilizing supply offers from generators and demand bids from Load Serving Entities (LSEs), which are submitted between midnight and 11 a.m. on the same day as part of forward financial contracting.
- Each day ends with the ISO producing and releasing a commitment schedule for Generators and LSEs for the following day. The LMPs for that day are used to settle the financially binding contracts.
- The Day-Ahead Market manages transmission grid congestion by incorporating congestion components into LMPs.

Five additional features of WPM incorporated in AMES are (a) measures provided to mitigate market power; (b) long-term contracts using bilateral trading; (c) financial transmission rights enabled; (d) ISO equipped with the capability to resolve security constraints for both the same day and the next day market; and (e) ISO conducts a Re-Bid period to ensure projected demands and reserve needs are satisfied.

The ISO is charged with the hourly calculations pertaining to power commitments, power to be dispatched, and the LMPs for the same day and the subsequent day, utilizing the DC OPF. The ISO employs QuadProgJ through the DCOPFJ, which serves as a

strictly convex quadratic programming (SCQP) solver module, in order to address its DC OPF challenges. While the trader learning process within the AMES framework is governed by a reinforcement learning module known as JReLM.

After data formatting according to AMES requirements, the 114-bus data based on actual cost was run in AMES for 4 days. AMES successfully converged on Day 4 and gave the DC OPF output for 4 days. Notably, Day 0 represents the DC OPF output based on actual cost data, while Day 1 to Day 4 represent the DC OPF output based on bid-wise data. Every operating day, AMES provides DC OPF outputs for all hours of the following day based on the cost data submitted by GenCos. Profit-driven GenCos gradually learn from their previous experiences to report the most profitable cost information by using a basic reinforcement learning algorithm to enhance their profits further. After obtaining the DC OPF output for Days 0 to 4, market power indices were calculated. Market power indices calculated without DC OPF output are based on installed capacity. Market power indices calculated on Day 0 DC OPF output are considered cost-wise electricity generation based. Market power indices calculated on Day 4 DC OPF output are considered for bid-wise electricity generation.

4.3 | DC OPF Formulation

The ISO resolves the DC OPF for each hour of the following day as follows:

Variable costs reported by the generators are to be minimized.

$$\sum_{i=1}^I [a_i^R p_{Gi} + b_i^R p_{Gi}^2]$$

Concerning the active power produced and voltage angles

$$p_{Gi}, i = 1, \dots, I; \quad \delta_k, k = 1, \dots, K$$

Subject to: Constraint to balance active power for every node $k = 1, \dots, K$:

$$0 = P_{Load\ k} - P_{Gen\ k} + P_{NetInject\ k}$$

where

$$P_{Load\ k} = \sum_{j \in J_k} p_{Lj}$$

$$P_{Gen\ k} = \sum_{i \in I_k} p_{Gi}$$

$$P_{NetInject\ k} = \sum_{km \text{ or } mk \in BR} P_{km}$$

$$P_{km} = B_{km} [V_o]^2 [\delta_k - \delta_m]$$

For every branch $km \in BR$, the active power thermal constraints:

$$|P_{km}| \leq P_{km}^U$$

Constraints reported for active power produced for each Generator $i = 1, \dots, I$:

$$Cap_i^{RL} \leq p_{Gi} \leq Cap_i^{RU}$$

The setting of the voltage angle at reference node 1:

$$\delta_1 = 0$$

To transform DC OPF into SCQP, the standard objective function of DC OPF is given as:

$$\sum_{i=1}^I [a_i^R p_{Gi} + b_i^R p_{Gi}^2] + \pi \left[\sum_{km \in BR} [\delta_k - \delta_m]^2 \right]$$

π represents a positive penalty weight. For detailed information about AMES, refer to Sun and Tesfatsion [42].

5 | Results and Discussion

In this study, market power indices are calculated using three bases: installed capacity, cost-wise electricity generation, and bid-wise electricity generation. Comprehensive results are presented by applying structural indices, including concentration ratio, HHI, NR5, and EC, to installed capacity, Day 0 cost-wise generation, and Day 4 bid-wise generation under varying demand conditions. In contrast, the behavioral index, that is, the LI, is applied to the marginal clearing prices obtained from Day 0 and Day 4 simulations. Furthermore, SMA and RSI are calculated by considering demand in three forms: maximum demand, minimum demand, and average demand.

Peak and off-peak periods were identified using a quartile-based classification of hourly demand. The six highest-demand hours, representing the upper 25% of the 24-h load profile, were classified as peak hours, while the six lowest-demand hours, representing the lower 25%, were classified as off-peak hours. This approach avoids relying solely on a single maximum or minimum hour and enables a more stable comparison of market power indicators across high and low load conditions. From the 24-h demand values, we define the top 25% highest-demand hours as peak hours and the bottom 25% lowest-demand hours as off-peak hours. Similarly, for Peak and off-Peak Prices, we define peak hours as the top 25% highest-priced hours and off-peak hours as the bottom 25% lowest-priced hours.

The graphical results reported for all indices represent aggregated outcomes on installed capacity, Day 0 (cost-wise generation), and Day 4 (bid-wise generation) to maintain consistency with the methodology adopted in the existing literature. In addition to the aggregated analysis, the results are examined under peak and off-peak conditions, as well as during maximum and minimum demand/price hours on Day 0 and Day 4, to provide a more comprehensive assessment.

5.1 | Concentration Ratio

Concentration Ratios, including CS1, CS3, CS4, and CS8, are evaluated and compared with respective concentration ratios in other countries. It is worth noting that researchers for most countries have calculated CS4 and CS8, whereas CS1 and CS3 were reported for Spain and Poland. Therefore, in Pakistan's case, concentration ratios are computed in both combinations. These concentration



FIGURE 3 | Eight largest suppliers of Pakistan 2018 and Pakistan 2009–14.

ratios are calculated based on installed capacity, cost-wise electricity generation, and bid-wise electricity generation.

Day 0 of the optimal power flow run on AMES is considered cost-wise electricity generation, as it dispatches using true-cost data. Among all days, Day 4 has been selected for bid-wise electricity generation, as it is the last fully converged day of the optimal power flow run on AMES and represents the maximum possible variation in generators' bids. This variation in bids results in variable prices and can reflect changes in bid-wise electricity generation compared to cost-wise electricity generation. Figure 3 presents the eight largest suppliers of Pakistan-2018 based on installed capacity, Day 0 cost-wise electricity generation, and Day 4 bid-wise electricity generation, along with Pakistan's earlier 2009–14 results. For Pakistan-2018, Tarbela-2 remains the largest supplier under all three assessment bases, with a share of 12.72% based on installed capacity, 17.01% based on Day 0 cost-wise generation, and 17.02% based on Day 4 bid-wise generation. This indicates that Tarbela-2 contributes more significantly in actual dispatch than its installed-capacity share suggests. However, its share remains below 20%, showing that the largest supplier does not hold a structurally dominant position. Compared with Pakistan's 2009–14 results, where Tarbela remained the leading supplier, Pakistan-2018 shows a relatively more distributed market structure among major suppliers.

Figure 4 presents the CS1 results for Pakistan-2018, Pakistan 2009–14, and other international electricity markets. In Pakistan-2018, CS1 is 12.72% based on installed capacity, 17.01%

based on Day 0 cost-wise generation, and 17.02% based on Day 4 bid-wise generation. These values are lower than most of the compared international cases. Poland recorded the lowest installed-capacity-based CS1 value at 12.70% in 1999, which is very close to Pakistan-2018 based on installed capacity. Pakistan's earlier results were higher, with 16.10% based on installed capacity during 2009–14 and 16.90% based on electricity generation during 2012–13.

In contrast, the largest suppliers in Spain, Turkey, and Poland in different years held considerably higher shares, ranging from 20.20% to 59.20%. Therefore, Pakistan-2018 shows limited single-supplier concentration compared with most international benchmarks.

Figure 5 presents the CS3 results, representing the combined market share of the three largest suppliers. For Pakistan-2018, CS3 is 23.43% based on installed capacity, 28.56% based on Day 0 cost-wise generation, and 28.57% based on Day 4 bid-wise generation. The increase from installed capacity to generation-based results indicates that the three largest suppliers have a relatively higher contribution in dispatch than in installed capacity. However, these values remain on the lower side compared with other countries. Poland, with 26.70% based on installed capacity in 1999, is close to Pakistan's installed-capacity-based result. However, other international cases show much higher CS3 values, ranging from 35.70% to 92.90%. Thus, Pakistan-2018 does not show strong concentration among the three largest suppliers.

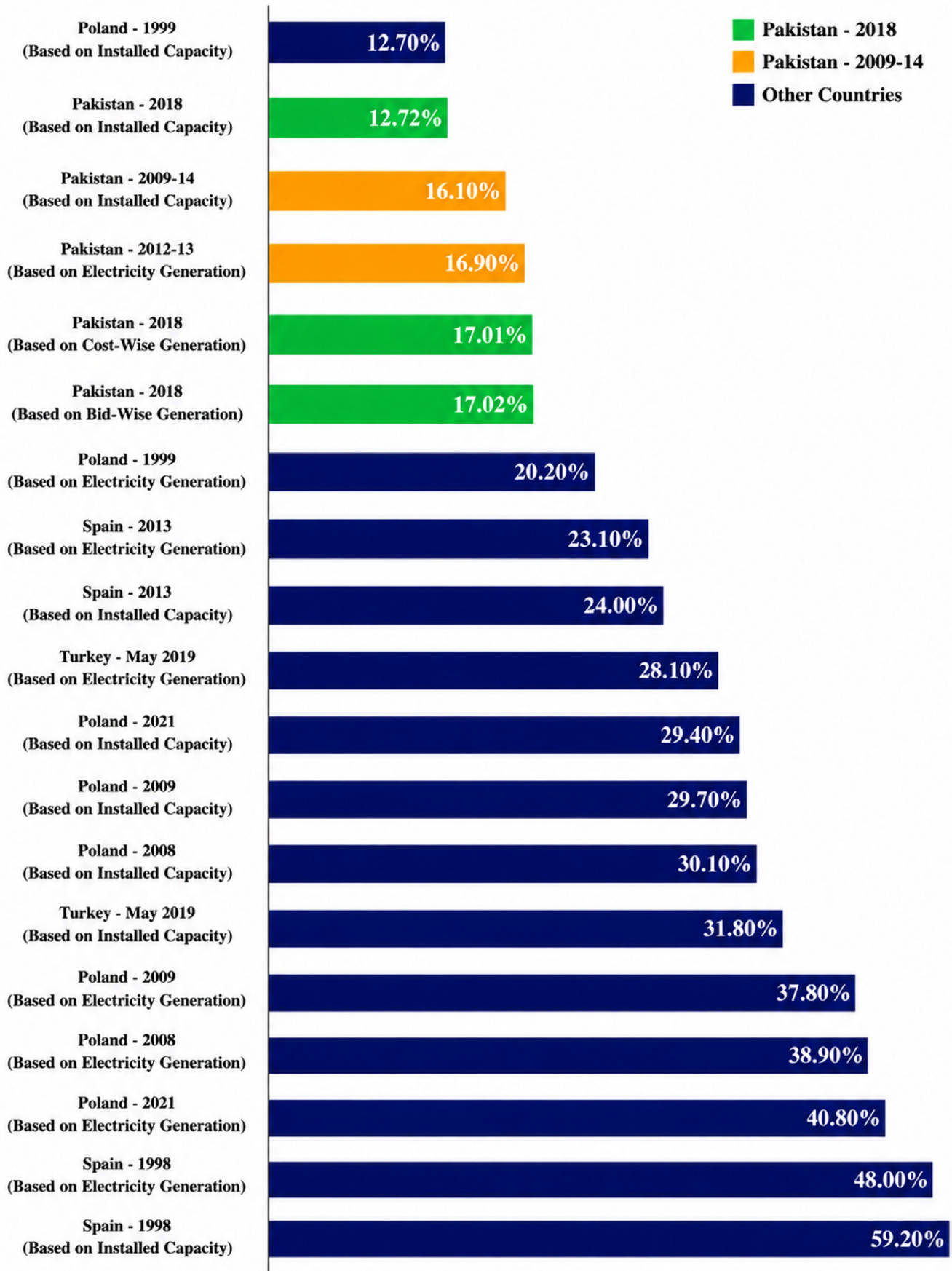


FIGURE 4 | CS1.

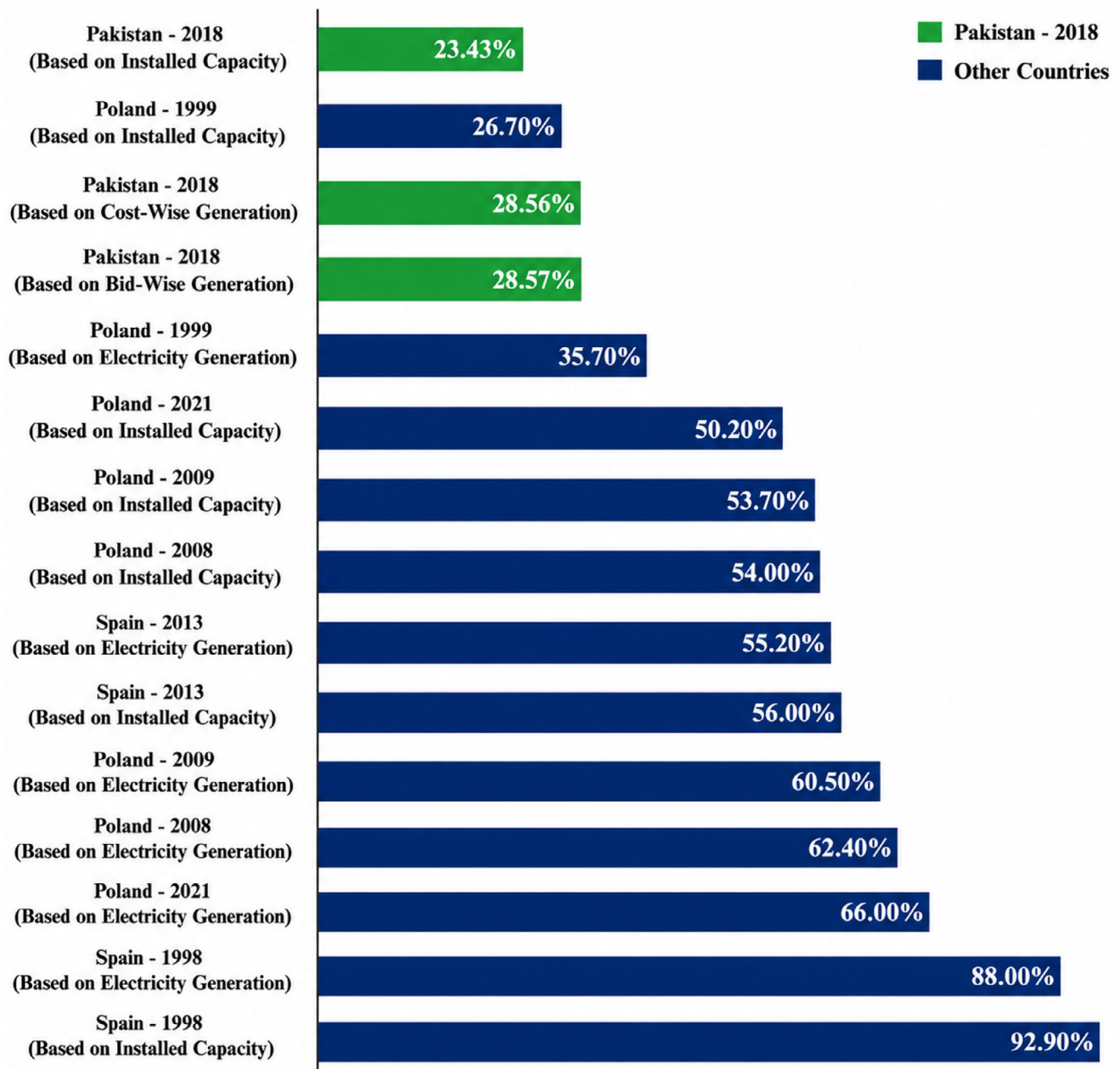
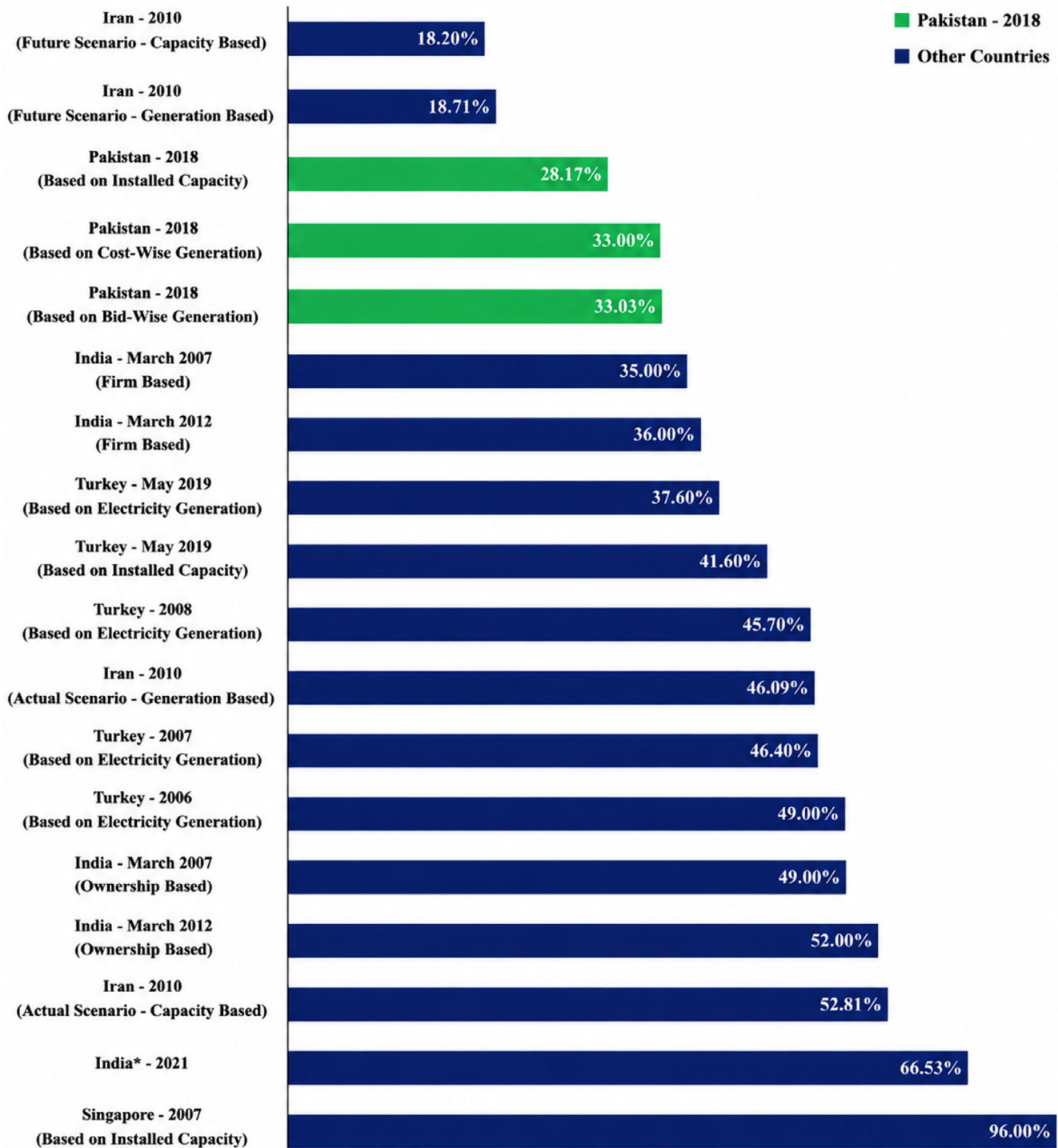


FIGURE 5 | CS3.

Figure 6 presents the CS4 results, which measure the combined market share of the four largest suppliers. In Pakistan-2018, CS4 is 28.17% based on installed capacity, 33.00% based on Day 0 cost-wise generation, and 33.03% based on Day 4 bid-wise generation. Although generation-based CS4 values are higher than installed-capacity-based values, they remain moderate compared with most international cases. Iran's future-scenario results are lower, ranging from 18.20% to 18.71%, while India's firm-based result of 35.00% in March 2007 is close to Pakistan's generation-based results. Other countries, including Turkey, Iran's actual scenario, India's ownership-based cases, and Singapore, show higher CS4 values, extending up to 96.00%. Therefore, Pakistan-2018 remains comparatively less concentrated at the four-supplier level.

Figure 7 presents the CS8 results, showing the combined market share of the eight largest suppliers. For Pakistan-2018, CS8 is 46.38% based on installed capacity, 49.42% based on Day 0 cost-wise generation, and 48.77% based on Day 4 bid-wise generation. These results indicate that nearly half of the market share is held by the eight largest suppliers. However, compared with several international electricity markets, Pakistan-2018 still lies within a relatively lower concentration range. Iran's future-scenario CS8 values are lower, ranging from 31.83% to 32.25%, while India's firm-based result of 48.00% in March 2007 is close to Pakistan's CS8 values. Other countries show higher values, ranging from 50.00% to 76.97%. Hence, even at the eight-supplier level, Pakistan-2018 shows moderate rather than excessive concentration.



* Modified-CS4 used by the authors.

FIGURE 6 | CS4. *Modified-CS4 used by the authors.

Table 4 presents the eight largest market suppliers of Pakistan-2018 based on installed capacity. Tarbela-2 holds the highest share at 12.72%, followed by Kapco 220 with 5.50%, Ghazi Brotha with 5.21%, Port Qasim and Sahiwal with 4.74% each, Haveli Bahadur Shah and Bhikki with 4.60% each, and Guddu 220 with 4.26%. These results show that installed capacity is relatively distributed among several suppliers. Although Tarbela-2

is the largest supplier, the remaining capacity is shared across multiple companies, indicating no excessive installed-capacity concentration.

Table 5 presents the eight largest suppliers of Pakistan-2018 based on Day 0 cost-wise generation under different operating conditions, including the 24-h average, off-peak period, peak

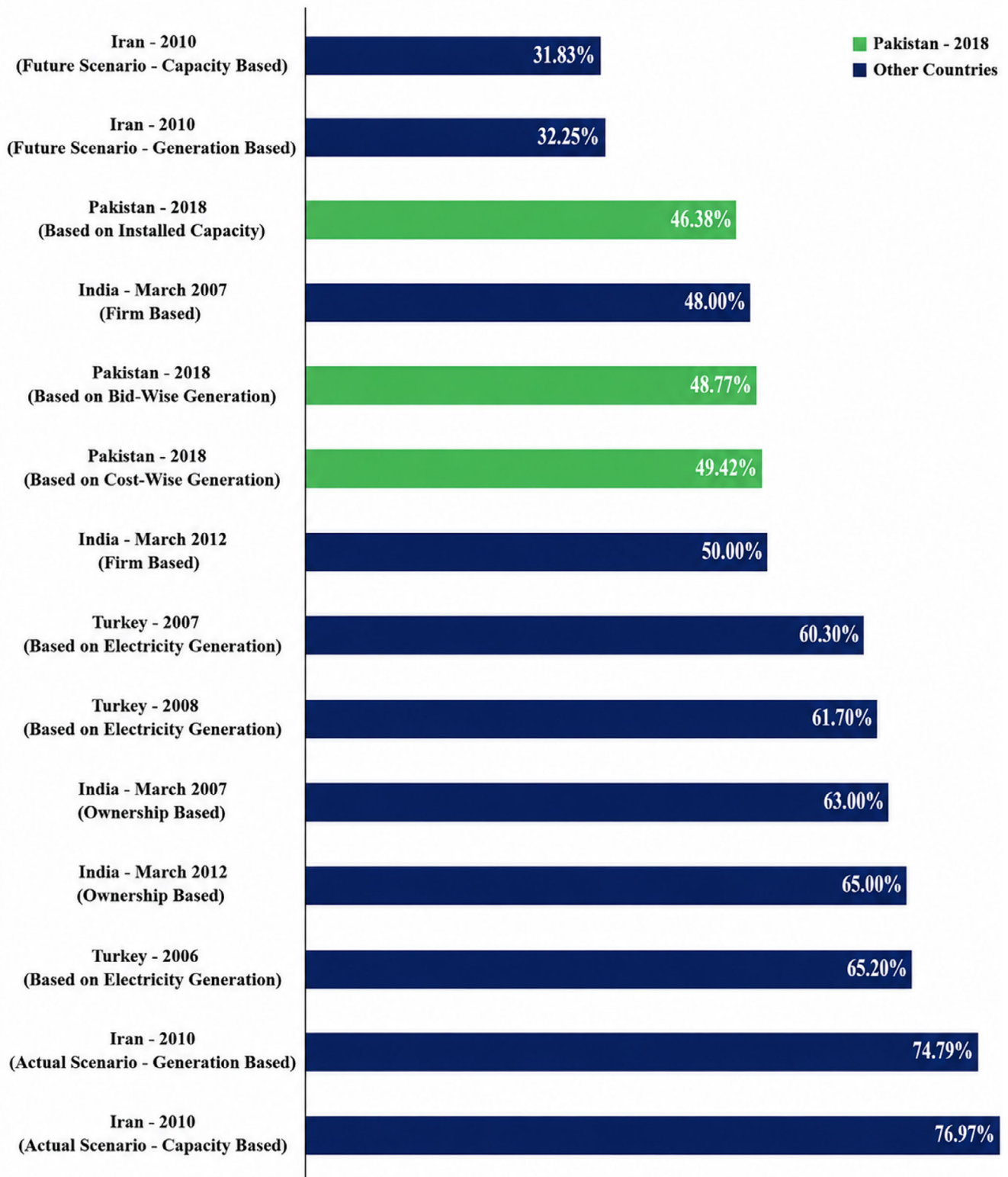


FIGURE 7 | CS8.

period, minimum-demand hour, and maximum-demand hour. Tarbela-2 remains the largest supplier in all cases. Its share is 17.01% on a 24-h average basis, 18.08% during off-peak hours, 15.24% during peak hours, 18.19% at the minimum-demand hour, and 16.49% at the maximum-demand hour. This shows that concentration is higher during off-peak and minimum-demand conditions, when fewer generators are required to meet system

demand. Conversely, concentration decreases during peak and maximum-demand periods because additional suppliers participate in dispatch.

Table 6 presents the Day 4 bid-wise generation results under the same operating conditions. Tarbela-2 again remains the largest supplier, with a share of 17.02% on a 24-h average basis, 17.34%

during off-peak hours, 16.70% during peak hours, 17.56% at the minimum-demand hour, and 16.49% at the maximum-demand hour. The Day 4 results show that bid-wise generation does not substantially increase the share of the largest supplier. Although concentration remains relatively higher during low-demand conditions, the distribution among leading suppliers becomes slightly more balanced compared with Day 0.

Table 7 summarizes CS1, CS3, CS4, and CS8 for installed capacity, Day 0 cost-wise generation, and Day 4 bid-wise generation under different demand conditions. In Day 0, the highest concentration is observed during the minimum-demand hour, where CS1, CS3, CS4, and CS8 reach 18.19%, 30.52%, 35.24%, and 51.59%, respectively. In Day 4, the highest concentration is also observed during the minimum-demand hour, where CS1, CS3, CS4, and CS8 reach 17.56%, 29.58%, 34.31%, and 50.54%, respectively. In both Day 0 and Day 4, concentration decreases during peak and maximum-demand conditions. This confirms that supplier concentration is more pronounced during low-demand hours and becomes less concentrated when system demand increases.

Overall, Figures 3–7 provide the aggregated concentration ratio results and compare Pakistan-2018 with Pakistan's earlier results and selected international electricity markets. The graphical results show that Pakistan-2018 generally lies on the

lower side of concentration compared with most international cases. Tables 4–7 further expand the analysis by examining Pakistan-2018 under installed capacity, 24-h average, off-peak, peak, minimum-demand, and maximum-demand conditions. These tables show that concentration is relatively higher during off-peak and minimum-demand hours, mainly because fewer suppliers are needed to meet demand. In contrast, concentration decreases during peak and maximum-demand periods due to wider generator participation. Importantly, the largest supplier's share remains below 20% under all assessment bases and operating conditions. Therefore, both the aggregated figures and the expanded tabular results indicate that Pakistan-2018 does not exhibit significant structural market power based on concentration ratio assessment.

According to the FERC, if the largest company's market share exceeds 20%, that company may exercise market power. In Pakistan, the largest company holds less than 20% of the market share across all concentration ratios (CS1, CS3, CS4, and CS8). Thus, the concentration ratio index indicates a lack of significant market power potential in the country.

5.2 | NR5

NR5 represents the number of suppliers with at least a 5% market share. Its value indicates the level of market competitiveness, as a higher number of suppliers with at least a 5% share suggests lower potential for market power and a more competitive market environment.

Figure 8 presents the aggregated NR5 results for Pakistan-2018 based on installed capacity, Day 0 cost-wise generation, and Day 4 bid-wise generation, along with comparable results from other countries. NR5 is calculated using unrounded supplier market shares; therefore, suppliers with actual shares below 5.00% are not counted, even if the rounded presentation displays them as 5%. Based on installed capacity, the NR5 value for Pakistan-2018 is 3, indicating that three suppliers hold at least an unrounded 5% market share. However, based on Day 0 cost-wise generation and Day 4 bid-wise generation, the NR5 value decreases

TABLE 4 | Eight largest market suppliers of Pakistan-2018 based on installed capacity.

Rank	Supplier	Market share (%)
1	Tarbela-2	12.72
2	Kapco 220	5.50
3	Ghazi Brotha	5.21
4	Post Qasim	4.74
5	Sahiwal	4.74
6	Haveli Buhadur Shah	4.60
7	Bhikki	4.60
8	Guddu 220	4.26

TABLE 5 | Eight largest market suppliers of Pakistan-2018 based on Day 0 (cost-wise generation).

Rank	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
1	Tarbela-2 (17.01%)	Tarbela-2 (18.08%)	Tarbela-2 (15.24%)	Tarbela-2 (18.19%)	Tarbela-2 (16.49%)
2	Ghazi Brotha (7.09%)	Ghazi Brotha (7.51%)	Ghazi Brotha (6.62%)	Ghazi Brotha (7.61%)	Ghazi Brotha (6.75%)
3	Kapco220 (4.46%)	Haveli Buhadur Shah (4.66%)	Kapco220 (4.99%)	Haveli Buhadur Shah (4.72%)	Guddu220 (4.68%)
4	Haveli Buhadur Shah (4.44%)	Bhikki (4.66%)	Guddu220 (4.40%)	Bhikki (4.72%)	Kapco220 (4.48%)
5	Bhikki (4.44%)	Tarbela-1 (4.35%)	Haveli Buhadur Shah (4.25%)	Tarbela-1 (4.41%)	Haveli Buhadur Shah (4.19%)
6	Tarbela-1 (4.13%)	Post Qasim (4.14%)	Bhikki (4.25%)	Post Qasim (4.20%)	Bhikki (4.19%)
7	Post Qasim (4.02%)	Jhampir-1 (4.03%)	Post Qasim (4.10%)	Jhampir-1 (4.09%)	Tarbela-1 (3.91%)
8	Jhampir-1 (3.84%)	Kapco220 (3.83%)	Tarbela-1 (3.91%)	Kapco220 (3.65%)	Post Qasim (3.74%)

TABLE 6 | Eight largest market suppliers of Pakistan-2018 based on Day 4 (bid-wise generation).

Rank	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
1	Tarbela-2 (17.02%)	Tarbela-2 (17.34%)	Tarbela-2 (16.70%)	Tarbela-2 (17.56%)	Tarbela-2 (16.49%)
2	Ghazi Brotha (6.94%)	Ghazi Brotha (7.18%)	Ghazi Brotha (6.72%)	Ghazi Brotha (7.30%)	Ghazi Brotha (6.64%)
3	Bhikki (4.61%)	Bhikki (4.67%)	Bhikki (4.60%)	Haveli Buhadur Shah (4.72%)	Bhikki (4.60%)
4	Haveli Buhadur Shah (4.46%)	Haveli Buhadur Shah (4.66%)	Haveli Buhadur Shah (4.34%)	Bhikki (4.72%)	Haveli Buhadur Shah (4.32%)
5	Tarbela-1 (4.14%)	Tarbela-1 (4.35%)	Post Qasim (4.02%)	Tarbela-1 (4.41%)	Post Qasim (4.04%)
6	Post Qasim (4.04%)	Post Qasim (4.14%)	Tarbela-1 (3.97%)	Post Qasim (4.20%)	Tarbela-1 (3.91%)
7	Jhampir-1 (3.84%)	Jhampir-1 (4.03%)	Kapco220 (3.70%)	Jhampir-1 (4.09%)	Kapco220 (3.76%)
8	Kapco220 (3.72%)	Kapco220 (3.61%)	Jhampir-1 (3.68%)	Chasma Nuclear Plant-2 (C-1/C-2) (3.54%)	Jhampir-1 (3.63%)

TABLE 7 | CS1 to CS8 for Pakistan-2018 based on installed capacity, Day 0, and Day 4.

Installed capacity					
Metric				Concentration ratios	
CS1 (%)				12.72	
CS3 (%)				23.43	
CS4 (%)				28.17	
CS8 (%)				46.38	
Day 0 (cost-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
CS1 (%)	17.01	18.08	15.24	18.19	16.49
CS3 (%)	28.56	30.26	26.85	30.52	27.92
CS4 (%)	33.00	34.92	31.25	35.24	32.40
CS8 (%)	49.42	51.28	47.76	51.59	48.44
Day 4 (bid-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
CS1 (%)	17.02	17.34	16.70	17.56	16.49
CS3 (%)	28.57	29.20	28.02	29.58	27.74
CS4 (%)	33.03	33.86	32.37	34.31	32.05
CS8 (%)	48.77	50.00	47.73	50.54	47.40

to 2. This shows that although three suppliers exceed the 5% threshold in installed capacity, only two suppliers retain at least a 5% share in generation-based outcomes. Compared with the international cases, Pakistan-2018 lies within the lower range of NR5 values, as some European countries report NR5 values

between 1 and 2, while others range from 3 to 9. Therefore, the aggregated graphical results indicate that Pakistan-2018 has a limited number of suppliers with market shares above the 5% threshold, particularly when assessed through generation-based measures.

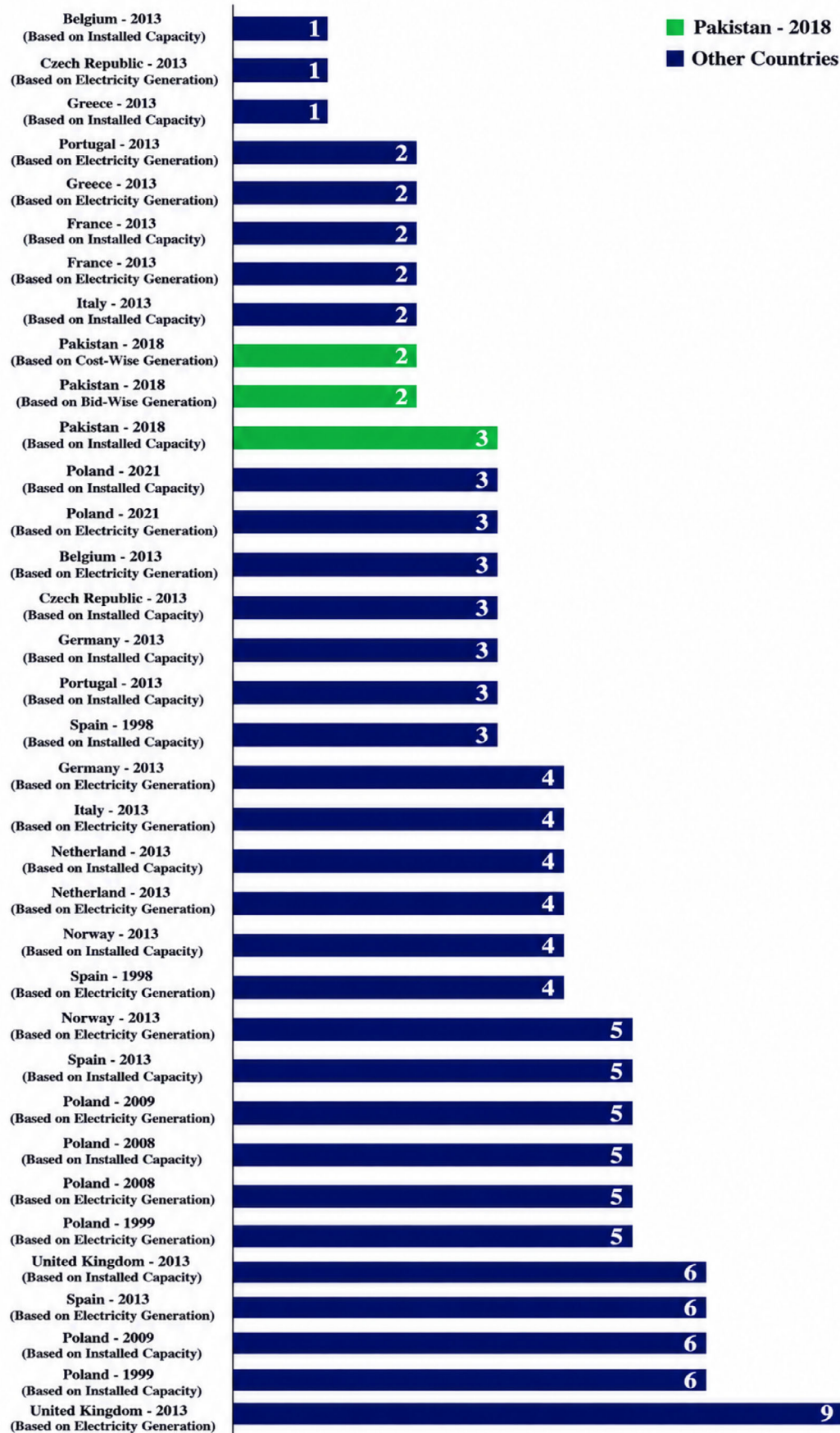


FIGURE 8 | NR5.

TABLE 8 | NR5 for Pakistan-2018 based on installed capacity, Day 0, and Day 4.

Installed capacity					
Metric					NR5
NR5					3
Day 0 (cost-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
NR5	2	2	2	2	2
Day 4 (cost-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
NR5	2	2	2	2	2

Table 8 shows NR5 for Pakistan-2018 based on Installed Capacity, Day 0 and Day 4 presents the NR5 results under the 24-h average, off-peak period, peak period, minimum-demand hour, and maximum-demand hour. The installed-capacity-based NR5 value is 3, whereas Day 0 cost-wise generation and Day 4 bid-wise generation consistently show an NR5 value of 2 across all operating conditions. This indicates that variations in peak/off-peak and maximum/minimum demand conditions do not change the number of suppliers crossing the unrounded 5% market-share threshold in Pakistan-2018.

5.3 | HHI

HHI is a widely utilized concentration ratio for assessing market power analysis. It calculates each participant's shares and reflects the disproportion in the market shares. HHI results have been divided into three regions: Asia-Pacific, European, and American, represented by figures, respectively.

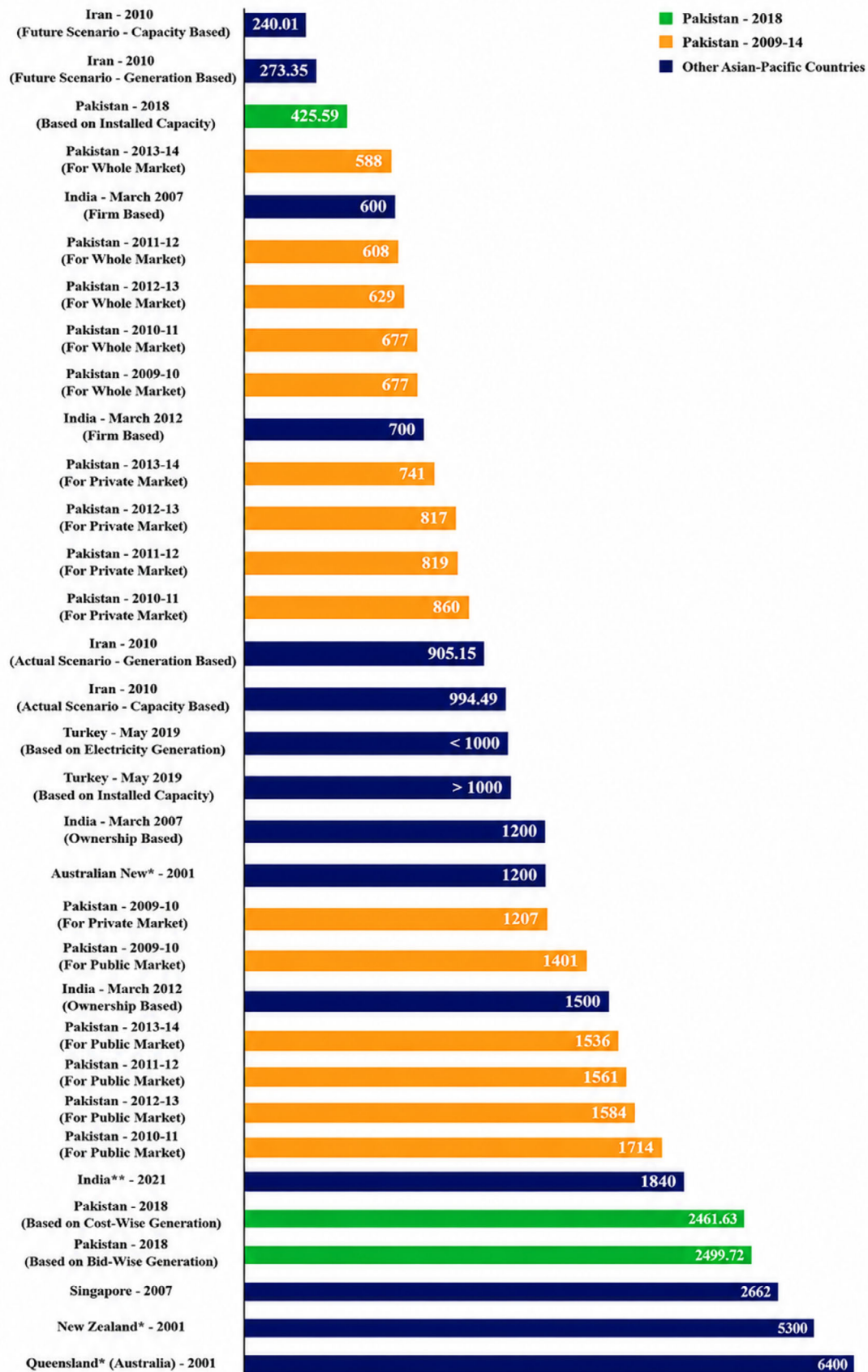
Figure 9 illustrates the results for HHI of Pakistan and Asia-Pacific countries. HHI for Pakistan and Asia-Pacific Countries/Regions presents the aggregated HHI results for Pakistan-2018 and comparable Asia-Pacific electricity markets. For Pakistan-2018, the installed-capacity-based HHI is 425.59, indicating an unconcentrated market structure. However, the HHI increases to 2461.63 based on Day 0 cost-wise generation and 2499.72 based on Day 4 bid-wise generation, placing the generation-based results near the upper limit of the moderately concentrated range. Compared with Pakistan 2009–14, where HHI values ranged from 588 to 1714 across the whole, public, and private market segments, Pakistan-2018 shows a lower concentration in installed capacity but higher concentration in generation-based results. Within the Asia-Pacific comparison, Pakistan-2018 remains below the highly concentrated cases but shows relatively higher concentration when assessed through cost-wise and bid-wise generation. In Figure 10, the results for the European Region are shown. For the European Region, HHI ranges from 484 to 8600. In Figure 11, the results for the American Region are shown. In the American region, HHI ranges from 600 to 4300.

Table 9 describes the HHI for Pakistan-2018 based on Installed Capacity, Day 0 and Day 4 further presents HHI under the 24-h average, off-peak period, peak period, minimum-demand hour, and maximum-demand hour. The installed-capacity-based HHI remains 425.59. For Day 0, HHI is 2461.63 on a 24-h average basis, while it decreases to 643.84 during off-peak hours, 595.84 during peak hours, 108.60 at the minimum-demand hour, and 96.84 at the maximum-demand hour. Similarly, for Day 4, HHI is 2499.72 on a 24-h average basis, while it decreases to 636.10 during off-peak hours, 619.90 during peak hours, 107.52 at the minimum-demand hour, and 103.16 at the maximum-demand hour. These results show that the aggregated 24-h HHI values are considerably higher than the individual peak/off-peak and maximum/minimum demand-hour values.

FERC modified the 1992 guidelines in 2010 and raised the threshold for HHI. The market is regarded as unconcentrated when HHI is below 1500. It is deemed moderately concentrated when HHI falls within the range of 1500 to 2500, and it is classified as highly concentrated when HHI surpasses 2500. In accordance with these thresholds for HHI, the market for Pakistan-2018, based on installed capacity, is unconcentrated, meaning that competition is healthy and that no participant can influence the prices. The market for Pakistan-2018, based on cost-wise and bid-wise electricity generation, is moderately concentrated, meaning that competition is moderate, and some participants can control the market and influence the price to some extent.

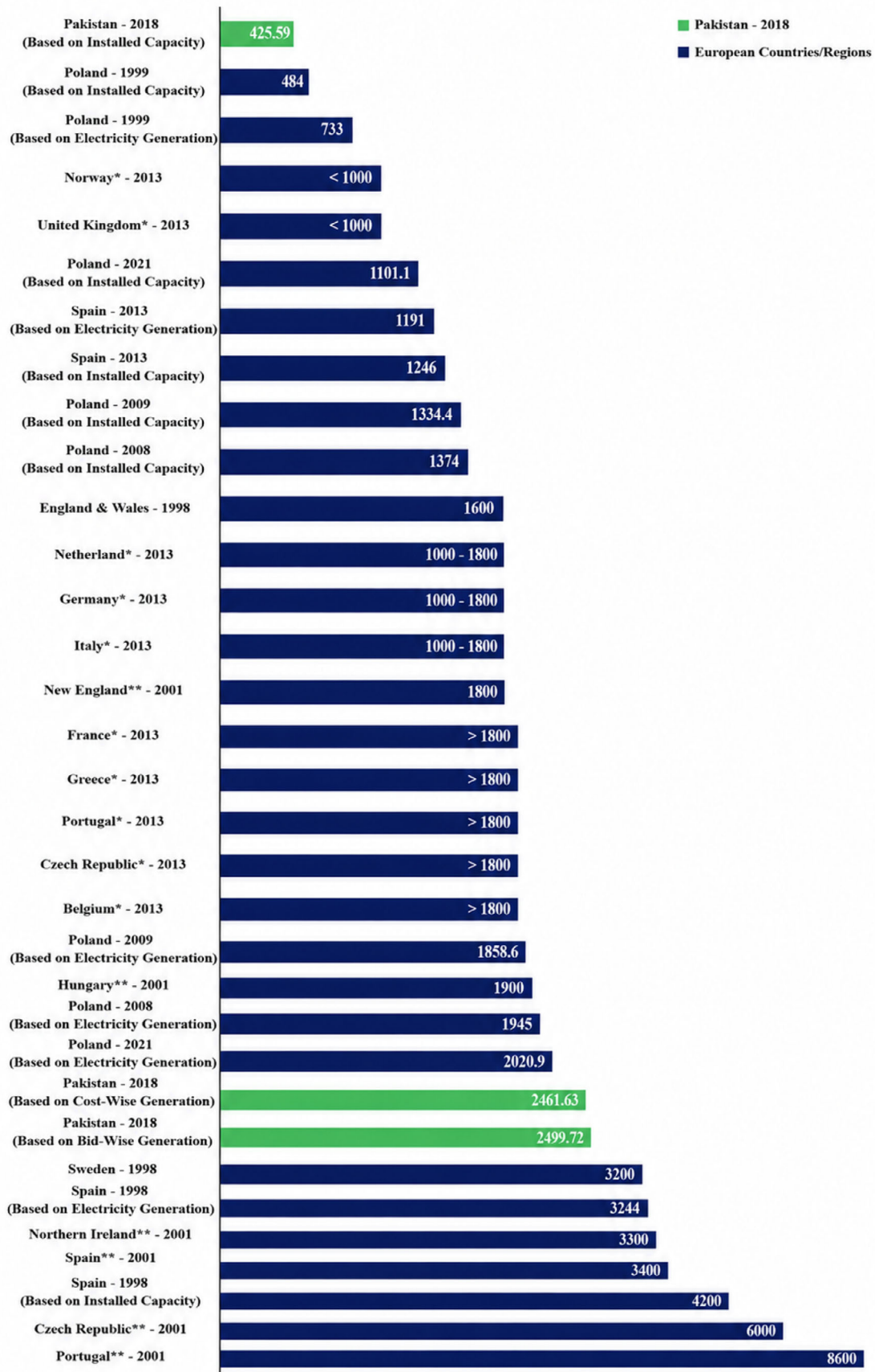
5.4 | Entropy Coefficient

Entropy coefficient is an alternative way of measuring the concentration in the market. Entropy coefficient decreases as market concentration increases, ranging from zero to infinity. Zero denotes monopoly, while infinity denotes perfect competition. Figure 12 compares entropy coefficient of Pakistan with other countries. Entropy coefficient for Pakistan for cost-wise and bid-wise generation is 4.90, while based on installed capacity it is 5.05, which signifies a lack of market concentration or the existence of competition. In comparison, Iran in the future-based scenario and both generation and capacity-based approaches



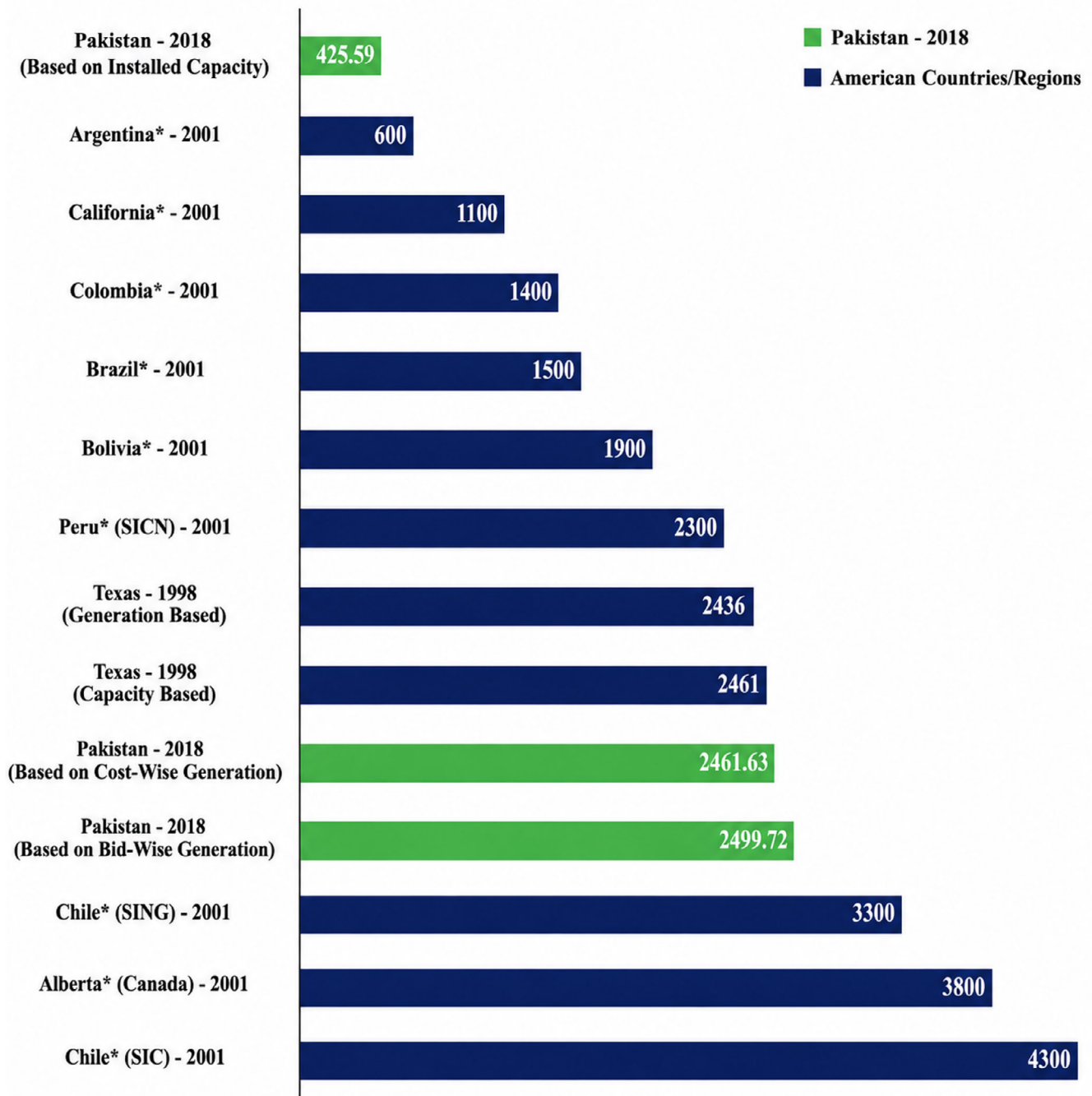
* reported by (Bacon and Besant-Jones, 2001) ** Modified-HHI used by the authors.

FIGURE 9 | HHI for Pakistan and Asia-Pacific countries/regions. *Reported by Bacon and Besant-Jones [49]. **Modified-HHI used by the authors.



* reported by (Ciarreta, Nasirov and Silva, 2016) ** reported by (Bacon and Besant-Jones, 2001)

FIGURE 10 | HHI for Pakistan and European countries/regions. *Reported by Ciarreta, Nasirov and Silva [11]. **Reported by Bacon and Besant-Jones [49].



* reported by (Bacon and Besant-Jones, 2001)

FIGURE 11 | HHI for American countries/regions. *Reported by Bacon and Besant-Jones [49].

have higher values of the entropy coefficient. In contrast, Spain and Poland have much lower values than Pakistan. Table 10 demonstrates entropy coefficient results during installed capacity, off-peak, peak, maximum peak hour, and minimum peak hour; in all cases, the market is found to be unconcentrated.

According to Asgari and Monsef [17], entropy coefficient above 3.32 is a rough indication of a non-concentrated market. In Pakistan, the entropy coefficient based on cost-wise electricity generation, bid-wise electricity generation, and installed capacity is more than 3.32, reflecting that the market is unconcentrated and competition is healthy.

5.5 | SMA

SMA determines whether peak demand in a market can be met without depending on a particular supplier's capacity. If the particular supplier's capacity is necessary to meet that demand, the supplier becomes pivotal and holds market power. In other words, if SMA is positive, then the particular supplier is pivotal; and if it is negative, then the particular supplier is not pivotal.

In Pakistan, based on available data and installed capacity, SMA is negative for all suppliers, suggesting that a supplier's capacity is not pivotal in the market. Figure 13 shows the results of all

TABLE 9 | HHI for Pakistan-2018 based on installed capacity, Day 0, and Day 4.

Installed capacity					
Metric				Herfindahl–Hirschman Index	
HHI				425.59	
Day 0 (cost-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
HHI	2461.63	643.84	595.84	108.60	96.84
Day 4 (bid-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
HHI	2499.72	636.10	619.90	107.52	103.16

papers that calculated SMA. Furthermore, SMA has been calculated under all three demands as shown in Table 11, and the negative result in all cases indicates that no particular supplier is pivotal.

5.6 | RSI

RSI calculates the remaining supply capacity when a specific supplier is subtracted. If RSI is below 1, then that particular supplier is pivotal. The market power of that particular supplier increases as RSI decreases. CAISO states that a market is competitive when RSI of unit i rises above 1.2. If RSI of unit i falls below 1, it indicates that the unit may influence the market.

Figure 14 and Table 12 both represent RSI results for Pakistan-2018. RSI is computed under three demand scenarios: RSI,max, RSI,avg., and RSI,min. Here, RSI,max pertains to the low-demand situation, yielding the highest RSI value. In contrast, RSI,min indicates the high-demand condition, producing the lowest RSI value. RSI,avg. represents the average demand, offering a middle-ground RSI value. Figure 14 compares the Pakistan-2018 RSI to those of the other countries. For Pakistan-2018, RSI,min is 1.71, RSI,avg. is 1.80, and RSI,max is 1.91. Pakistan 2009–14 also calculated RSI in the form of RSI,max and RSI,min. For Pakistan 2009–14, each year's maximum and minimum values are considered among the 12 months of a year. RSI for Pakistan 2009–14 ranged from 1.08 to 2.29. Spain has the lowest value of RSI, being 0.60 in the year 1998. According to the CAISO threshold for RSI, RSI in all three demand scenarios for Pakistan-2018 is greater than 1.2, suggesting that the market is fairly competitive in Pakistan.

5.7 | LI

LI serves as a behavioral metric utilized to evaluate the degree to which a firm exerts its market power. In a perfectly competitive market, LI equals zero and rises with increasing market power. LI is one when a firm can exercise market power. For simplicity, this

paper treats LI and Price Cost Mark-up as equivalent. Figure 15 shows a comparison of LI for Pakistan with other countries. LI for Singapore with long-run marginal cost is the lowest, being 0.03, among all countries, while for India with short-run marginal cost it is the highest, being 0.74. According to the threshold given by Chang [24], the market for Pakistan is reasonably competitive based on the calculated LI of 0.39 for cost-wise electricity generation. However, the market power rating of Pakistan moves from low to medium because LI rises to 0.63 for bid-wise electricity generation.

The relationship between RSI and LI highlights the distinction between potential and exercised market power. Sheffrin [18] showed that RSI is useful for assessing market power because of its relationship to price–cost markups. Since the LI is a normalized price–cost markup, a lower RSI is generally expected to correspond to a higher LI. However, this relationship is not deterministic because RSI captures structural pivotality, whereas LI captures realized price–cost margins after dispatch, marginal pricing, network constraints, and bidding behavior are accounted for. As Table 13 shows, under Day 0 cost-wise generation, the 24-h average LI is 0.39, with off-peak and peak values of 0.17 and 0.53, respectively. The minimum-price and maximum-price hour LI values are 0.15 and 0.80, respectively, indicating strong hourly variation in realized market-power outcomes. Under Day 4 bid-wise generation, the 24-h average LI is 0.63, with off-peak and peak values of 0.58 and 0.68, respectively. The minimum-price and maximum-price hour LI values are 0.57 and 0.69, respectively, showing that price–cost margins remain evident across different demand and price conditions after strategic bidding. Thus, structural indices such as RSI identify the potential for market power, while LI reveals the extent to which this potential is actually exercised under simulated bidding and dispatch conditions.

The results indicate that although Pakistan's market appears structurally competitive, strategic bidding can substantially increase price–cost margins (LI), potentially leading to higher consumer costs and reduced social welfare; therefore, the LI result is interpreted as an early warning that even a structurally unconcentrated market can produce welfare losses if

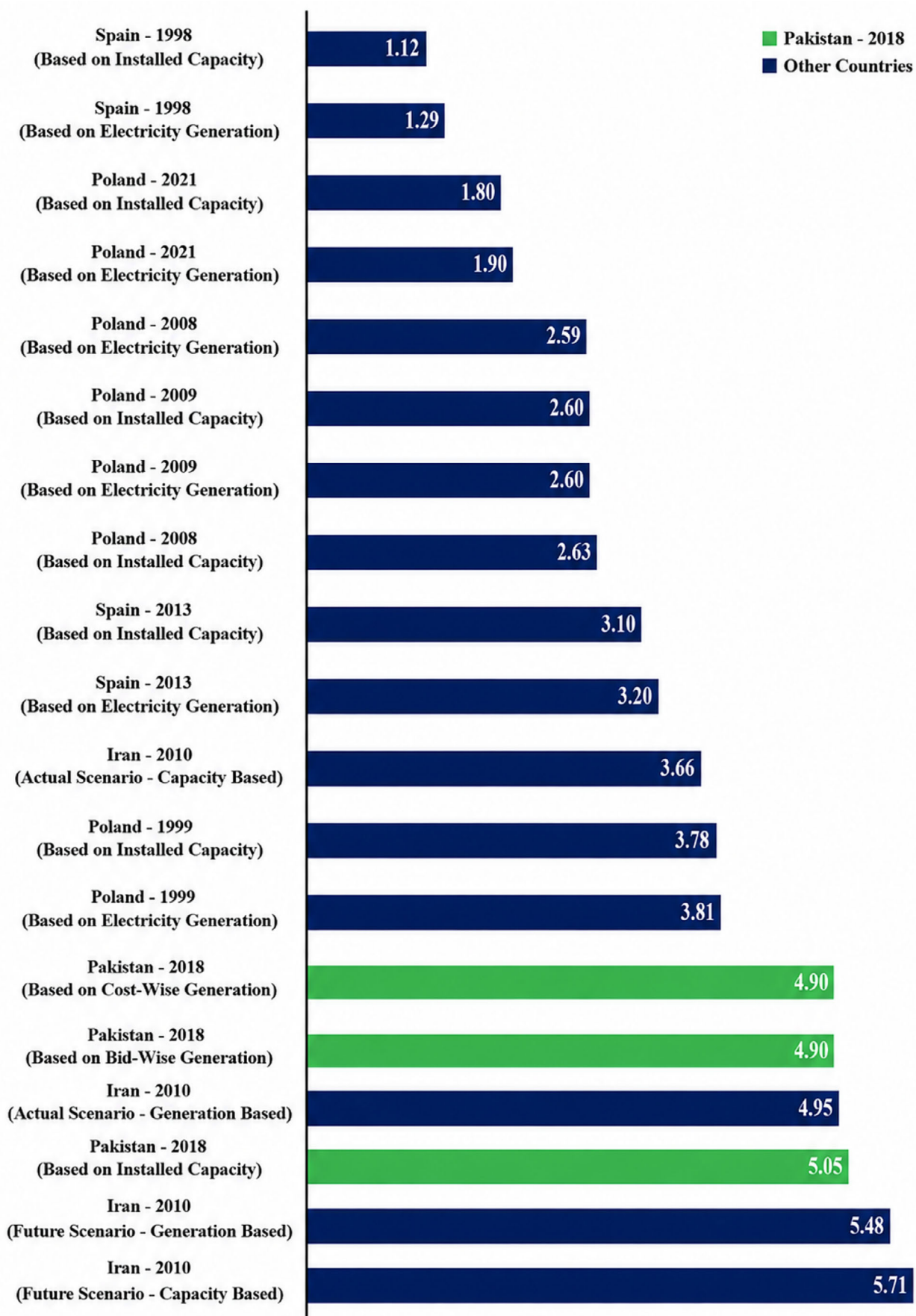


FIGURE 12 | Entropy coefficient.

strategic bidding is not monitored and mitigated. These findings provide important guidance for regulators in designing market monitoring and mitigation mechanisms during the transition toward CTBCM and beyond.

Since LI calculations require nodal prices that are affected by transmission congestion, the results for the five most congested lines are shown in Table 14 to reiterate that the presented research results depend on an explicit transmission network model and to identify locations suffering from congestion-induced market power.

On another note, fuel price volatility can influence marginal costs, thereby affecting the LI by altering market-clearing prices and generators' profitability. A $\pm 20\%$ marginal-cost sensitivity has been discussed conceptually: an increase in fuel cost narrows the LI if market-clearing prices do not rise proportionately, whereas strategic bid increases can preserve or expand the LI.

6 | Conclusion and Future Work

This study reveals critical insights about market power in Pakistan's transitioning electricity sector through a comprehensive structural and behavioral analysis. While traditional capacity-based indices suggest generally low market concentration, the moderate HHI and our behavioral simulations tell a more nuanced story. By implementing Pakistan's first bid-based LI analysis through AMES simulations of a 114-bus

TABLE 11 | Supply Margin Assessment under Min, Avg, and Max Demand.

Demand	Supply Margin Assessment
Min Demand	Negative
Avg Demand	Negative
Max Demand	Negative

TABLE 10 | Entropy coefficient for Pakistan-2018 based on installed capacity, Day 0, and Day 4.

Installed capacity					
Metric					Entropy coefficient
Entropy coefficient					5.05
Day 0 (cost-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
Entropy coefficient	4.90	4.84	4.95	4.84	4.91
Day 4 (bid-wise generation)					
Metric	24 h average	Off-peak period, hours 02:00–07:00	Peak period, hours 12:00–17:00	Minimum-demand hour, hour 07:00	Maximum-demand hour, hour 16:00
Entropy coefficient	4.90	4.87	4.92	4.86	4.93

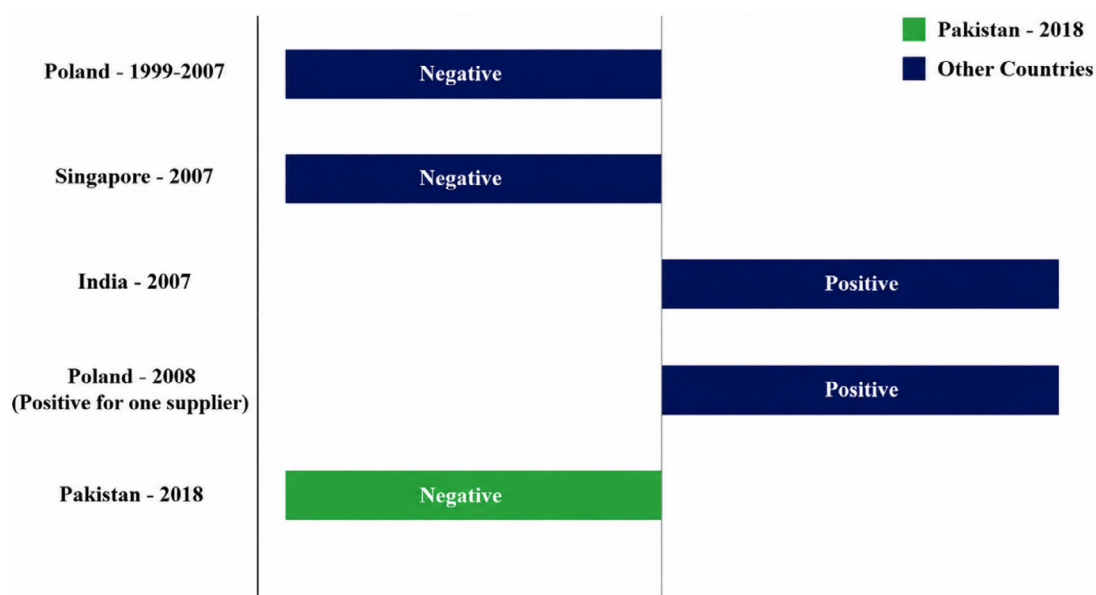
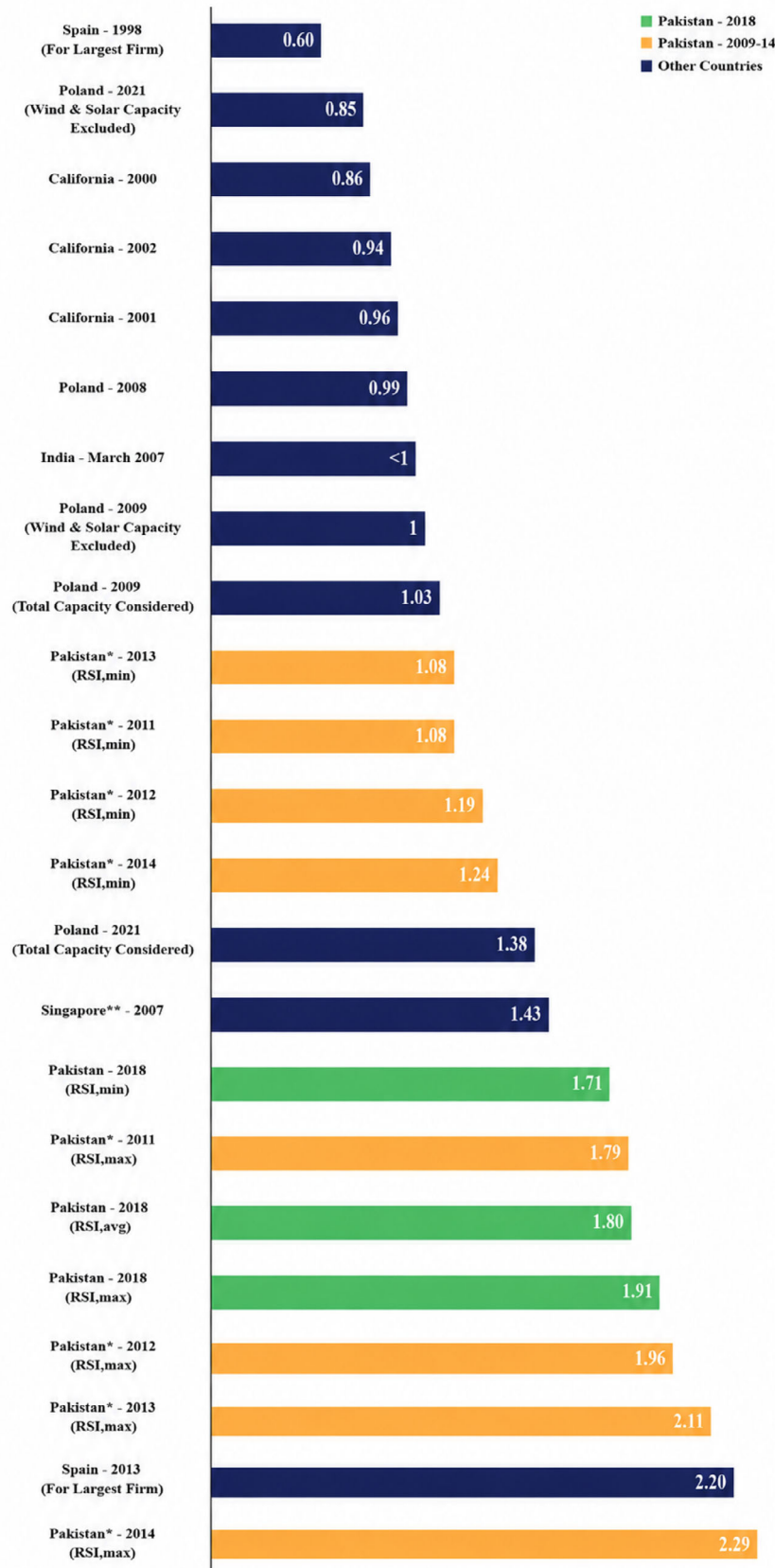


FIGURE 13 | Supply Margin Assessment.



* Each year's maximum and minimum values are considered among 12 months of a year

** Average taken for all companies involved

FIGURE 14 | Residual Supplier Index. *Each year's maximum and minimum values are considered among 12 months of a year. **Average taken for all companies involved.

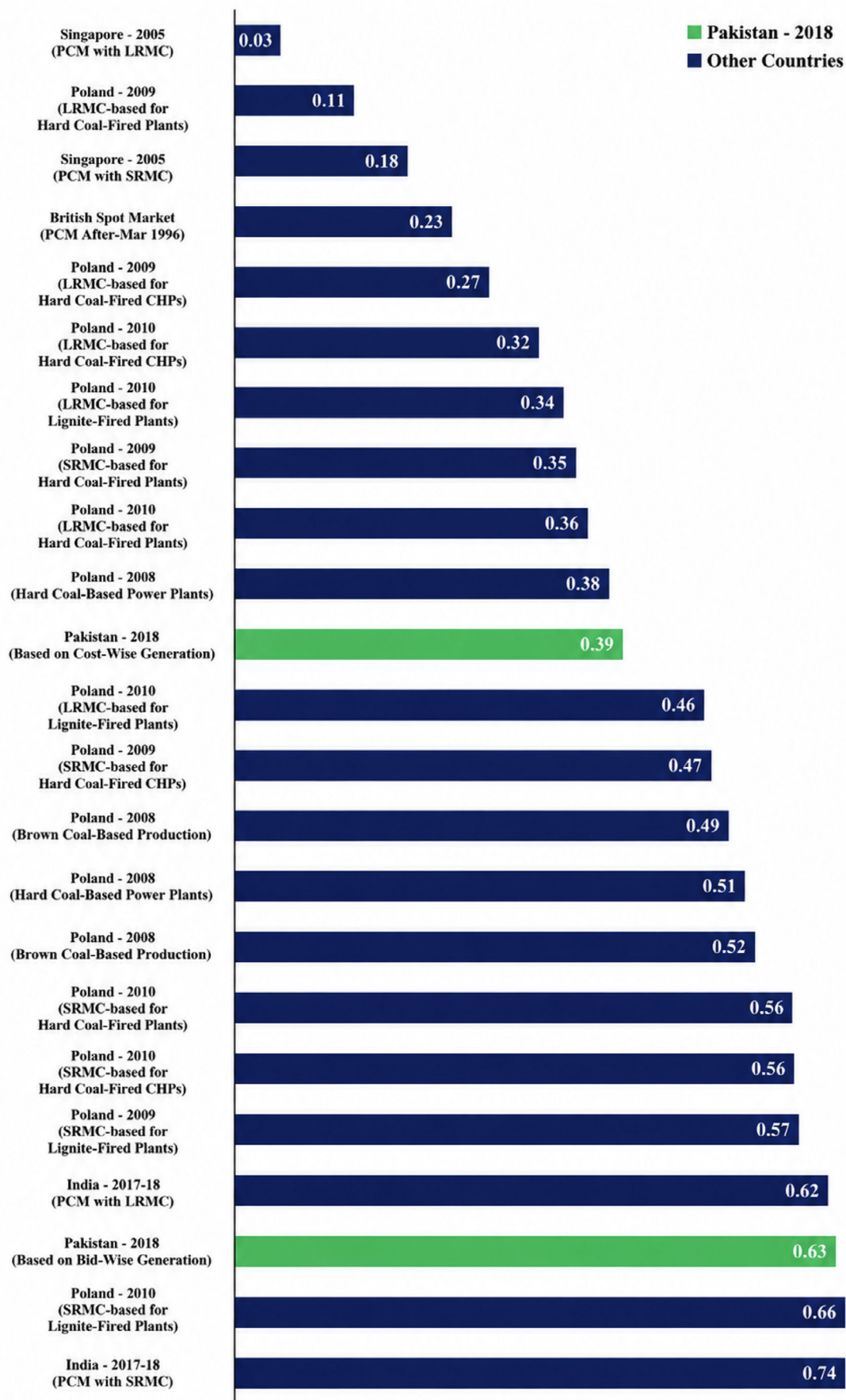


FIGURE 15 | Lerner Index.

network model, we demonstrate how strategic bidding behavior significantly alters market dynamics. LI jumps 62% from 0.39 (cost-based) to 0.63 (bid-based), indicating medium market power potential when generators optimize profits, leading to a 2% rise in cleared energy prices (from 14.89\$ to 15.33322\$/MWh).

The peak/off-peak analysis of the LI provides a clearer indication of transient market power dynamics than the aggregate 24-h average alone. Using the average hourly LMP to classify price conditions, the off-peak price block corresponds to h02–h07, while the peak price block corresponds to h12–h17. The results show that the LI increases from 0.17 during the off-peak price block to 0.53 during the peak price block, compared with the 24-h average value of 0.39. This indicates that LI values are substantially higher during high-price operating conditions. The single-hour extremes further reinforce this pattern: the LI is lowest in the minimum-price hour h07, at 0.15, and highest in the maximum-price hour h15, at 0.80. Therefore, while the average LI provides an overall market-wide benchmark, the peak/off-peak and extreme-hour results show that market power risk is more pronounced during high-price hours and may be diluted when only aggregate averages are reported.

The study provides regulators with both a methodological framework (through our AMES implementation) and substantive findings to inform market design and monitoring strategies. Practical market power mitigation measures are necessary to limit dominant generators' ability to influence electricity prices, particularly under transmission constraints and concentrated ownership structures. Market Power Mitigation measures, such as bid caps, must-offer rules, virtual divestiture, and congestion-management mechanisms, can reduce strategic withholding, restrict excessive bidding, and improve competitive discipline in the market. These measures support transparent price formation, enhance market efficiency, and protect consumers from unjustified price increases while maintaining system reliability.

Future research has been proposed to include: research on updated post-2018 network data, explicit contract/contestable-capacity modeling, renewable integration, nodal/load-pocket market power indices, AC OPF-based validation, alternative bidding strategies, and policy testing of mitigation tools such as bid caps, must-offer rules, virtual divestiture, and congestion-management mechanisms.

TABLE 12 | RSI under Min, Avg, and Max Demand.

Rank	Demand	RSI
1	Max Demand	1.71
2	Avg Demand	1.80
3	Min Demand	1.91

Author Contributions

Aqeel Ahmad: data curation, investigation, methodology, software, visualization, writing – original draft, writing – review and editing. **Kashif Imran:** conceptualization, methodology, data curation, investigation, supervision, visualization, project administration, writing – original draft, writing – review and editing. **Atif Naveed Khan:** data curation, resources. **Shahbaz Ul Haq:** data curation, visualization. **Abdullah**

TABLE 13 | Lerner Index for Pakistan-2018 based on Day 0 and Day 4.

Lerner Index					
Day 0 (cost-wise generation)					
Metric	24 h average	Off-peak period hours 02:00–07:00	Peak period hours 12:00–17:00	Minimum-price hour (07:00)	Maximum-price hour (15:00)
Lerner Index	0.39	0.17	0.53	0.15	0.80
Day 4 (bid-wise generation)					
Metric	24 h average	Off-peak period hours 02:00–07:00	Peak period hours 12:00–17:00	Minimum-price hour (07:00)	Maximum-price hour (16:00)
Lerner Index	0.63	0.58	0.68	0.57	0.69

TABLE 14 | Five most congested transmission branches under Day 0 and Day 4 simulations.

Branch	From bus	To bus	Congested locations (from bus–to bus)	Capacity (MW)	Day 0 Avg flow (MW)	Day 0 Avg loading %	Day 4 Avg flow (MW)	Day 4 Avg loading %
Branch 136	75	106	Muzaffar Garh-1–Jhimpir-1	380	355.72	93.61	357.56	94.09
Branch 56	25	102	Niki–Niki-220	1200	1060.57	88.38	1043.98	87.00
Branch 9	3	42	Rawat-N–Rawat220-1	1350	1062.41	78.70	1044.39	77.36
Branch 18	6	54	Lahore–Lahore (Chichoki Hydro)	2400	1609.70	67.07	1708.71	71.20
Branch 6	3	4	Rawat-N–Nokhar 500 kV	1300	893.64	68.74	909.69	69.98

Abusorrah: visualization, writing – review and editing. **Muhammad Akmal:** supervision, writing – review and editing.

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Disclosure

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Pakistan's national grid data used in this study involves detailed information about power plants, loads, and transmission networks of the National Transmission and Dispatch Company (NTDC). NTDC is the predecessor of the newly formed Independent System and Market Operator (ISMO) and National Grid Company (NGC) of Pakistan. Since the specifics of national grids are critical energy infrastructure data, they are not publicly available, and non-disclosure agreements govern their research use.

Peer Review

For transparency, the peer review documents associated with this article are available at <https://doi.org/10.1002/eng2.71104>.

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