
The Renewable Energy Paradox: Second-Generation Economic Challenges in the Global Energy Transition

Submitted 20/07/25, 1st revision 09/08/25, 2nd revision 21/08/25, accepted 23/09/25

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Abstract:

Purpose: This paper analyzes the "second-generation challenges" of the global energy transition, moving beyond the initial success of cost reduction. It investigates the interconnected problems of market value erosion due to price cannibalization, the widening investment gap in developing economies, the evolution of policy towards active market shaping, and the critical need for electricity market redesign to ensure stability in high-renewable systems.

Design/Methodology/Approach: This paper, based on a systematic review and comparative analysis of data from leading international agencies, analyzes the complex interplay between market value erosion, investment risk in developing economies, and the evolution of policy instruments.

Findings: The results indicate that: (1) price cannibalization, resulting from the merit-order effect, poses a fundamental threat to the profitability of renewable energy (RE) projects, necessitating a shift from the LCOE metric to a more holistic value-adjusted indicator (VALCOE); (2) the global capital divide is primarily driven by a differentiated weighted average cost of capital (WACC), and the effectiveness of de-risking instruments is highly dependent on regional context; (3) policy instruments, such as auctions with Contracts for Difference (CfDs) and non-price criteria (NPCs), are transforming the role of the state from a passive subsidizer to an active market architect; and (4) systems with high penetration of variable renewable energy (VRE) require a fundamental market redesign toward a service-based model that explicitly remunerates flexibility and firm capacity.

Practical implementations:

Originality/Value: The global energy transition has entered a new, more complex phase. While record-breaking deployments and declining levelized costs of energy (LCOE) signal the successful conclusion of the first phase of the transition, a new set of "second-generation challenges" has emerged.

Keywords: Renewable energy, energy transition, price cannibalization, derisking, electricity market design, RE auctions, contracts for difference, energy policy.

JEL codes: Q48, Q51,

Paper type: Systematic review.

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1. Introduction

Context: The Bifurcation of the Global Energy Transition:

The current moment in the global energy transition is characterized by a fundamental paradox. On one hand, the transition exhibits unprecedented momentum. The year 2024 saw a record 585 GW of renewable capacity added, a 15.1% annual increase, dominated by solar photovoltaic (PV) (452 GW) and wind (113 GW). Renewables now account for 46% of global installed generation capacity and a staggering 92.5% of all new capacity additions (IRENA Renewable Capacity Statistics 2025).

On the other hand, this progress is dangerously insufficient and geographically uneven. The world is still not on track to meet the COP28 goal of tripling capacity to over 11 TW by 2030, which would require nearly doubling annual capacity additions to over 1,120 GW (IRENA Renewable Capacity Statistics 2025).

Moreover, deployment is heavily concentrated: Asia (led by China) accounts for 72% of new capacity, while Africa, a continent with vast, untapped potential, represents a mere 0.7% (Solar adds record 452 GW to global renewables capacity in 2024. PV Magazine, 2025). This dichotomy creates a dual narrative of remarkable success and impending failure.

The global energy transition is bifurcating. One path, in developed countries and China, focuses on managing the complexities of high penetration of variable renewable energy (VRE). The other, in most of the developing world, still struggles with fundamental barriers to attracting initial investment. This geographical and quantitative divide signifies more than just a difference in pace; it represents a fundamental divergence in the nature of the problem being solved.

One path is a "problem of success"—managing the systemic intricacies of abundant zero-marginal-cost energy. The other is a "problem of failure"—overcoming basic hurdles to attract even the first wave of investment. Using a single global narrative of "the energy transition" is no longer adequate; we are dealing with a series of fragmented, asynchronous transitions.

Table 1. *Global Trends in Renewable Energy Deployment, 2022-2025.*

Year	Annual Capacity Additions (GW)				Regional Breakdown (GW)					
	Solar PV	Onshore Wind	Offshore Wind	Other Renewables	Total Renewables	Asia	Europe	North America	Africa	Rest of World
2022	240	75	9	16	340	204	57	32	2.4	44.6

2023	375	108	11	13	507	345	71	40	3.6	47.4
2024	452	113	6	14	585	413	72	46	4.2	50
2025 (est.)	480	120	10	15	625	440	78	50	5.0	52

Source: Author's compilation based on data from IRENA Renewable Capacity Statistics (1). Data for 2022–2023 are historical, 2024 is based on preliminary reports, and 2025 is a projection based on current trends.

2. Literature Review

The Emergence of Second-Generation Challenges:

The initial phase of the energy transition was defined by a single goal: reducing the cost of renewable technologies. This goal has been achieved with remarkable success. However, this very success has given rise to a new, more complex set of interconnected challenges that define the current era, which we categorize as follows:

- **Economic Challenges:** The erosion of the market value of renewables caused by their own success (the "price cannibalization" effect) e.g., (Liebensteiner and Naumann, 2022; López *et al.*, 2019; Kozlovas *et al.*, 2024, Wilson *et al.*, 2024).
- **Financial Challenges:** A persistent and deepening investment gap between the Global North and South, driven by risk perception and high capital costs eg. (Montague *et al.*, 2024; Babayomi, 2022).
- **Systemic Challenges:** The technical and market hurdles of integrating vast amounts of variable generation while maintaining grid stability and resource adequacy e.g., (Hussain and Cho, 2024; Babu *et al.*, 2020).
- **Policy Challenges:** The need for policy instruments to evolve from simple deployment incentives to sophisticated mechanisms that can manage market integration, supply chain resilience, and social equity eg (May and Neuhoff, 2021; Jacobs *et al.*, 2020; Hunt *et al.*, 2024).

These challenges do not form a simple list but create an interconnected system. This article aims to demonstrate how they are causally linked in a feedback loop, preparing the reader to look for these connections in the subsequent analysis.

Research Questions and Paper Structure:

This article is structured around four central research questions that address these second-generation challenges:

- *How have the fundamental economics of renewable energy shifted from a focus on the levelized cost of energy (LCOE) to a more complex valuation*

- that incorporates system costs and market value (price cannibalization)?*
- *What are the primary drivers of the significant disparity in renewable energy investment between developed and developing economies, and how effective are current de-risking instruments in closing this gap?*
 - *How are policy mechanisms (e.g., auctions, Contracts for Difference) evolving to meet not only cost-efficiency requirements but also broader objectives such as supply chain resilience, social equity, and system integration?*
 - *What are the most critical market design reforms necessary to ensure grid stability and investment viability in a future dominated by variable renewable energy (VRE)?*

3. Methodology

Research Design:

This study employs a systematic review and comparative analysis of secondary data. This research design was selected to synthesize a broad and complex body of evidence from diverse sources to identify overarching trends, patterns, and causal relationships in the global energy transition. The choice of this method is strategic, as the problem of second-generation challenges is multidimensional and global.

A single primary study would be unable to capture the interconnections between economics, finance, technology, and policy on a global scale. This approach facilitates the integration of quantitative data, policy analyses, and modeling results into a coherent analytical framework, enabling a holistic, system-level assessment of the problem.

Data Sources and Collection:

To ensure rigor and credibility, this analysis utilizes data from leading, internationally recognized institutions, agencies, and peer-reviewed academic literature. The data collection process included the following categories of sources:

- *Institutional Data:* Reports and statistical databases from the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), BloombergNEF (BNEF), and the World Bank Group (including MIGA and IFC). These sources provided fundamental data on installed capacity, investment trends, technology costs, and policy implementation.
- *Financial Data:* Levelized cost of energy (LCOE) and weighted average cost of capital (WACC) analyses from regular reports by Lazard, which are considered an industry benchmark for assessing the cost-competitiveness of energy technologies.
- *Market Data:* Reports on the functioning of European electricity markets from the Agency for the Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E). These provided detailed information on market design, auction outcomes,

and grid constraint management.

- *Academic Literature:* Peer-reviewed scientific articles identified through Scopus, Web of Science, and RePEc databases, using keywords such as "price cannibalization," "renewable energy auctions," "de-risking," "capacity markets," and "hydrogen policy." These formed the basis for in-depth theoretical and empirical analyses, including econometric and financial modeling.

Case Study Selection and Analytical Framework:

The selection of case studies was based on their relevance to the phenomena under analysis, allowing for an in-depth illustration of key challenges and policy mechanisms. The selected cases serve as archetypes for specific phenomena:

- *Price Cannibalization:* California was selected due to its high VRE penetration and well-documented market data, enabling a clear analysis of this phenomenon.
- *De-risking:* Sub-Saharan Africa and Southeast Asia were chosen for a comparative analysis due to their significant RE potential, persistent investment gaps, and status as key target regions for de-risking programs by multilateral development banks (MDBs). This allowed for an assessment of instrument effectiveness in different institutional contexts.
- *Policy and Market Design:* The United Kingdom, Germany, and Denmark were selected for their pioneering role in developing CfD-based auctions and implementing non-price criteria. ERCOT (Texas) and PJM were selected as archetypal examples of energy-only and capacity markets, respectively.

The analytical framework is based on a comparative synthesis. This paper does not conduct new, primary modeling but instead critically evaluates and integrates quantitative results from existing models and empirical studies cited in the literature to build a comprehensive, evidence-based argument.

4. Research Results and Discussion

The Economics of Abundance: From LCOE to Price Cannibalization and its Financial Impact:

This section establishes the first, fundamental link in the paper's central argument: technological success (zero marginal cost) directly causes economic value erosion (price cannibalization), which in turn creates a serious financial threat (unprofitability).

- *The Decline and Stabilization of LCOE:*

A fundamental success of the first phase of the energy transition was the dramatic reduction in the levelized cost of energy (LCOE) for solar PV and onshore wind. Data from Lazard and IRENA indicate that in 2024, 91% of new, utility-scale RE projects generated electricity at a lower cost than the cheapest fossil fuel alternative.

Unsubsidized utility-scale solar PV (\$38–78/MWh) and onshore wind (\$37–86/MWh) have remained the most cost-effective forms of new generation for a decade. This cost decline was driven by technological progress, economies of scale, and manufacturing efficiencies (IRENA Renewable Capacity Statistics 2025, Lazard report 2025).

However, this long-term downward trend has recently been curbed. Macroeconomic factors such as inflation, supply chain disruptions, and, most importantly, rising interest rates have contributed to a stabilization and even a slight increase in LCOE (Land-Based Wind Market Report 2023). High interest rates have a disproportionately larger impact on capital-intensive RE projects than on fossil fuel-based projects, which are characterized by higher ongoing fuel costs.

An analysis by Oxford University indicates that higher financing costs in the US raised the LCOE for solar PV by 18%, while for combined-cycle gas turbines (CCGT), the increase was only 9% (Wilson *et al.*, 2024). This suggests that the era of steep, effortless cost declines has ended, and the focus is shifting from technology costs to the financial and revenue side of the business model.

- *The Price Cannibalization Effect:*

The increasing penetration of variable renewable energy (VRE) sources like wind and solar significantly impacts wholesale electricity markets. Because these technologies have a near-zero marginal cost of production, they displace more expensive generators, leading to a decline in wholesale electricity prices, particularly during periods of high renewable output. This phenomenon, known as the merit-order effect, gives rise to "price cannibalization," where an increasing supply of wind and solar power progressively undermines its own market value.

A time-series econometric analysis of the California wholesale electricity market (CAISO) between 2013 and 2017 provides a detailed quantification of this effect (Lopez *et al.*, 2020). The study confirms that as VRE penetration grows, it suppresses wholesale prices and erodes the unit revenues for both wind and solar generators. This absolute cannibalization effect was found to be more severe for solar power, which experienced a revenue decline of \$1.295/MWh for each percentage point increase in its penetration. The impact on wind power was also significant, with a revenue decline of \$0.838/MWh per percentage point of penetration.

The research also identified a relative cannibalization effect, where the "value factor" (the revenue per MWh relative to the average electricity price) for both technologies declines as their market share grows. Furthermore, the analysis uncovered complex cross-cannibalization effects between the two technologies. While increased wind penetration was found to reduce the value of solar power, higher solar penetration actually increased the value factor for wind, especially at high penetration and low consumption levels. The study notes that these

cannibalization effects are generally stronger during periods of low electricity demand. These findings suggest that the long-term competitiveness of both wind and, most notably, solar power could be jeopardized by their own success. The authors conclude that without mitigation measures—such as the deployment of energy storage, improved demand-side management, and enhanced grid interconnections—the continued viability of these critical renewable sources may be at risk.

- *Modeling the Impact on Project Profitability (IRR):*

The erosion of market value poses a direct threat to the profitability and bankability of RE projects. Traditional metrics like LCOE, which focus solely on the cost side, are blind to this revenue risk (Manzolini et al., 2024). To quantify this threat, it is necessary to model the impact of price cannibalization on the internal rate of return (IRR) of projects.

Academic studies using real options analysis and discounted cash flow (DCF) modeling provide concerning results. Reichenberg *et al.* (2023) demonstrated that including the cannibalization effect in financial models can reduce the projected profit-to-investment-cost ratio from 33% to a range between 13% and even -40%, depending on assumptions about the future expansion rate of VRE capacity (Reichenberg *et al.*, 2023).

Another study, modeling the Baltic markets through 2033, projects that an increase in RE capacity will halve market prices, with revenue losses due to price cannibalization for onshore wind ranging from €10.5 to €22.0/MWh. The authors conclude that after 2029, revenues generated by RE producers may not guarantee project profitability without additional support mechanisms or flexibility markets (Kozlovas et al. 2024). These findings clearly indicate that the primary economic challenge for RE is no longer minimizing capital expenditures (CAPEX) but stabilizing future revenue streams in the face of systemic price deflation.

- *Beyond LCOE: The VALCOE Metric:*

The limitations of LCOE as a decision-making indicator in high-VRE systems have led to the development of more advanced metrics. The International Energy Agency (IEA) has introduced the concept of the Value-Adjusted LCOE (VALCOE) (IEA. Projected Costs of Generating Electricity 2020). VALCOE provides a more comprehensive indicator by incorporating a technology's value to the system across three dimensions:

- **Energy Value:** When the energy is generated (e.g., during peak demand hours).
- **Capacity Value:** Contribution to resource adequacy and security of supply.
- **Flexibility Value:** Ability to provide ancillary services.

IEA analysis shows that while a new solar PV plant may have a lower LCOE than a coal plant, its VALCOE can drop significantly as its market share increases,

reflecting the declining value of intermittent, daytime energy in a sun-saturated grid(18). This metric is essential for making rational, system-wide investment decisions in a VRE-dominated future.

Table 2. *Comparative Levelized and Value-Adjusted Cost of Energy (LCOE and VALCOE), 2025.*

Technology	Unsubsidized LCOE Range (\$/MWh)	Key LCOE Cost Drivers	VALCOE at 10% VRE Penetration (\$/MWh)	VALCOE at 40% VRE Penetration (\$/MWh)
Solar PV (Utility-Scale)	38–78	CAPEX, WACC	55	40
Onshore Wind	37–86	CAPEX, WACC, O&M	60	48
Offshore Wind	75–140	CAPEX, WACC	90	80
Gas CCGT	48–107	Fuel, Carbon Cost, CAPEX	75	95
Coal	69–168	Fuel, Carbon Cost, O&M	90	110
Nuclear	120–220	CAPEX, WACC, Construction Time	150	160

Source: *Author's compilation based on Lazard data for LCOE ranges and IEA concepts and illustrative data for VALCOE. VALCOE values are estimates intended to illustrate trends, not to provide precise forecasts.*

The Global Capital Divide and the Effectiveness of De-risking Instruments: A Comparative Analysis:

This section builds the second element of the argument: the financial threat identified in the preceding part is compounded by the high baseline WACC in emerging and developing economies (EMDEs), making capital, rather than technology, the main bottleneck.

- *Quantifying the Investment Imbalance:*

Data unequivocally show a vast geographical disparity in clean energy finance. Although global investment in the energy transition reached a record \$2.1 trillion in

2024, over 80% of this is concentrated in developed economies and China. Emerging markets and developing economies (EMDEs), home to two-thirds of the world's population, receive only about 15% of this capital. Data from BloombergNEF (BNEF, 2025) and the IEA illustrate this gap, highlighting that investment in many EMDEs has remained flat despite growing needs.

- *The Central Role of the Cost of Capital (WACC):*

The single most important factor explaining the investment gap is the high cost of capital. Renewable projects, with their high upfront capital expenditures (CAPEX), are far more sensitive to the weighted average cost of capital (WACC) than fossil fuel projects (Wilson *et al.*, 2024). Analyses show that financing costs can account for nearly half of a project's total LCOE in developing countries (Citi Private Bank. ENERGY 2030).

The WACC in many EMDEs is significantly higher due to a combination of perceived and real risks, including macroeconomic instability, political and regulatory uncertainty, currency volatility, and the creditworthiness risk of the offtaker (typically a state-owned utility)(OECD. Bridging the clean energy investment gap).

- *Comparative Empirical Analysis of De-risking Instruments: Sub-Saharan Africa vs. Southeast Asia:*

This subsection provides a systematic assessment of public and blended finance mechanisms designed to lower the WACC and mobilize private capital.

- a. *Blended Finance and Concessional Capital:* Blended finance uses catalytic capital from public or philanthropic sources (e.g., concessional loans, first-loss equity) to mitigate risk and improve the risk/return profile for private investors(Systemiq. Mobilising Capital for Water: Blended Finance Solutions to Scale Investment in Emerging Markets) Examples from the Green Climate Fund (GCF) and the African Development Bank (AfDB) show how such instruments have mobilized significant private capital for renewable projects(IEA. The role of multilateral climate funds in the energy sector – Analysis; 2025).
- b. *Guarantees and Insurance:* This part focuses on instruments that directly backstop specific risks. A case study analysis will be conducted on the World Bank's Partial Risk Guarantees (PRGs), which cover sovereign/offtaker default, and MIGA's Political Risk Insurance (PRI), which covers risks like expropriation, breach of contract, and currency inconvertibility(Climate Policy Initiative. Mapping the World Bank Group Risk Mitigation Instruments for Climate Change). The Bujagali hydropower project in Uganda serves as a key case study, demonstrating how the combined use of an IDA PRG and MIGA PRI was essential to mobilizing significant financing, including the refinancing of over \$400 million in loans and up to \$423 million in guarantees (Climate Policy Initiative. Risk

Mitigation Instruments for Renewable Energy in Developing Countries: A Case Study on Hydropower in Africa). The International Finance Corporation's (IFC) "Scaling Solar" program in Zambia will also be analyzed, which bundled advisory services, standardized documents, and World Bank Group guarantees into a "one-stop-shop" package, resulting in record-low solar tariffs in Africa at the time (World Economic Forum. Case Study Details - Playbook of Solutions - One-stop-shop for Renewable Energy Permits).

- c. *Mitigating Currency Risk:* Currency volatility is a major deterrent for foreign investors, as revenues are generated in local currency while debt is often in hard currency (Energy for Growth. The Quantifiable Advantages of Local Currency on African Energy Projects). The role of specialized institutions like The Currency Exchange Fund (TCX) is analyzed, which provides long-term currency hedging products (swaps, forwards) in over 80 developing country currencies where such markets are illiquid or non-existent (CIF. Managing Currency Exchange Rate Risk for Climate Solutions). Analysis by the Climate Policy Initiative shows that mitigating currency risk alone can reduce project costs by up to 30% (CIF. Managing foreign exchange rate risk for transformational climate solutions).

The effectiveness of de-risking instruments is multiplied when they are bundled into programmatic platforms (like Scaling Solar) rather than applied on a one-off, project-by-project basis. Individual projects face high transaction costs and long timelines negotiating bespoke de-risking packages with multilateral development banks (MDBs).

The Scaling Solar program in Zambia showed that by pre-packaging technical assistance, standardized, bankable contracts, and a suite of guarantees, the entire tender process could be streamlined, attracting multiple high-quality bidders and achieving record-low prices.

This approach moves beyond simply de-risking a single asset to de-risking the entire market environment for a specific tender round. It creates transparency, predictability, and credibility, signaling a credible, long-term government commitment backed by MDBs, which effectively lowers the country risk premium.

- *The Evolution of Policy Support: From Subsidies to Market Architecture:*

The third element of the argument indicates that the financial risks identified in the previous sections are forcing governments to evolve policy from simple subsidies to complex risk management and market-shaping instruments, such as Contracts for Difference and non-price criteria.

Table 3. *Comparative Framework and Effectiveness Assessment of De-risking Instruments in EMDEs.*

Instrument Type	Primary Function	Targeted Risk	Key Providers	Case Study Example	Effectiveness Assessment and Regional Context
Concessional Loans / First-Loss Capital	Lower cost of debt, enhance equity returns	Commercial viability, project bankability	GCF, AfDB	GCF Africa Program	Effective in improving project financial metrics; often used within blended finance frameworks in both regions.
Partial Risk Guarantees (PRGs)	Backstop against off-taker payment default	Sovereign/off-taker default	World Bank (IDA)	Scaling Solar Zambia	Highly catalytic in Sub-Saharan Africa, where off-taker risk is a key barrier.
Political Risk Insurance (PRI)	Protect against government actions	Expropriation, breach of contract, civil disturbance	MIGA	Bujagali Hydro Project, Uganda	Crucial for infrastructure projects in regions with high perceived political instability, particularly in Africa.
Currency Hedging	Lock in exchange rates against adverse movements	Foreign Exchange (FX) volatility	The Currency Exchange Fund (TCX)	InfraCredit Nigeria	Essential in both regions, but particularly critical in Africa due to less liquid currency markets.

Source: Author's compilation based on a synthesis of reports from the World Bank, MIGA, IEA, Climate Policy Initiative and academic literature.

- *The Shift from Feed-in Tariffs (FiTs) to Auctions:*

Global RE support policy has undergone a significant evolution from administratively set schemes, such as feed-in tariffs (FiTs), to competitive procurement through auctions (CIF. Managing Currency Exchange Rate Risk for Climate Solutions). While FiTs were crucial for developing nascent industries, auctions have proven more effective at discovering the true costs of mature technologies and minimizing support costs for consumers (Climate Policy Initiative. Risk Mitigation Instruments for Renewable Energy in Developing Countries: A Case Study on Hydropower in Africa). Data indicate a rapid global adoption of auctions, which are now the dominant support mechanism worldwide (The Quantifiable Advantages of

Local Currency on African Energy Projects).

- *Analysis of European Auction Designs:*

European markets serve as a laboratory for advanced auction designs, where two elements play a key role: Contracts for Difference (CfDs) and non-price criteria (NPCs).

- Contracts for Difference (CfDs):** Two-sided CfDs have become the preferred revenue stabilization instrument in Europe (Doku, 2016). A CfD is a financial contract that pays out the difference between a variable market reference price and a fixed "strike price" agreed upon in an auction. This mechanism provides producers with long-term revenue certainty, which drastically lowers their financing costs (WACC), while also protecting consumers from high prices (as producers pay back the difference when market prices exceed the strike price). The UK's CfD scheme is a flagship example, having significantly contributed to driving down the costs of offshore wind and attracting substantial investment in new projects.
- Non-Price Criteria (NPCs):** As auction systems mature, policymakers are increasingly incorporating non-price criteria (NPCs) to achieve broader policy goals beyond the lowest cost. The EU's Net-Zero Industry Act and state aid guidelines now explicitly allow or mandate the use of NPCs, which can account for 30% to 50% of the bid evaluation (Del Rio and Kiefer, 2022a).
- Comparative Analysis: Germany vs. the Netherlands:** A comparison of offshore wind auctions in Germany and the Netherlands illustrates different approaches. Early German auctions were purely price-based and allowed for "negative bidding" (where developers pay for the right to build), which drew criticism for raising costs for consumers and the supply chain (Del Rio and Kiefer, 2022b). While later German auctions introduced some qualitative criteria, price remains the dominant factor (Khodadadi, 2024). In contrast, the Netherlands has extensively used NPCs, where criteria such as biodiversity protection or system integration can account for up to 90% of the evaluation (WindEurope. Executive summary). This shows a policy evolution from pure cost-efficiency to a more holistic concept of "value."

Econometric analyses of European auction results confirm that high competition levels and the use of ceiling prices are correlated with lower prices, while the impact of NPCs on prices is not statistically conclusive, suggesting they can be implemented without a significant increase in support costs if designed appropriately (Windtech International).

- *Market Design Reform for High-VRE Systems:*

This section closes the causal loop. The policies described earlier, such as CfDs, can weaken price signals, exacerbating the "missing money" problem and hindering the financing of flexibility resources needed for VRE integration. This systemic challenge requires fundamental market reform.

- *The Flexibility Imperative:*

High VRE penetration fundamentally changes the dynamics of the power system. Managing the variability and unpredictability of wind and solar generation requires a suite of "flexibility" resources that can balance supply and demand across different timescales, from seconds to seasons (Agora Energiewende. Germany's 2024 Offshore Wind Auction Results). Traditional grids, dominated by dispatchable thermal power plants, are not designed for this challenge, creating a need for new sources of flexibility and market reforms that remunerate them.

- *A Comparison of Market Models: Energy-Only vs. Capacity Markets:*

The debate over ensuring long-term resource adequacy is centered on two main paradigms.

- Energy-Only Markets (EOMs):** This model, exemplified by the ERCOT market in Texas, is based on the premise that high price spikes during periods of power scarcity (scarcity pricing) will provide sufficient investment signals for new dispatchable capacity. The advantage of this approach is its theoretical efficiency and strong price signals for flexibility. However, in high-VRE systems where energy prices are often near zero, EOMs face the "missing money" problem, which undermines the ability to finance any asset—both renewable and backup (WindEurope. Negative bidding continues to burden offshore wind development). Analyses by the Brattle Group indicate that while EOMs can function, they require very high price caps and create significant risk for investors (Brattle Group. Real Reliability: The Value of Virtual Power; 2023).
- Capacity Markets:** This model, common in the northeastern US (e.g., PJM) and parts of Europe, creates a separate market for "firm capacity" (\$/MW-year) e.g. (Anatolitis et al., 2022; Aagaard and Kleit, 2022, Hancher et al. 2023). Producers receive payments for being available to generate, which provides a stable revenue stream and guarantees resource adequacy. The advantage is investment certainty. The disadvantages, however, include the potential risk of over-procurement of capacity, higher costs for consumers, and a tendency to favor existing, inflexible units over new, flexible technologies like energy storage (PwC. How battery storage can increase grid stability and efficiency in the European energy market).
- Hybrid Models and Evolution:** A growing consensus indicates that pure EOM models are insufficient in decarbonized systems. Many jurisdictions, including Germany, are experimenting with hybrid models, such as strategic reserves, that combine an energy market with adequacy mechanisms. The evolution is toward markets that not only remunerate energy and capacity but also create liquid, transparent markets for flexibility services (e.g., reserves, frequency regulation).

- *Enabling Flexibility Providers:*

The key to the reliable operation of a high-VRE system is removing market barriers for new sources of flexibility.

- Energy Storage:** The dramatic 93% decline in the cost of battery energy storage systems (BESS) since 2010 makes them a key flexibility resource(1). Their profitability depends on the ability to "stack revenues" by providing multiple services in different markets—energy arbitrage in the wholesale market, frequency regulation in ancillary services markets, and capacity payments(PwC. How battery storage can increase grid stability and efficiency in the European energy market; Sustainability Directory. What Policies Enhance Renewable Energy Storage?).
- Virtual Power Plants (VPPs) and Demand-Side Resources (DSR):** The aggregation of distributed energy resources (DERs)—such as rooftop solar, residential batteries, smart thermostats, and electric vehicle chargers—into virtual power plants (VPPs) represents a vast, untapped flexibility potential eg. (U.S. Department of Energy. Virtual Power Plants: Pathways to Commercial Liftoff; 2023; Gao et al., 2024).
- Grid Modernization:** The role of Grid-Enhancing Technologies (GETs) in optimizing existing transmission infrastructure will be explored. The focus will be on Dynamic Line Rating (DLR), which uses real-time weather data and sensors to update the thermal capacity of power lines, often unlocking 20-40% of additional capacity at a fraction of the cost and time of building new lines(Dynamic line ratings: A smart business decision. pv magazine USA, 2025.). Case studies from utilities like PPL and AES will demonstrate significant congestion cost savings(Smart Energy. Grid enhancing technologies and managing new cybersecurity risks.).

Table 4. Cross-Jurisdictional Comparison of Market Design Philosophies for High-VRE Systems.

Jurisdiction	Core Market Philosophy	Resource Adequacy Mechanism	Flexibility/Ancillary Service Market Design	Key VRE Integration Policies
PJM (USA)	Capacity Market	Forward Capacity Auction	Co-optimized with energy market	FERC Order 2222, minimum offer price rules
ERCOT (USA)	Energy-Only Market	Operating Reserve Demand Curve (ORDC)	Real-time ancillary service markets	Scarcity pricing, no capacity market

Germany	Hybrid (Energy Market Reserve) +	Strategic reserve, capacity market discussions	Separate markets for ancillary services	Auctions with Non-Price Criteria (NPCs)
Denmark/Nordics	Energy-Only Market	High interconnector capacity	Liquid, integrated balancing markets	High interconnection, DSR participation

Source: Author's compilation based on a synthesis of reports from ACER, ENTSO-E, the Brattle Group, and national regulators.

Synthesis of Results: The Interconnected Nature of Second-Generation Challenges
The results presented in this paper indicate that the second-generation challenges of the energy transition are not isolated issues but form a system of interconnected dependencies. The analysis reveals a causal chain that defines the current paradigm and constitutes the main conclusion of the study:

- **Technological success (low LCOE) leads to economic value erosion.** The zero marginal cost of VRE, the basis of their cost-competitiveness, is also the cause of price cannibalization, which undermines their profitability.
- **Value erosion increases financial risk.** Uncertainty about future revenues, resulting from price cannibalization, directly translates into a higher perceived risk profile for RE projects. This, in turn, leads to a higher cost of capital (WACC), which is particularly acute in developing countries where baseline risk is already high.
- **Financial risk forces policy evolution.** To counteract revenue risk and lower the WACC, policy has had to evolve from simple subsidies (FiTs) to revenue-stabilizing mechanisms like Contracts for Difference (CfDs). This has transformed the role of the state from a subsidizer to a guarantor of market risk.
- **Policy evolution creates new systemic challenges.** Traditional CfDs, by guaranteeing a fixed price for every MWh produced, can weaken incentives for producers to respond flexibly to market signals (e.g., curtailing production during negative prices). This, in turn, exacerbates challenges related to system integration and grid stability.
- **Systemic challenges require fundamental market reform.** The low value of energy and the need for flexibility render energy-only markets inefficient. A fundamental reform toward a service-based model that creates new revenue streams for capacity, flexibility, and other ancillary services becomes necessary, thus closing the loop by attempting to solve the "missing money" problem created at the outset by the very success of VRE.

This sequence shows that solving one problem (cost) in an unintegrated manner has given rise to a series of more complex problems (value, risk, integration).

Policy Implications:

The identified interconnections have profound implications for policymakers at various levels.

- **For Multilateral Development Banks and International Policymakers:** The comparative analysis of de-risking in Africa and Southeast Asia indicates that a "one-size-fits-all" approach is ineffective. A shift from project-level de-risking to creating scalable, programmatic platforms that combine financial instruments with technical assistance and policy reforms (e.g., a "Scaling Solar 2.0") is necessary. The priority should be to finance instruments that address the highest-impact risks, especially currency volatility and offtaker creditworthiness.
- **For National Governments:** The design of "holistic" support policies is essential. This means moving from simple price-based auctions to auctions that use CfDs to stabilize revenues and incorporate strategic NPCs to build resilient domestic supply chains and ensure social acceptance. It is crucial that support for generation is integrated with a forward-looking plan for grid expansion and flexibility procurement.
- **For Regulators and System Operators:** Urgent market design reform is needed to create liquid, transparent, and technology-neutral flexibility markets. This includes removing barriers to participation for energy storage, demand-side response (DSR), and VPPs in all relevant market segments (energy, capacity, ancillary services). Mandating data transparency and investing in advanced grid technologies (GETs, DERMS) and forecasting capabilities (AI/ML) are necessary to operate the system more efficiently and reliably.

Limitations of the Study:

It should be noted that this study is based on a synthesis of existing data and models, not on the generation of new, primary modeling results. Consequently, its conclusions are conditioned by the quality and assumptions of the underlying sources.

Furthermore, the energy transition is a highly dynamic process; quantitative results, such as specific auction prices or LCOE values, represent a snapshot in time and are subject to continuous change. The comparative analysis of de-risking is also limited by the lack of publicly available, standardized quantitative data on the financial outcomes of individual projects, often necessitating a reliance on qualitative analyses and case studies.

Avenues for Future Research:

This analysis identifies several key knowledge gaps that should be the subject of future scientific inquiry:

- **Longitudinal empirical studies** on the effectiveness and cost impact of

different non-price criteria in auctions and their effect on supply chain development.

- **Quantitative analysis of the macroeconomic impacts** of large-scale de-risking programs in EMDEs, including the effects on GDP growth, public finances, and the balance of payments.
- **A comparative political economy analysis of electricity market reform**, examining why some jurisdictions (e.g., Denmark) successfully adapt their markets while others face political gridlock.
- **Techno-economic modeling of optimal integration pathways** for long-duration energy storage and green hydrogen to address the seasonal variability of VRE.

6. Conclusions

The global energy transition has reached a pivotal point. The success in solving the "first-generation problem" of reducing the cost of renewable technologies has, paradoxically, created a set of more complex "second-generation challenges" related to economic value, investment risk, and system integration. This paper has demonstrated that these challenges are deeply interconnected, forming a systemic feedback loop where success in one area generates tensions in another.

The main conclusions of the analysis are as follows:

- **The economic paradigm has shifted from cost to value.** Price cannibalization is an inevitable consequence of high VRE penetration in current market structures and poses a fundamental threat to investment profitability, rendering the LCOE metric insufficient.
- **Capital, not technology, is the main bottleneck in developing countries.** The high cost of capital (WACC) is a key barrier, and effective de-risking instruments must be precisely tailored to the specific risk profile of a given region.
- **Policy is evolving toward active market shaping.** The use of advanced instruments, such as auctions with CfDs and NPCs, indicates that the state is no longer just a passive sponsor but an active architect, aiming to achieve complex industrial and systemic objectives.
- **Market design must be fundamentally re-engineered.** High-VRE systems cannot operate based on a market model that solely remunerates energy. A transition to a service-based model that creates explicit revenue streams for capacity, flexibility, and other attributes essential for system reliability is necessary.

To address these challenges, an integrated, multi-level policy framework that simultaneously addresses all these areas is required. This framework must be based on three pillars:

- **At the international level:** A shift from fragmented de-risking to the creation of scalable platforms that combine financial instruments with technical assistance and support for regulatory reforms.
- **At the national level:** The design of holistic policies that integrate support for generation with planning for grid expansion and flexibility markets, using auctions with CfDs and NPCs to achieve both energy and industrial objectives.
- **At the regulatory level:** Urgent implementation of market reforms to create liquid and open markets for all flexibility providers and investment in digital technologies to optimize system operation.

Overcoming the second-generation challenges requires a paradigm shift—from thinking in terms of deploying megawatts to thinking in terms of designing a resilient, flexible, and economically sustainable energy system.

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