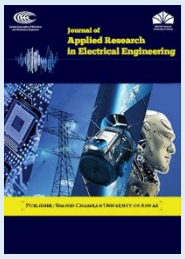
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Review Article

A Review of Reliability in the Restructured Power System: Concepts, Classification and Challenges

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Abstract:
Restructured power systems, have transformed traditional vertically integrated monopolies into dynamic, market-driven entities. However, it also introduces significant complexities in ensuring system reliability. Reliability assessment has accordingly evolved from traditional deterministic methods to more sophisticated probabilistic approaches capable of capturing these uncertainties. A particular concern in market-based systems is economic curtailment of variable renewable resources. Nevertheless, it creates indirect reliability risks by reducing the effective capacity credit of variable renewables to resource adequacy. Consequently, not all installed renewable capacity can be reliably counted upon during periods of highest system need. This review paper examines the critical role of reliability in restructured power systems. It covers: key concepts and definitions, commonly used reliability indicators, assessment methods and tools, principal challenges introduced by restructuring and impacts of market mechanisms on system reliability. While restructuring generally improves economic efficiency and has the potential to lower long-term costs, it simultaneously poses new threats to maintaining a reliable electricity supply. The advantages and disadvantages of restructured systems with respect to reliability are discussed, and the major challenges in reliability assessment within market-based environments are systematically classified. A comprehensive review of relevant studies is presented to highlight current approaches, gaps, and emerging trends. This article aims to provide a solid foundation for future research on achieving a reliable and resilient modern power grid. It also underscores the necessity of thoughtful market design, appropriate regulatory frameworks, and well-calibrated reliability mechanisms to safeguard continuous and secure electricity supply for consumers.

Keywords: Classification, evaluation indicators, improvement, reliability, structured power system.

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1. INTRODUCTION

Energy serves as the fundamental resource for the generation, transmission, distribution and consumption of electricity in the power system, and is of great importance for sustainability and environmental impact [1,2]. Energy powers homes, industries and infrastructure, and powers everything from lighting and heating to complex industrial processes and digital technologies. Without reliable energy, modern societal functions would struggle [3-6]. Power systems powered by

energy sources (e.g. fossil fuels, renewables, nuclear) support economic growth by enabling production, trade and innovation. The availability of energy has a direct impact on industrial production, job creation and gross domestic product. A sustainable power system ensures a stable energy supply, reduces dependence on external sources, and mitigates risks from geopolitical tensions or supply chain disruptions. Diversifying energy sources (e.g., solar, wind, hydro, natural gas) increases power system resilience [7-10].

Power systems require a stable energy supply to maintain grid stability. Energy sources must be distributable or combined with storage solutions (e.g., batteries) to balance supply and demand, and prevent outages or voltage fluctuations. Reliability in power systems includes resource adequacy (sufficient capacity to meet demand), operational reliability (real-time balancing of supply and demand), and resilience (ability to withstand disturbances). The electricity industry has undergone significant transformation in recent decades, moving from vertically integrated monopolies to restructured systems characterized by deregulation and market competition [11-14]. In a restructured electricity system, the functions of generation, transmission, and distribution are separated, providing competitive markets in which customers can choose suppliers based on price, reliability, and other factors. This restructuring is aimed at increasing efficiency and reducing costs, and includes deregulation to promote competition, efficiency, and cost reduction, but it also introduces complexities such as bilateral contracts, ancillary services markets, and independent system operators. In restructured systems, reliability shifts from a focus on public services to a focus on the market, balancing economic incentives with supply adequacy [15-18].

So far, various studies have been presented in the field of restructured power system [19-21].

The challenges of maintaining the balance between generation and demand in power systems with the increasing integration of renewable energies have been pointed out in [22], which causes generation interruptions, which require advanced strategies to ensure stability and reliability. For this purpose, a demand response (DR)-based approach is proposed within the framework of automatic generation control (AGC). Demand response prioritizes demand-side management for frequency regulation in a hybrid two-zone power system without deregulation. It involves monitoring and adjusting demand to match generation fluctuations. Also, a rule-based fractional control scheme with a two-degree-of-freedom topology is used for frequency regulation, which is used to manage the complexities of a hybrid power system with the integration of renewable resources.

The challenges of uncertainty in renewable energy generation and load demand in a restructured power system are addressed in [23], where a combined control method of a robust unknown input observer (UIO) and an interval type 2 fuzzy logic controller (IT2FLC) is used. Accurate state estimation is crucial for effective control, especially in systems with high renewable energy penetration where uncertainties are prevalent. UIO estimates the actual dynamic state of the power system (e.g. frequency deviations, transmission line load distribution) in real time, even in the presence of unknown inputs or disturbances (e.g. unmolded dynamics, external disturbances). IT2FLC is also used for adaptive load frequency control in interconnected power systems with high renewable energy penetration.

The improved frequency regulation (IFR) approach in an interconnected hybrid power system operating in a restructured environment is investigated in [24], where the hybrid power system includes a thermal power system, biogas plant, and distributed generation with solar and wind energy as renewable energy sources. Electric vehicles are integrated to manage part of the uncontracted demand, increasing the flexibility of the system. Also, to make the system more realistic, nonlinearities in the thermal and biogas systems are considered, reflecting real-world operational constraints. A combined fuzzy proportional integral (FPI), linear active disturbance rejection (ADRC) control is proposed for IFR, which aims to maintain system frequency stability under varying conditions in a restructured electricity market. A quasi-opposition-based artificial electric field algorithm (QO-AEFA) is used to optimize the controller gain parameters, which ensures the optimal performance of the IFR system.

In [25], load frequency control in a two-zone regenerative multi-unit thermal reheat power system is presented and the frequency fluctuations caused by high-power and high-capacity devices in a competitive electricity market are investigated. The frequency stability challenge caused by insufficient damping and delay in mechanical power output from thermal power plants is shown, which is mitigated by using an inter-line power flow controller (IPFC) in series with the tie line and redox flow batteries (RFB) at the first zone terminal. The Bacterial Search Optimization (BFO) algorithm optimizes the integral gains of the LFC under different market transactions, ensuring compliance with the north American electric reliability council (NERC) standards. Simulation results show that the combination of RFB with IPFC significantly enhances the dynamic performance of the system.

In restructured environments, reliability is complicated by price fluctuations, demand response, and the integration of intermittent renewable energy sources such as wind and solar. Reliability assessment in these systems is crucial because it shifts the focus from overall system performance to individual customer load points, influenced by bilateral contracts, reservation agreements, and market dynamics. This paper provides an overview of the concepts and challenges of reliability in restructured power systems. In restructured power systems, reliability is not just a technical criterion, but also a competitive differentiator. Low reliability can lead to financial penalties, customer loss, or market instability. In summary, the highlights of this study can be summarized as follows:

- An overview of applied indicators in power system reliability assessment

- Description and classification of restructured power systems

- Review of studies on reliability challenges in restructured power systems

The structure of the paper is as follows. The structure and types of restructured power systems are described in section 2. Reliability indicators in power systems quantify the ability of the power grid to deliver electricity without interruption. These indicators are applied to generation, transmission, and

distribution systems to identify weaknesses, predict failures, and improve the quality of service to consumers. Section 3 discusses reliability in the power system along with evaluation indicators. Reliability in a restructured power system refers to the ability of the system to continuously deliver electricity to customers with minimal interruption. The evolution of the restructured power system can create new challenges and opportunities for maintaining reliability. Section 4 reviews a number of studies conducted in this field. Finally, section 5 concludes the discussion.

2. RESTRUCTURED POWER SYSTEM

In the context of power systems, "deregulated" and "restructured" power systems refer to approaches that aim to move away from traditional, vertically integrated, regulated monopolies (where a single company performs generation, transmission, distribution, and retail sales under close government supervision) to more competitive markets. While these terms are often used interchangeably, they are not the same: restructuring describes the broader process of reorganizing the structure of an industry to create competition, while deregulation refers specifically to the removal or reduction of regulations, particularly in the generation sector, to allow market forces to determine prices and operations. Restructuring includes deregulation and other reforms such as unbundling (the separation of functions into separate entities) and the creation of independent market operators. Both models contrast with regulated systems, in which public utilities operate in a monopoly at rates set by public utility commissions (PUCs) to ensure reliability and affordability, often at the expense of innovation and efficiency [26-29]. A restructured power system (or restructured electricity market) is an electricity industry model that breaks up the traditional, vertically integrated monopoly of single electric utilities into separate, competitive companies for generation, transmission, and distribution, as shown in Figure (1) [30,31]. This change is intended to increase efficiency, reduce costs, and improve service quality by creating competition and private participation. The challenges of a restructured power system include market power, renewable energy integration, and infrastructure investment. New grid management strategies are needed to accommodate the integration of renewable sources such as wind and solar energy [32-36]. Key aspects of restructured power systems are deregulation and unbundling. The distinct entities, as shown in Figure (2), are: generation companies (GENCO), transmission companies (TRANSCO), distribution companies (DISCO), and independent system operators (ISO). Power exchanges (PX) or spot pricing groups facilitate trade between generators and consumers [37]. Deregulation removes the monopoly of state-owned companies by allowing private companies to generate and sell electricity. Consumers also gain the ability to choose their electricity suppliers and competition is enhanced [38,39].

The classification of restructured power systems is based on the structure, organization, and operational framework of electricity markets after deregulation. These systems are classified based on market models, degree of competition, and operational mechanisms. A classification of restructured power systems focusing on their primary frameworks and characteristics is shown in Figure (3) [40,41]. Table (1) summarizes the advantages and disadvantages of a restructured power system. However, real-world experience in restructured/deregulated markets shows that these theoretical advantages do not always materialize, particularly under extreme conditions. Notable examples include the rolling outages in California during the August 2020 heat wave (affecting hundreds of thousands of customers) and the catastrophic blackout in Texas during Winter Storm Uri in February 2021 (leaving millions without power for days and causing numerous fatalities). These events highlight increased risks from market-driven under-investment in weatherization, reserve margins, and winterization/summarization measures, as well as challenges in coordinating reliability across many independent entities in high-renewable-penetration systems [42-45].

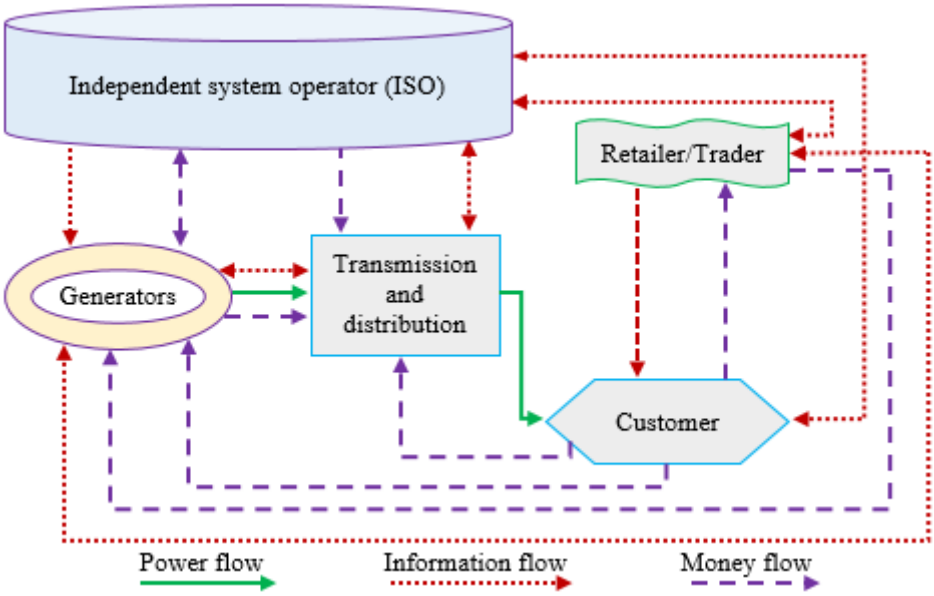


Fig. 1: Structure of restructured electric system with independent entities

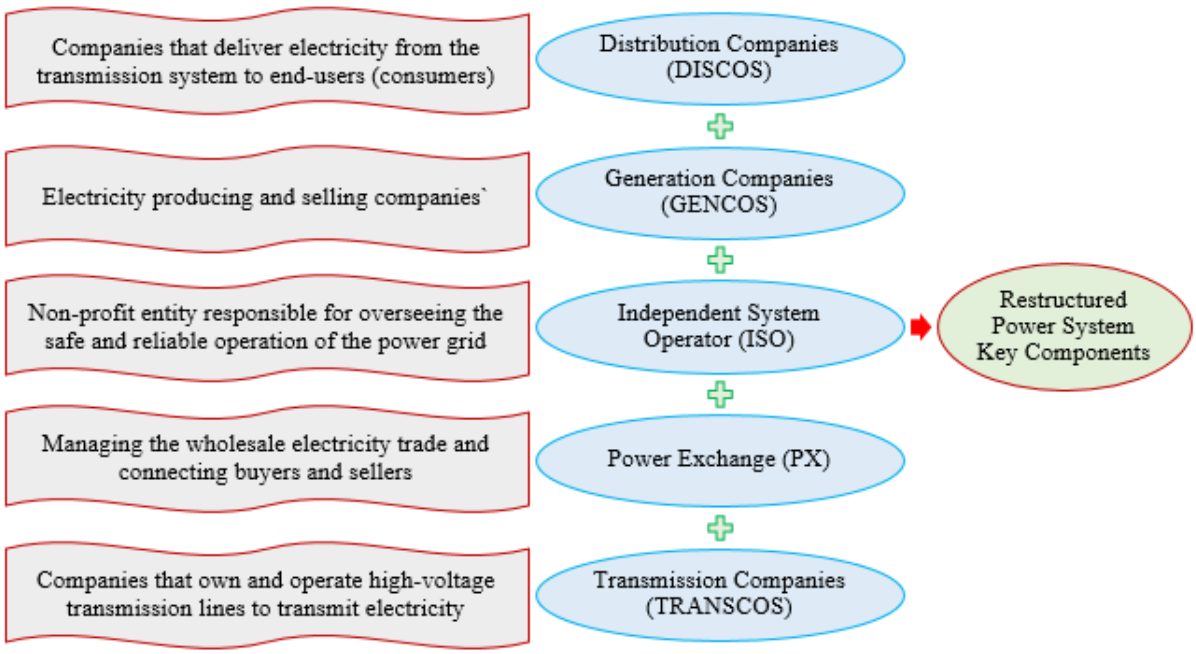


Fig. 2: Classification of restructured power systems based on market participants

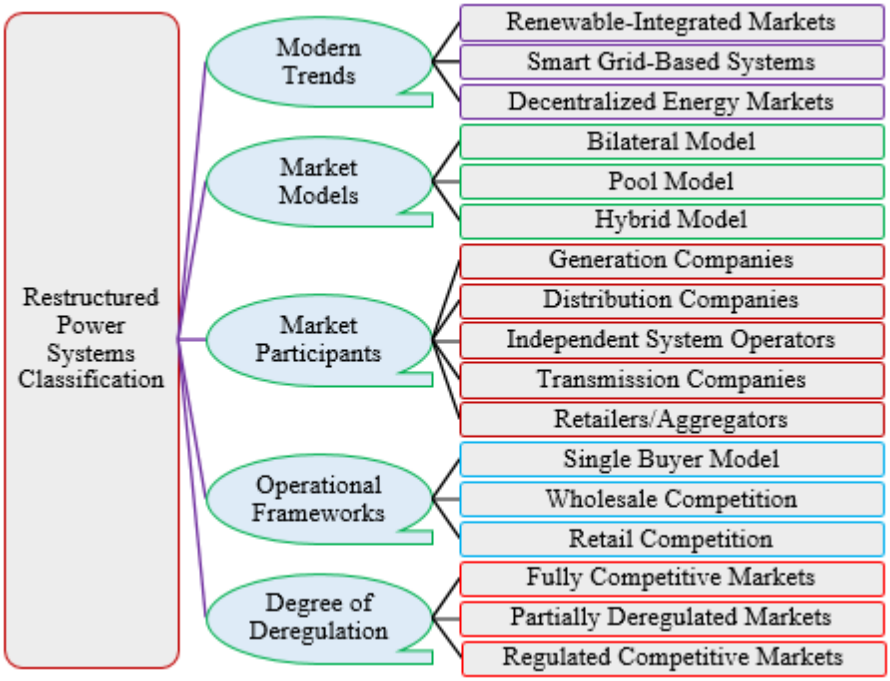


Fig. 3. Restructured power systems classification

These high-profile events highlight that, in the absence of strong regulatory oversight, market-driven cost minimization can lead to under-investment in critical infrastructure hardening and reserve capacity, especially under increasing penetration of variable renewables, thereby elevating the risk of large-scale reliability events rather than mitigating it. The "deregulated" and "restructured" power systems aim to increase competition and efficiency, but have major differences in scope, mechanisms, and consequences, which are summarized in Table (2).

2.1. Market volatility in the restructured power system

A restructured power system separates generation, transmission, and distribution, introduces competition in generation and retail supply, and often uses wholesale spot markets (e.g., pools or nodal pricing) to determine prices. This contrasts with traditional regulated systems where vertically integrated utilities recover costs under oversight. Market volatility refers to sharp fluctuations in wholesale electricity prices, including spikes, negative prices, and high variability, often measured by metrics like price velocity or standard deviation. Restructuring has mixed effects on volatility, with advantages stemming from efficiency and competition, but notable disadvantages from increased exposure to supply-demand imbalances. The advantages of restructured power systems in terms of market volatility include [46-49]:

a) Better price signals for efficiency and investment: Competitive markets reflect true scarcity and marginal costs,

encouraging investment in flexible resources that reduce long-term volatility. Scarcity pricing rewards flexibility, helping maintain reliability during tight conditions without overbuilding capacity.

b) Incentives for risk management and hedging: Participants use financial tools like forward contracts, contracts for differences, or bilateral agreements to hedge against volatility. Retail competition allows fixed-rate plans where suppliers absorb wholesale risk, insulating many consumers from spot price swings.

Table 1: Advantages and Disadvantages of a Restructured Power System*

Aspect	Advantages	Disadvantages
Consumer choice	Providing consumers with options to choose suppliers and better pricing and service	Excessive or limited in practice, especially in less competitive markets
Competition	Increasing competition between producers and potentially reducing costs and improving efficiency	In the absence of proper regulation, market manipulation or price volatility
Innovation	Incentives in service due to market-based incentives and technological innovation	Discourages investment in less stable markets due to high upfront costs of new technologies
Efficiency	Improves operational efficiency using market-based resource allocation and cost management	Efficiency gains are uneven, with some regions or utilities held back due to market failure
Investment	Attracting private investment in manufacturing and infrastructure due to free markets	Risk of underinvestment in critical infrastructure if proper incentives are not provided
Pricing	Potential for electricity prices to fall in competitive markets due to cost optimization	Consumers harmed by sudden price increases during peak demand or supply shortages
Reliability	Competitive pressures may incentivize better operational efficiency and innovation in some cases	Significant risk of reduced reliability due to price volatility, under-investment in reserves & resilience, coordination failures among market participants, and inadequate preparation for extreme events, as evidenced by major incidents in California (2020 rolling outages) and Texas (2021 blackout)
Environmental impact	Promoting adoption of renewable energy and cleaner technologies due to market incentives	Prioritizing cheaper and less polluting energy sources due to short-term profit incentives

*Real-world experience in some restructured markets shows that competition does not always improve reliability.

Table 2: Key Differences Between Deregulated and Restructured Power Systems

Subject	Restructured power system	Deregulated power system
Entities involved	Similar to a deregulated power system with an emphasis on independent coordinators to balance supply and demand, and power pools to distribute electricity	Includes generation companies, transmission companies, distribution companies, and retail service providers
Goals and outcomes	Promote regional integration, efficiency and technical innovation while maintaining reliability Delay full competition if contracts with affiliated companies continue Foster a service-oriented market rather than a purely energy supply market	Reducing costs through competition, attracting private investment and improving efficiency. Creating price volatility Need strong oversight to prevent abuse of market power
Regulation level	Acting in combination, abandoning competitive segments, restructuring non-competitive segments	Less regulation, market forces dominate pricing, supervision only to prevent abuse
Scope of change	Inclusion of the entire supply chain (production, transmission, distribution)	Mainly affecting manufacturing and retail, with transmission/distribution remaining under supervision
Primary emphasis	Broader reorganization, unbundling of power companies and transfer of transmission oversight to regional/federal levels	Create free market competition by eliminating price regulation and entry into generation and retail
Consumer impact	More gradual selection, emphasis on reliability through regional carriers, and varying retail selection in each state	High choice in providers/plans, potential for lower rates with volatility and complexity

c) Potential for lower average prices over time: Evidence from restructured markets (e.g., in parts of the US) shows efficiency gains and no dramatic price increases relative to regulated states, with some studies indicating prices lower than they would have been under continued regulation. Volatility is partly offset by innovation and demand response.

d) Adaptation to renewables: In high-variable renewable energy (VRE) futures, competitive markets can integrate renewables more dynamically, with volatility signaling the need for balancing resources, ultimately stabilizing systems through market-driven flexibility.

The disadvantages of restructured power systems in terms of market volatility are:

a) Higher inherent volatility in wholesale prices: Spot markets (especially uniform-price auctions) amplify fluctuations due to non-storability of electricity, inelastic demand, and weather-dependent renewables. This leads to frequent spikes, negative prices during oversupply, and greater intra-day/hourly swings compared to regulated systems with smoother cost recovery.

b) Exposure to market power and manipulation: In concentrated markets, strategic behavior can exacerbate spikes and volatility (e.g., historical examples in the UK or California). Market power makes prices more volatile under certain auction designs.

c) Challenges for consumers and planning: Even with hedging, volatility increases uncertainty, risk premiums in contracts, and potential for higher retail costs in some cases. Vulnerable consumers or those on variable plans face budgeting difficulties, and extreme events (e.g., weather-driven shortages) can cause dramatic swings.

d) Interaction with renewables and grid constraints: Rising VRE penetration (common in restructured markets) increases volatility through variable output, duck-curve effects, and ramping needs. Without sufficient flexible capacity or transmission, this amplifies price swings, curtailment, and reliability risks.

Overall, restructuring tends to increase short-term wholesale price volatility compared to regulated systems (where prices are smoothed via rate-base regulation), but it can mitigate long-term risks through better incentives for efficiency, flexibility, and innovation. Mitigation strategies include improved market designs (e.g., ramping products, scarcity pricing reforms), expanded hedging, demand response, storage incentives, and transmission coordination. Experiences vary by region, e.g., Texas (ERCOT) shows high volatility with renewables, while some PJM or ISO-NE markets have evolved mechanisms to manage it. In summary, the trade-off is between short-term instability (a key disadvantage) and long-term economic efficiency and adaptability (a core advantage).

2.2. High penetration of renewable energy in the restructured power system

High renewable energy penetration (especially variable sources like wind and solar) introduces challenges such as intermittency, low marginal costs, reduced system inertia, and the need for flexibility. Restructured systems influence how these are managed compared to traditional regulated systems. The advantages of restructured power systems for high penetration of renewable energies include [50-53]:

a) Improved Efficiency and Cost-Effective Integration: Competitive markets enable more efficient real-time dispatch and better utilization of resources across wider geographic areas (e.g., via larger balancing areas in ISOs/RTOs). This harnesses regional renewable advantages, reduces the need for expensive backup capacity, and lowers overall system costs. Studies show restructured markets (with ISOs/RTOs) facilitate higher renewable investment and integration by improving coordination and access to diverse resources.

b) Stronger Price Signals for Flexibility: Market designs reward flexible resources (e.g., through scarcity pricing, ramping products, or balancing markets) needed to balance variable renewables. This incentivizes investments in storage, demand response, and fast-ramping generation, supporting higher penetration levels without excessive curtailment.

c) Accelerated Renewable Deployment in Some Contexts: Restructuring (especially via ISOs/RTOs or reduced barriers to entry) correlates with higher renewable capacity additions. It can enable more market-driven entry of renewables, sometimes advancing decarburization by fostering competition and innovation over rigid regulated planning.

d) Potential for Lower Wholesale Prices: High renewable penetration often drives down wholesale prices via the merit-order effect (zero-marginal-cost renewables displace higher-cost fossil fuels). Competitive markets amplify this benefit, potentially leading to more stable long-term costs by reducing exposure to fuel price volatility.

e) Enhanced Resource Adequacy Mechanisms: Modern restructured markets adapt capacity mechanisms to value flexibility and weather-dependent renewables, better supporting high-penetration scenarios than legacy regulated approaches.

The disadvantages of power systems restructured for high penetration of renewable energies include:

a) Challenges with Revenue Adequacy and Investment Incentives: As renewable penetration rises, average wholesale prices can fall significantly (due to near-zero marginal costs), creating a "missing money" problem. This makes it harder for all resources (including flexible ones) to recover fixed costs through energy markets alone, potentially requiring additional capacity payments or out-of-market supports.

b) Increased Price Volatility and Risk Exposure: Renewables amplify short-term price swings (e.g., negative prices during over generation or very high prices during scarcity). Exposing generators (including renewables) to full market risks can deter investment unless mitigated by hedging or supports; some designs shield renewables from risks, but this can distort efficient responses at high penetration.

c) Need for Ongoing Market Redesign: Legacy restructured designs (e.g., heavy reliance on day-ahead markets) suit dispatch able thermal plants better than variable renewables. High penetration exposes mismatches, such as inadequate incentives for flexibility or poor handling of uncertainty, often requiring costly reforms (e.g., new products for ramping or intraday markets).

d) Potential for Higher Integration Costs if Poorly Designed: Without adaptations, competitive markets can lead to inefficient outcomes like excessive curtailment, overbuild of inflexible resources, or grid instability. Some evidence shows that certain restructuring forms slow renewable growth if they increase risks without adequate supports.

e) Political and Implementation Risks: Restructuring can face backlash during crises (e.g., price spikes), leading to partial reversals or interventions that undermine market signals. This can complicate the transition to high renewables compared to more controlled regulated systems.

In summary, well-designed restructured markets offer powerful tools for efficient, flexible, and market-driven integration of high shares of renewables (often outperforming traditional models in large, interconnected systems). However, they require continuous evolution to address emerging challenges like low/volatile prices and flexibility needs. Poorly adapted designs can exacerbate integration difficulties. Real-world outcomes vary by jurisdiction (e.g.,

successes in parts of the US with ISOs vs. challenges elsewhere), and many systems now combine market mechanisms with targeted policies for renewables.

3. Power System Reliability

Power system reliability refers to the ability of the grid to deliver power to consumers continuously to meet demand, safely and with minimal interruption, and is crucial to modern society. Power system reliability includes adequacy (ensuring sufficient generation, transmission and distribution capacity to meet demand under normal and peak conditions), security (the ability of the system to withstand disturbances without widespread outages), and resilience (the ability to recover quickly from disturbances).

Assessing and enhancing power system reliability is a complex task, involving various analytical and simulation techniques, and is a major focus of power system planning and operation [54,55]. Factors affecting power system reliability include the age and maintenance of infrastructure, generation mix, cybersecurity and demand growth. Strategies to improve power system reliability include increasing component reliability, adding redundancy, minimizing outage times, demand response programs and preventive maintenance. Reliability at the system level is divided into three categories: generation, transmission, and distribution [56,57]. Achieving 100% reliability in a power system is neither economically nor technically feasible due to factors such as equipment failure, natural disasters, and cost constraints. So far, various studies have been presented on increasing power system reliability using FACTS devices [58], evaluating and optimizing microgrid reliability [59], improving reliability in wind farms [60], increasing reliability using the distribution system reconstruction (DSR) method [61], and evaluating reliability with energy storage and renewable resources [62]. Table (3) lists a number of review articles on reliability assessment in power systems.

$$\text{SAIFI} = \frac{\sum \text{Number of customer interrupted} \times \text{Number of customer served}}{\sum \text{Number of customer served}} \quad (1)$$

$$\text{SAIDI} = \frac{\sum \text{Number of customers interrupted} \times \text{Interruption duration in minutes}}{\text{Total number of customers served}} \quad (2)$$

$$\text{MAIFI} = \frac{\sum (\text{Number of momentary interruptions} \times \text{Affected customers for each interruption})}{\text{Total number of customers served}} \quad (3)$$

$$\text{CAIDI} = \frac{\sum \text{Number of customers interrupted} \times \text{Interruption duration for each event}}{\sum \text{Number of customers interrupted}} \quad (4)$$

Table 3: A Number of Review Studies in the Field of Power System Reliability Assessment

Ref.	Subject	General description of the review conducted
[63]	Modelling approach based on quantum computing theory	A framework for power system reliability assessment using quantum computing principles is described, addressing the inefficiencies of classical methods that sample states sequentially. By exploiting quantum superposition, this approach generates and evaluates all possible system states simultaneously, potentially accelerating computations for large networks. The main focus is on modelling, sampling, and estimating key reliability metrics such as load loss probability and expected energy not supplied.
[64]	Indicators in renewable energy environments	Power system reliability indicators are essential metrics for assessing the performance of generation, transmission, and distribution systems, especially in grids that integrate renewable energy sources and are subject to variability and intermittency. These indicators help operators identify vulnerabilities, comply with regulatory standards, and plan for smart grid improvements, such as advanced metering and distributed energy resources. International standards provide frameworks for calculating and reporting these indicators, ensuring consistency across utilities.
[65]	Hybrid power systems and advanced computational approaches	Reliability assessment methods for hybrid power systems, focusing on the integration of renewable energies such as wind and solar that introduce variability and uncertainty, and advanced computational techniques are presented. The studies conducted are organized into three main categories: research studies, planning and optimization studies, and performance evaluation studies, and a structured classification is presented.
[66]	High share of renewable energy sources	A structured approach is presented to describe and evaluate reliability indicators for power systems with a high share of renewable energy sources. By analysing the indicators based on relevance, ease of use, data availability, and reliability, critical gaps are identified, and practical directions for future research and practical implementation are suggested.
[67]	High penetration of inverter-based resources	The integration of renewable energy sources alongside inverter-based resources brings about a reduction in inertia and dependence on power electronics. Traditional reliability metrics, rooted in synchronous generator-dominated systems, struggle to capture these dynamics, necessitating the need for updated metrics and multi-level modelling approaches. Studies on reliability at the device, component, and system levels are reviewed, and their interrelationships are outlined.

Table 4: Distribution/Customer-centric indicators (mainly the responsibility of DISCOs)

Index	Abbreviation	Description	Relevance to Restructured Systems
System average interruption duration index	SAIDI	Measure the average annual power outage duration per customer (in minutes or hours)	Reflecting distribution reliability under deregulated operations
System average interruption frequency index	SAIFI	Measuring the average number of power outages per customer per year	Highlighting the effects of transmission density
Momentary average interruption frequency index	MAIFI	Average frequency of momentary outages (very short interruptions) per customer	Monitors distribution quality; used in PBR for penalties/incentives
Mean time to repair	MTTR	Average time it takes to repair a component and restore service after a failure	Using probabilistic techniques to consider MTTR and considering components as multi-state models based on failure rates

Integrating the complexities of demand response (DR) resources, especially focusing on uncertainties arising from consumer behaviour, is a sophisticated approach to assessing the reliability of hybrid power systems, which is reviewed in [68]. Demand response is recognized as a critical tool for maintaining electricity balance and facilitating the integration of renewable energy sources.

However, its effectiveness is challenged by the unpredictability of consumer behaviour that affects the price elasticity curve of DR resources. This study incorporates consumers' psychological and consumption behaviours into the DR model, as consumer responses to price changes are not purely deterministic and also involve behavioural uncertainties. The uncertainty index (IU) is defined to quantify the uncertainty in consumer behaviour in response to electricity price fluctuations, which provides a measurable way to assess the variability in DR effectiveness. Also, to depict the complex and uncertain relationships between electricity prices and the IU index, an advanced super-sigmoid model is proposed, which is designed to reflect the nonlinear and probabilistic nature of consumer responses to price changes.

3.1. Reliability measurement metrics

In traditional power systems, power flows unidirectional from centralized power plants to end users, but failures in any component can cascade, leading to widespread outages or voltage dips. This vulnerability is exacerbated by slow mechanical switches and limited automation in legacy systems. The evolution towards modern grids, the integration of distributed generation, renewable energy sources, and smart technologies, introduces new uncertainties, including intermittent generation and bidirectional power flows. These changes require robust reliability assessments to ensure continuous and cost-effective power supply in the face of increasing electricity demand and aging infrastructure [69].

Reliability metrics such as the mean system outage duration index, the mean system outage frequency index, and the expected energy not delivered measure the reliability of a power system. However, different indicators and metrics are used for generation (such as forced outage rate), transmission (such as bulk power system reliability indicators), and distribution (such as customer outage duration index), and integrated studies often combine these to assess overall system performance. Reliability indicators are used to assess performance and identify areas for improvement. Reliability assessment in power systems uses probabilistic indicators to quantify the risks of outages. In restructured power systems, the criteria are adapted to take into account market-based operations and decentralized control.

In restructured systems, these two areas are generally completely separated and responsibilities are defined separately.

3.1.1. Distribution Reliability Indicators (Customer-Focused, Primarily DISCO Responsibility)

These metrics, standardized under IEEE 1366, measure the actual experienced interruptions at the customer level, primarily due to issues in the distribution network (e.g., local lines, transformers, feeders, vegetation, weather-related faults on distribution assets, or restoration delays). They reflect delivery reliability, how reliably power reaches end-users once generated and transmitted.

Common metrics are listed in Table (4) along with a description of each. In renewable systems, market elements such as bilateral contracts and customer loss functions (CDFs) should be considered to determine the indices for modelling price-responsive demand [70-72].

The replacement of synchronous generators with IBRs significantly reduces system inertia, leading to faster frequency changes (higher RoCoF, Rate of Change of Frequency) and lower frequency nadir following disturbances. Traditional adequacy-focused indices do not adequately reflect these short-term frequency stability and transient dynamic risks. Emerging literature and industry reports emphasize the need for new or supplementary metrics that better characterize frequency response, inertia-related performance, and resilience under low-inertia conditions. Examples of such emerging metrics include: (a) Frequency Nadir and RoCoF-based indices (used to quantify the lowest frequency reached and the initial rate of frequency decline after a major disturbance, (b) Frequency Stability Margin (FSM) (a recently proposed index that represents the maximum tolerable power imbalance while still satisfying frequency stability criteria, inertial response timeframe, and operational security constraints), (c) Inertia estimation metrics and synthetic/virtual inertia adequacy indicators (evaluating the effective system inertia provided by grid-forming inverters or other fast-response technologies) and (d) Energy-Adjusted or resilience-oriented metrics such as Expected Operating Reserve (EOR) or Expected Over/Under Frequency Protection (EOP) (related indices, which attempt to link probabilistic adequacy with dynamic frequency performance) [73-77].

This section refers to the characteristics of common reliability indicators [78-87].

These are distribution-level, customer-impact metrics. They are heavily influenced by: (1) Distribution system design, maintenance, and operations, (2) Local events (storms on distribution feeders, equipment failures, switching, etc.) and (3) Utility response and restoration practices. In restructured systems, these fall under the responsibility of distribution companies (DISCOs / LDCs). Regulators often set performance targets, incentives/penalties, and require reporting (often excluding or separately reporting major event days for fair assessment of controllable performance) [88-90].

3.1.1.1. System average interruption frequency index

The system average interruption frequency index (SAIFI) is a key performance metric used in power system reliability engineering to quantify the frequency of power outages experienced by customers in an electrical distribution network. It provides utilities, regulators, and stakeholders with a standardized way to assess the impact of ongoing outages on an average customer, and helps assess the overall reliability of the power supply. SAIFI is particularly important in the context of modern power systems, where factors such as aging infrastructure, adverse weather, vegetation management, and increased demand for electricity (e.g., electric vehicles) can affect reliability. SAIFI is calculated from (1).

3.1.1.2. System average interruption duration index

The System Average Interruption Duration Index (SAIDI) is a key performance metric used in the electricity industry to assess the reliability of electricity distribution systems. It quantifies the average total duration of outages experienced by customers over a specific period, typically a year, and provides insight into the length of time customers are without power due to outages. This metric help utilities, regulators, and policymakers evaluate system performance, identify areas for improvement, and ensure compliance with reliability standards. A high SAIFI combined with a low SAIDI may indicate frequent but short-term outages. SAIDI is calculated from (2).

3.1.1.3. Momentary average interruption frequency index

The Momentary Average Interruption Frequency Index (MAIFI) is a key reliability metric, specifically designed to measure the frequency of short-term power outages. It quantifies the average number of momentary outages experienced by a typical customer over a defined period, usually a year. Utilities use MAIFI to assess the performance of their distribution systems in managing transient events that are common but can accumulate and impact overall reliability. Unlike sustained outage metrics (which are tracked by metrics such as SAIFI or SAIDI), this index targets flicker or short-term fluctuations in service. MAIFI is calculated from (3).

3.1.1.4. Customer average interruption duration index

The Customer Average Interruption Duration Index (CAIDI) is a key reliability metric used in power system engineering to assess the performance of utility companies, particularly in distribution systems. It measures the average duration of power outages experienced by customers who are actually affected by a power outage, and provides insight into the speed of service restoration after an outage. Unlike broader metrics that average across all customers, CAIDI focuses specifically on customers experiencing power outages, making it valuable for assessing the efficiency of power restoration. CAIDI is calculated from (4).

3.1.2. Aggregate/Hybrid System Indicators (System Adequacy, Primarily ISO/RTO, GENCOs, TRANSCOs, Resource Planning)

These probabilistic metrics assess resource adequacy, whether there is sufficient generation capacity (plus imports, demand response, etc.) and transmission to meet forecast demand across the bulk power system, before considering distribution delivery. They focus on the risk of load shedding due to insufficient supply (generation shortfall or transmission constraints affecting the bulk system), often during peak or stressed conditions (e.g., extreme weather, low renewables output).

3.1.2.1. Loss of Load Probability

In loss of load probability (LOLP), probability that load will exceed available generation (and firm imports) in a given time period (e.g., hour, day, or year). Often expressed as a percentage. LOLP is computed using probabilistic methods, often via: (1) Monte-Carlo simulations (sampling many possible scenarios of generator outages, variable renewable output, load forecast errors, etc.), (2) Convolution of the load duration curve with the outage probability distribution of generating units (e.g., using effective capacity or de-rated margins) and (3) Tools like RECAP, GE MARS, or similar reliability models [91-93].

LOLP does not capture transmission constraints, distribution issues, or cascading failures, it primarily measures generation adequacy.

3.1.2.2. Loss of Load Expectation

In loss of load expectation (LOLE), expected number of days (or hours, as LOLH) per year when load exceeds supply (commonly a target of 0.1 days/year, or "1 days in 10 years"). Widely used in North America by ISOs/RTOs (e.g., PJM, MISO, ISO-NE, NYISO, ERCOT).

Loss of load expectation is a key probabilistic metric used in power system reliability and resource adequacy planning. It quantifies the expected number of periods (typically hours or days) per year during which the available generation capacity is insufficient to meet electricity demand, leading to a potential shortfall (loss of load). LOLE represents the expected count of shortfall events over a given time horizon (usually one year), calculated from probabilistic models that account for uncertainties in: Load (demand) variations, Generation outages (forced/unplanned), Variable renewable output (wind, solar) and Other factors like fuel availability or transmission constraints. LOLE is typically computed using Monte-Carlo simulations or convolution methods [94,95].

3.1.2.3. Expected Energy Not Served

In expected energy not served (EENS) or EUE (expected unserved energy), expected amount of energy (MWh) that cannot be supplied per year due to adequacy shortfalls. Increasingly used (or considered alongside LOLE) in modern

assessments to better capture duration and severity of events, especially in systems with high variable renewables. These are bulk system / hierarchical level 1 & 2 metrics (generation and bulk transmission adequacy). They are calculated via probabilistic simulations considering: generation fleet availability/outages, load forecast uncertainty, variable renewable output, transmission limits (though often modeled separately) and Interregional assistance.

In restructured markets, these fall primarily under ISO/RTO oversight for system planning, capacity markets, and resource adequacy requirements. GENCOs (generators) provide capacity through markets or bilateral contracts, while TRANSCOs ensure bulk transmission supports adequacy. States/LSEs often have ultimate responsibility for procuring adequate resources, but ISOs calculate and enforce targets.

Probabilistic indicators (LOLP, LOLE, EENS) in Table (5) have dominated production investment in rehabilitated environments due to uncertainty arising from renewables, market bidding, bilateral contracts, and reduced control over the level of exploitation.

3.2. Reliability assessment methods

Reliability assessment in power systems evaluates the ability of a power grid to deliver electricity to consumers without interruption, under various operating conditions. This is very important to ensure a stable, efficient and flexible power supply. Key factors in reliability assessment include component reliability, system configuration, load characteristics, integration of renewable resources and external factors. Reliability analyses are applied to various systems and components as well as at different stages of the engineering process [96,97].

3.2.1. Classification based on methodological approach

Methodological approaches to reliability assessment in power systems are broadly classified into deterministic and probabilistic methods, with probabilistic methods themselves divided into analytical and simulation-based techniques. Hybrid methods, which combine elements of these categories, are also emerging. This classification reflects the evolution from simple, scenario-based assessments to more comprehensive, uncertainty-aware analyses. Assessment methods are divided into three groups based on methodological approach [98,99].

3.2.1.1. Deterministic methods

These methods rely on predefined scenarios and worst-case assumptions without considering the probabilities of events. They are straightforward, computationally efficient, and widely used for planning and operational reviews, but they do not effectively quantify risks or uncertainties. The advantages of this method are simple implementation and no need for statistical data.

3.2.1.2. Probabilistic methods

These methods model uncertainties (such as component failure rates, load variations, renewable generation frequency) using probability distributions, and provide indicators such as expected outage duration or probability of load loss. They provide a more realistic assessment, but require historical data and higher computational resources. Probabilistic approaches are divided into analytical methods (which use mathematical models and closed-form solutions to directly calculate reliability indices) and simulation-based methods (which use repeated sampling or stochastic processes to estimate reliability under different scenarios, and handle large-scale, complex systems where analytical solutions are not feasible) [100-102].

3.2.1.3. Hybrid methods

These methods integrate deterministic, analytical, and/or simulation techniques to exploit the strengths of each (e.g., using deterministic screening to reduce probabilistic calculations). Hybrid methods are widely used in modern renewable energy systems and smart grids to balance accuracy and efficiency [103].

3.2.2. Classification based on hierarchical levels

A fundamental classification of power system reliability, which has been applied to restructured environments, divides the classification based on the scope of the system being assessed. This framework, originally derived from hierarchical level (HL) models, takes into account the complexities of competitive markets, such as independent operators and economic load distribution. The three hierarchical levels are:

3.2.2.1. Level 1 (Generation Level)

Reliability in a generation system is its ability to continuously meet the aggregate electricity demand of the loads, despite the inherent uncertainties and uncertainties arising from energy sources and demand. At this level, the ability of generation sources to meet demand, regardless of transmission constraints, is assessed. Generator adequacy in competitive bidding is assessed by probabilistic indicators such as expected loss of load (LOLE) and expected energy not provided (EENS). Market effects such as rolling reserves and bilateral contracts are considered. Analytical models and Monte-Carlo simulations are used to integrate renewable energy at this level [104].

3.2.2.2. Level 2 (Generation and Transmission Level):

At this level, both generation and transmission are considered to deliver electricity to the bulk supply points. Reliability in a transmission system refers to its ability to continuously and continuously perform its intended function without failure or interruption. It refers to the congestion of transmission in deregulated markets using reliability network equivalents (RNE) to model market players. Key strategies for ensuring reliability include reliability modelling and analysis, incorporating redundant components, using appropriate design criteria such as the N-1 criterion, and continuous monitoring and evaluation. Most of the research conducted emphasizes this level due to its relevance to restructured environments, where conventional techniques are inadequate to manage uncertainties arising from competition and new technologies [105].

3.2.2.3. Level 3 (Distribution Level)

At this level, the focus is on delivery from major points to end customers, including sub-distribution and distribution networks. Reliability in an electricity distribution system refers to its ability to continuously provide uninterrupted power to customers with minimal outages and rapid service recovery. At the hybrid power system level, various

indicators such as SAIFI and SAIDI are used for evaluation and are improved through techniques such as advanced automation, underground cables, and integration of microgrids and distributed generation.

The power system reliability assessment at three main levels is summarized in Table (6). Classical/deterministic indicators such as the N-1 security criterion, the N-k rule and the fixed reserve margin have the advantages of being simple and easy to implement, but are overly conservative or insufficient in high uncertainty conditions. Probabilistic indicators are based on Monte Carlo, Markov models or hybrid approaches. Mainstream indicators such as LOLP, EENS, Value of Lost Load (VOLL) and Expected Customer Outage Cost (ECIC) explicitly take into account the real probability of events (e.g. wind/solar variability, forced unit outages). In regenerative markets, probabilistic indicators have gained considerable importance due to higher levels of uncertainty (especially from renewables).

A number of practical challenges and links to specific market issues are listed in Table (7). In summary, the key practical challenges include the following:

- Gap between system-level and customer-level indices: HL I and HL II indices often do not guarantee desired HL III performance (especially with high renewable penetration).

- Misaligned economic incentives: Generators in energy-only markets may withhold production during scarcity if fixed reliability payments or bilateral contracts provide sufficient revenue.

- Computational complexity: Probabilistic models with high uncertainty (renewables + load + outages) require intensive simulations.

- Value of reliability: Need to translate technical indices (e.g., EENS) into economic terms (VOLL, customer damage functions) for market-based decisions.

Ultimately, the main proposed directions include moving toward performance-based mechanisms, genuine scarcity pricing, and locational / non-uniform reliability indices to better connect classical/probabilistic metrics with the realities of restructured markets. In contexts such as Iran, with growing bilateral contracts and increasing renewable integration, similar challenges are emerging, highlighting the need to revise traditional reliability criteria.

3.3. Reliability assessment techniques in restructured power systems

Restructured power systems, also known as deregulated or competitive electricity markets, are changing from vertically integrated power companies to market-based operations involving generation companies, transmission companies, distribution companies, and independent system operators. This structure introduces complexities such as market risks, bidding strategies, bilateral contracts, transmission congestion, and price fluctuations that affect reliability. Reliability assessment in this context assesses the system's ability to provide sufficient electricity while minimizing outages, costs, and risks. Traditional techniques from regulated systems are adapted to take these market dynamics into account, focusing on generation adequacy, transmission security, and demand-side management.

Reliability in restructured power systems requires new assessment techniques to navigate the complexities of the market and renewable integration. By focusing on customer-centric indicators and advanced simulations, stakeholders can ensure a resilient and efficient electricity supply, balancing competition with security. Various techniques have been developed to assess reliability in restructured power systems, some of which are discussed in this section. Reliability is typically divided into adequacy (long-term capacity to meet demand), security (short-term response to contingencies), and resilience (recovery from extreme events).

3.3.1. Reliability Network Equivalent Techniques (RNET)

These techniques model the system as equivalent multi-state providers of generation, storage, and transmission, simplifying the analysis of bilateral markets and storage agreements. Complex networks are represented by equivalent multi-state models. Power generation companies are treated as equivalent generation providers and power transmission companies as equivalent transmission providers. This simplifies the assessment of non-uniform reliability in deregulated markets, where customer choices and demand-side bids affect load points. Pseudo-sequential simulation combines non-sequential state sampling with time-based evaluation for efficiency. Developed by calculating the maximum deliverable capacity (MDC) using genetic algorithms, it incorporates load effects and reduces the computation time when evaluating load point indices. The method identifies transmission deficiencies, and supports corrective actions such as network reinforcement. The method is applied in subscription-based or hybrid markets to assess supply-side and demand-side reliability.

3.3.2. Optimization-based methods

Optimum power forwarding (OPF) with Probability Analysis: Integrates reliability into market settlement by minimizing load shedding or costs under probabilities. In regenerative systems, objectives are modified to consider customer loss functions (e.g., outage costs) alongside generation and storage bids. These models integrate reliability into distribution, and include load shedding and generation redistribution over probabilities. They minimize outage costs by considering market schedules and node prices.

3.3.3. Probabilistic and multi-objective methods

Mathematical models such as state counting or Markov processes are used to calculate accurate probabilities. These methods are faster for smaller systems, but are computationally intensive in retrofitted settings due to multi-state units (e.g., generators with full states, capacity reduction, or forced outages). Multi-state Markov models for components, combined with probabilistic ranking and fuzzy logic, identify deficiencies. Voltage-reduced forced outage rates (DAFOR) reduce downtime by modelling minor failures, and improve indices such as SAIFI and SAIDI. Monte-Carlo simulation A stochastic method that samples random system states (e.g., generator outages, load changes) to estimate reliability indices. In regenerative systems, it models market uncertainties such as bid prices and variability of renewable energies. Its variants include non-sequential MCS for efficiency and variance reduction techniques (e.g., cross-entropy method) for handling large state spaces.

Table 5: Aggregate/Combined System Adequacy Indicators (Generation and Transmission Adequacy – mostly ISO/RTO, GENCOs, TRANSCOs)

Index	Abbreviation	Description	Relevance to Restructured Systems
Expected energy not supplied	EENS	Estimated energy shortages due to insufficient generation or transmission constraints	Economic-oriented index; used in market models to value reliability, reserve markets, and customer interruption costs
Loss of load expectation	LOLE	Quantify the expected number of hours or days per year that the load cannot be supplied.	Standard North American resource adequacy target (1 day in 10 years); directly affected by market dynamics and renewable penetration
Loss of load probability	LOLP	Probability that available generation capacity is insufficient to meet demand in a given period (often calculated hourly or daily)	Core probabilistic index for resource adequacy (HL I); used to set reserve margins and assess market-based generation investment risks
Energy emergency alert levels	EEA Levels	NERC-defined emergency levels (EEA 1–3) indicating increasing risk of energy emergency / controlled load shed	Modern operational reliability metric; reflects real-time market and system operator actions under stress (increasingly important with renewables and IBRs)
Equivalent forced outage rate–demand	EFORD	Probability a unit is unavailable or de-rated during periods of system demand	Key generator performance metric used in capacity accreditation, reserve margin calculations, and market settlement in restructured environments
Expected Unserved Energy	EUE	Similar to EENS (sometimes used interchangeably)	Common in probabilistic adequacy studies for restructured systems with high renewables
Hourly LOLP	HLOLP	LOLP calculated for each hour (time-specific)	Captures variability from renewables, load uncertainty, and market bidding in short-term operations
Rate of change of frequency	RoCoF	Maximum initial rate of frequency change following a disturbance (Hz/s)	Critical in low-inertia systems with high Inverter Based Resources (IBR) penetration; limits relay settings and risk of cascading trips
Frequency stability margin	FSM	Maximum tolerable power imbalance (MW deficit) while satisfying frequency stability criteria, inertia response, and security constraints	Emerging index for low-inertia grids; quantifies operational margin under dynamic frequency constraints

Table 6: Hierarchical Levels of Power System Reliability Assessment

Level	Performance	Description	Key indices	In Restructured Markets
1	Generation Adequacy	Focuses on the balance between generation and demand (without considering transmission).	LOLP, LOLE, EENS	Influenced by installed capacity, capacity mechanisms (Capacity Markets or Reliability Options), renewable uncertainty, and long-term contracts.
2	Composite (Generation + Transmission) Adequacy	Considers both generation and bulk transmission system.	Nodal reliability indices	Affected by transmission constraints, non-uniform reliability across regions, economic merit order, and renewable variability.
3	Distribution / Customer Reliability	Focuses on end-user reliability.	SAIFI, SAIDI, CAIDI, ASAI, ENS, etc.	Less directly impacted by wholesale markets but influenced through retail contracts and demand response programs.

Table 7: Practical Challenges and Linkage to Specific Market Issues

Specific Market Issue	Related Classical / Deterministic Index	Key Practical Challenge in Restructured Environments	Proposed / Emerging Approaches
Bilateral Contracts	Reserve Margin, N-1	Contracts occur outside the spot market, therefore lack of transparency in real available capacity, risk of system-wide shortage during peaks	Reliability-based reserve management, hybrid bilateral + pool models, nodal reliability index evaluation
Renewable Uncertainty	LOLP, EENS	Variable and anti-correlated output with demand, therefore increased need for storage/backup, reduced effective reliability	Reliability Options (e.g., Colombia model), stochastic unit commitment, conditional EENS indices based on renewable profiles
Non-uniform Reliability	Nodal LOLP and other locational indices	Different regions experience significantly different reliability levels (due to transmission limits or renewable concentration)	Locational reliability indices, nodal reliability pricing, locational capacity markets
Hybrid Market Models	Combination of energy-only + capacity market	Mixing energy market + forward contracts + reliability options → conflicting incentives (e.g., perverse incentives observed in Colombia's Forward Contracts + Reliability Options design)	Performance-based capacity mechanisms, real scarcity pricing, stochastic market clearing models

Table 8: Practical Barriers to Advanced Probabilistic Methods in Restructured Power Systems

Aspect	Description	Impact
Computational Burden	Advanced probabilistic methods (such as sequential Monte Carlo, stochastic unit commitment, or hybrid probabilistic-optimization approaches) require a very large number of scenarios, simulation repetitions, and solving complex optimization problems, which demand high computational time (sometimes hours or days), while market operations and real-time decision-making typically occur in 5–15 minute intervals.	Severe limitation in practical application for daily operations and day-ahead/real-time markets; requirement for very expensive hardware or high-performance computing (HPC); delays in decision-making that can create operational risks.
Lack of Sufficient High-Quality Real Data	Accurate modelling of uncertainties (variable renewable generation, price-responsive demand behaviour, component failure rates, weather and market correlations) requires long-term, high-precision, and up-to-date historical data, which is not yet fully available or of sufficient quality in many systems (especially in emerging markets or regions with rapid changes).	Reduced accuracy and reliability of probabilistic model results; increased prediction and risk assessment errors; difficulty in justifying results to regulators and stakeholders.
Regulatory and Institutional Resistance	Deterministic criteria (N-1, N-1-1) are transparent, repeatable, easily defensible in legal challenges, and compatible with existing NERC/FERC standards. Complex probabilistic methods can lead to differing interpretations, difficulty in proving compliance, and increased legal liability risk in case of incidents.	Strong resistance from ISOs (e.g., PJM, CAISO, ERCOT) and regulators to changing mandatory standards; need for extensive revision of rules and approval processes; slow adoption and implementation.
Complexity in Pricing and Market Incentives	Outputs from probabilistic methods (such as probability distributions of prices, expected EENS costs, or variable LOLE) can result in highly complex, volatile, and unpredictable energy, reserve, and capacity prices for market participants.	Reduced acceptance by GENCOs, consumers, and retailers; difficulty in designing bilateral contracts and incentives; increased risk of market manipulation or lack of transparency.
Integration with Existing Market & EMS Frameworks	Current energy management systems (EMS) and market software (SCED, SCUC, RTCA) are primarily designed for deterministic inputs/outputs; full integration of probabilistic methods requires fundamental redesign of software architecture and operational processes.	Very high cost and time for system upgrades; risk of incompatibility and errors during transition; limitation in achieving practical hybrid application.

This method is particularly useful for hybrid generation-transmission systems with high penetration of renewable energies, as it scales well without strong size dependence. Time-sequential simulations handle load variations, and operational reliability is assessed in hybrid two-way markets. These methods use analytical or Monte-Carlo approaches, which are adapted to the complexities of deregulation [106]. The main practical barriers to advanced probabilistic methods in restructured power systems are listed in Table (8).

4. Literature Review- Reliability Challenges in Restructured Power Systems

Restructuring a power system, which involves the separation of generation, transmission, and distribution, poses new challenges to maintaining reliability. While restructuring is aimed at improving efficiency and potentially reducing costs through competition, it can also complicate reliability management. This is because multiple entities with different incentives and priorities are now involved, potentially leading to coordination problems and increasing complexity in assessing and ensuring reliable performance.

Reliability studies in the context of restructured power systems focus on ensuring adequate supply, minimizing outages, and balancing economic incentives with system security. These studies have evolved from traditional integrated power models to address market-driven uncertainties, such as variable renewables integration, bilateral contracts, and demand-side management. Studies in this area can be broadly classified into several categories, although this is not an exhaustive list, but it is possible to outline common frameworks used in the field. In this section, studies are categorized based on reliability challenges or specific objectives in restructured power systems.

4.1. Market and economic uncertainties

Deregulation creates price volatility and risk assessment challenges. Generating companies prioritize profits and potentially invest less in reserves, leading to price spikes and reliability risks. Hybrid markets complicate this, as joint and bilateral transactions must be balanced using optimal power flow (OPF) techniques [107].

A framework for determining optimal long-term investment strategies for hybrid wind-thermal companies operating in a restructured (irregular) electricity market is presented in [108]. The framework addresses the complexities of integrating renewable (wind) and conventional (thermal) energy sources in a competitive market environment, and considers both stochastic (random) and rational (strategic) uncertainties. In this study, Markov chain process is used for modelling to simulate market dynamics and optimize investment decisions. Also, wind uncertainty assessment based on data mining technique, and simulation of electricity demand and fuel price using Monte-Carlo method are performed.

A two-zone interconnected power system including thermal and gas fuel cell units with a reheat turbine, battery storage and an integrated power flow controller is investigated in [109]. The power system performance is analysed under different deregulated market conditions, and the emphasis is on providing ancillary services of electric vehicles and distributed generation to reduce contract

violations. Also, a robustness analysis is performed with different system parameters. Also, a stability analysis is presented including changing key system parameters (such as controller gains, time constants) to evaluate the impact of these changes on system performance and controller effectiveness.

An optimization method using optimal power flow to determine load shedding and generation redistribution in restructured power systems with a Polco market structure is presented in [110], where the objective is to minimize the total system costs (generation, storage, and interruption) while respecting market and network constraints. This method can evaluate conventional and restructured systems and provide insights for the independent system operator, generators, and customers. It also determines the best load shedding and generation redistribution actions for each possible scenario (e.g., equipment failure).

The challenges in deregulated (restructured) electricity markets are noted in [111], as competition can pose risks to system reliability beyond traditional infrastructure issues. A Markov state space diagram is used to model the electricity market as a continuous-use system, and states are defined based on market performance indicators. Transition rates between states are also extracted from historical data. The results show that ignoring market risks in planning can underestimate outages or costs in competitive environments.

In [112] it focuses on reliability assessment and pricing in a hybrid electricity market, where electricity and reserves are traded through a centralized power supply or bilateral contracts. Models for power supply and bilateral suppliers are developed using reliability network equivalents, which simplify the representation of complex agreements between market participants, and allow for easier integration into market operations. Customer responses to price changes are modeled using customer loss functions (CDFs), which quantify the economic impact on customers due to uncertain or unreliable supply, and relate price signals to reliability preferences. Reliability and price issues are also formulated using improved OPF techniques.

The challenges of reliability management in restructured power systems [113] are reviewed, and a technique for assessing reliability in such systems is presented, in which market players (such as generation companies and transmission providers) are represented using equivalent reliability network techniques. The generation company is modeled as an equivalent multi-state generation provider, which considers several operational states (e.g., fully operational, partially outage, or fully outage). The transmission system is represented as an equivalent multi-state transmission provider, and incorporates the reliability characteristics of the transmission network. These models simplify the complex interactions in a deregulated system, while maintaining the accuracy of reliability assessment. By introducing the concept of non-uniform reliability, customer choices about reliability can be easily implemented using this approach.

A framework for managing supply and demand contingencies in hybrid electricity markets for reliability assessment is presented in [114], in which a model is considered for the independent system operator (ISO) to coordinate the storage and load reduction proposals during the contingencies, aiming to balance the value and cost of reliability. The load reduction and generation redistribution are optimized to minimize the outage costs in the market. This framework uses a non-sequential Monte-Carlo simulation to assess customer reliability in restructured power systems under a hybrid market model, and the modified IEEE Reliability Testing System (RTS) is used to illustrate this approach.

4.1.1. Missing money in the restructured power system

The phrase "missing money in the restructured power system" refers to the well-known "missing money problem" in deregulated (or restructured) electricity markets. In traditional regulated utility systems, vertically integrated utilities recover fixed costs (e.g., building power plants) through regulated rates approved by regulators. In restructured systems, generation is competitive and separated from transmission/distribution, with prices set by wholesale markets (energy markets for electricity sold in real time or day-ahead, plus ancillary services). The missing money problem arises because generators often fail to recover their full fixed costs (capital, maintenance, etc.) from short-term energy market revenues alone. This leads to underinvestment in new generation capacity or early retirements, risking reliability (e.g., potential shortages or blackouts). Several factors contribute to the problem of lost money, including Price caps in wholesale energy markets, political and operational limits, Public good nature of reliability and inelastic demand. In short, the "missing money" isn't literal theft or accounting error, it's a structural flaw in competitive market design that requires additional mechanisms (like capacity payments) to ensure reliable investment in generation. Without fixes, restructured systems risk inadequate supply during peak stress [115-118].

4.2. Integration of renewable energy sources

The transition towards low-emission power systems, driven by the integration of renewable energy sources (RES) such as solar photovoltaics (PV) and wind turbines, alongside inverter-based resources (IBR), is reshaping the grid architecture. Inverter-based resources reduce inertia, and increase the risks of frequency deviations during events [119-122].

The penetration of renewable energy increases stability, but raises reliability issues due to intermittency. Battery and energy storage systems (BESS) introduce uncertainties, which require probabilistic analyses. The variable output of renewable energy sources depends on weather conditions, requiring robust forecasting and storage capacity. Reliability management in power systems with significant integration of renewable energy sources is challenging due to the variability and intermittency of renewable resources such as wind and solar [123-126].

Economic curtailment occurs when renewable generators are deliberately reduced (curtailed) not due to immediate technical grid stability constraints (e.g., frequency/voltage issues or congestion), but primarily for economic reasons, such as: negative or very low wholesale prices during periods of oversupply, inflexible conventional generation that cannot ramp down sufficiently, market design features that prioritize must-run thermal plants, or contractual/regulatory

arrangements that limit the economic incentive to absorb all available renewable output. Economic curtailment (also called market-driven curtailment) occurs when generators voluntarily reduce output because real-time market prices drop too low (often to zero or negative levels) due to oversupply from renewables during periods of low demand or mismatched timing (e.g., midday solar peaks or overnight wind surges). This acts as a legitimate, short-term mechanism to maintain real-time supply-demand balance without physical instability, preventing issues like over-frequency or voltage problems. In well-designed markets with negative pricing allowed (e.g., CAISO in California or parts of Europe), these signals incentivize flexible resources like batteries to charge or demand response to ramp up, absorbing excess energy efficiently. However, persistently high curtailment levels, especially when they exceed modest single-digit percentages of annual renewable output and become systematic rather than occasional, frequently signal deeper structural shortcomings in the system:

a) Inadequate transmission infrastructure: Renewables are often sited in resource-rich but remote areas (e.g., wind in rural Midwest US or northern Europe, solar in deserts or Brazil's Northeast). Bottlenecks prevent excess power from reaching demand centres, leading to local congestion curtailment. This has driven surging rates in places like the US, Europe, and elsewhere. Globally, congestion-related waste has contributed to billions in lost revenue and foregone emissions reductions.

b) Insufficient storage and flexibility: Without enough batteries, pumped hydro, or demand-side options to shift energy from high-production/low-demand periods to high-demand periods, surpluses are wasted. Modelling shows storage can reduce curtailment cost-effectively in many cases, but deployment lags behind generation growth. High curtailment then forces greater reliance on fossil backups during ramps (e.g., evening "duck curve" in solar-heavy regions), undermining environmental gains.

c) Suboptimal market design: Rigid rules, lack of granular pricing (e.g., 5-minute intervals), insufficient incentives for flexibility (e.g., weak capacity markets for storage or demand response), or policies that cap negative prices can distort signals. This weakens investment in the very solutions needed, more transmission, storage, or hybrid projects, and perpetuates inefficiency.

In the long term, elevated curtailment distorts investment signals by eroding project revenues (often 15-25% reductions in returns), inflating level zed costs of energy (LCOE) for new renewables, deterring financiers, and slowing deployment needed for de-carbonization. It also indirectly harms reliability by increasing dependence on aging fossil plants for balancing, raising blackout risks during tight supply events, and delaying grid modernization. Recent trends show curtailment hitting records in multiple regions despite renewable growth, underscoring that while some curtailment is inevitable and even economically rational at low levels (cheaper than overbuilding infrastructure for rare peaks), high and rising rates are a red flag for policy and investment priorities: accelerated transmission buildout (e.g., HVDC lines), storage incentives, market reforms for better price signals, and integrated planning to align generation with grid capabilities. In short, moderate economic curtailment is a useful real-time tool, but chronic high levels reveal systemic gaps that, if unaddressed, undermine both the economic viability of renewables and the long-term resilience of the power system [127-129].

In Germany, while average annual curtailment remains lower than in some regions of China, spring/summer midday solar surpluses combined with inflexible lignite/coal minimum loads have led to noticeable re-dispatch volumes and curtailment levels (estimated 5–10% in specific high-renewable hours or seasons in recent years), contributing to increased system costs and emissions from additional thermal operation [130-132]. In China (another major restructured/maturing market), curtailment rates for wind/solar have historically hit 5–15% in certain provinces (especially northwest), though national averages have improved somewhat with policy interventions [133-136].

An incentive-based fuzzy fault tree analysis (NIBFFTA) approach for restructured power systems is presented in [137], which considers the impact of hybrid wind-solar energy integration based on electric vehicles (EVs) and renewable energy sources (RERs). This approach combines the effects of different component failure rates and the effects of the incentive Gaussian distribution under an induced fuzzy fault tree framework for RERs and grid-integrated EV configurations. Predictors for different fundamental events are evaluated, allowing for a realistic assessment of their consequences on the system. The NIBFFTA approach is found to be more relevant and efficient than conventional FTA for risk assessment in restructured power systems with the integration of EVs and RERs. Conventional long-term reliability assessment methods are well-developed, focusing more on planning and development than on the operation of power systems. A method for assessing the operational reliability of power systems with high wind penetration in a restructured environment is proposed in [138], in which reliability network equations are combined with time-series simulation. The method models wind farms, conventional generation, storage providers, and the transmission network using reliability network equations. A probability management scheme, together with a day-ahead market, is also presented. Time-series Monte-Carlo simulation is used to capture the temporal aspects of these equations, along with a simplified method for computational efficiency. This approach enables customer reliability assessment by considering the variability of wind power during system operation.

A modified optimal load factor (OPF)-based method for assessing load point reliability in restructured power systems, especially with high penetration of renewable energy sources, is presented in [139], in which the generation and transmission systems are modelled using equivalent multi-state models. The impact of each component (generation and transmission) on load point reliability is also evaluated separately, and the uncertainties introduced by renewable generators are considered. The use of multi-state models takes into account the variability of renewable resources, making the approach robust to fluctuations. The ability of this method to simplify the reliability assessment under changing conditions also makes it valuable for dynamic power systems.

4.3. Operational and Resilience Issues

Maintenance in rebuilt systems shifts from utility-based to market-based, potentially delaying upgrades. A critical review of the evolution of power system maintenance identifies the need for predictive strategies to increase adequacy and security. Cyber-physical threats and aging infrastructure further strain resilience.

The impact assessment of demand response programs (DPR) on the reliability and efficiency of restructured power systems is reviewed in [140], which aims to quantify the impact of DRPs on improving the reliability of power systems, reducing financial costs and problems caused by failures. The model includes the characteristics of the demand curve, including penalties for non-compliance with load shedding and incentives for participation in load shedding. A mixed-integer DC optimal power flow model is used to evaluate load shedding and generation re-dispatch under possible scenarios (transmission and generation failures). Supply-side reliability (for generation companies) and demand-side reliability (for customers) are calculated. Analytical evaluation through the IEEE RTS 24-bus system and real-world application in the Iranian power grid demonstrate its practical application.

An approach using genetic algorithm to optimize the placement, operating conditions and number of flexible multi-type AC transmission system devices, such as STATCOM and SSSC, in restructured power systems is presented in [141], which aims to simultaneously determine the optimal location, operating point and number of FACTS devices to minimize the cost of nodes and their standard deviation in a restructured environment. It uses two separate algorithms within the genetic algorithm framework, so that it uses a heuristic search to significantly reduce the possible search space and improves the computational efficiency. It introduces a desirability criterion to evaluate the suitability of the optimization results.

In a restructured power system, the concerns of system operators include optimal maintenance coordination, which is closely related to the reliability and security of the power system. A reliability-based approach to maintenance coordination of generation and transmission, focusing on the perspective of the independent system operator, is presented in [142], in which a two-phase mechanism is used, considering the reliability and commitment of the unit with security constraints, and a method for evaluating maintenance sensitivity is proposed. The model is a multi-objective problem that encompasses reliability and social welfare and is solved by a genetic algorithm and quadratic programming. The proposed method combines fuzzy set theory and Gaussian distribution to model uncertainties in component failure rates and incentive effects related to the integration of electric vehicles and renewable energy sources. The advantages of the above method include the possibility of more accurate assessment of system risks.

The main objective of an electric power system is to provide electricity to consumers in an efficient, reliable and high-quality manner. In the context of a deregulated electricity market, the assessment of power system reliability, especially in bulk power systems, is becoming increasingly important. The incorporation of multi-state generation unit models, the evaluation of system performance indicators and the identification of transmission deficiencies in complex system adequacy assessments are reviewed in [143]. It also examines the impact of market risk on investment decisions for new infrastructure, and presents a method for identifying and addressing transmission constraints using probabilistic methods. The results show how market risks in rehabilitated environments affect investments in new generation and transmission infrastructure. It also proposes a method for identifying transmission deficiencies, and suggests corrective measures using probabilistic techniques to assess the adequacy of the combined system.

Capacity development analysis is crucial for addressing future load demands and minimizing system risk in power systems. It involves assessing the peak load carrying capacity (PLCC) under different conditions, such as varying levels of unavailability of generating units and addition of new units. Key reliability indicators, such as expected load loss (LOLE), expected demand unmet (EDNS), expected energy unsupplied (EENS), and demand power unavailability index (DPUI), are used to assess system performance. These indicators help quantify the risk level and reliability impacts of capacity development and transmission switching under different peak load scenarios. In addition, the impact of maintenance of generating units is also analyzed, as it affects the overall system risk levels and reliability. By optimizing capacity development and maintenance programs, the system can better meet future demand while maintaining regulatory and environmental compliance. The impact of capacity expansion in restructured power systems on increasing reliability and reducing risk is investigated in [144]. By analyzing the impact of adding new generating units and considering factors such as unavailability of generating units and transmission switching, the peak load carrying capacity and various reliability indices are investigated under different peak load conditions. The impact of maintenance of generating units on system reliability is also evaluated.

A method for assessing the reliability of a restructured power system operating under a two-way market is presented in [145], in which reliability network equivalent techniques are combined with pseudo-sequential simulation. The reliability network equivalent is integrated into Monte-Carlo simulation, to reduce computational complexity by simplifying the network model while maintaining reliability criteria. It increases the efficiency of non-sequential Monte-Carlo methods and incorporates the temporal aspects of market transactions and system operations. Multi-state Markov models are used to model generation and transmission systems, allowing for an accurate representation of component states and transitions.

4.4. Emerging Demand-Side Pressures: AI/Data Centres and Electrification

The electricity sector faces significant demand-side pressures from two major emerging trends: the explosive growth of AI-driven data centers and broader electrification across transport, buildings, industry, and manufacturing. These forces are reversing decades of flat or slow electricity demand growth in many regions, driving accelerated consumption, straining grids, and prompting urgent investments in generation, transmission, and infrastructure. The rapid adoption of artificial intelligence, particularly

generative AI, large language models, and high-performance computing—has transformed data centers into one of the fastest-growing sources of electricity demand. These facilities require massive, constant (24/7) power for servers, cooling, and infrastructure, often concentrated in specific regions, creating localized grid stress.

In summary, AI/data centers and electrification represent a watershed moment for energy systems. They offer tremendous economic and technological potential but demand proactive planning to ensure reliable, affordable, and sustainable power. Forecasts remain uncertain due to efficiency gains, market trajectories, and policy responses, but the direction is clear: electricity is entering a high-growth era.

5. Demand Response Mechanisms and the Role of Consumers in Enhancing Reliability

Demand response (DR) mechanisms play a pivotal role in modern power systems by enabling active participation from consumers in managing electricity demand. This enhances overall grid reliability, particularly in distribution networks, by reducing peak loads, alleviating network stress during contingencies, and minimizing the impacts of faults or overloads. DR operates through two primary categories of mechanisms [146-151]:

a) Price-based DR (also known as implicit DR): This includes time-of-use (TOU) pricing, critical peak pricing, real-time pricing, and variable tariffs. Consumers respond voluntarily to price signals by shifting or reducing consumption during high-price periods, which typically align with peak demand or grid stress. This encourages load management without direct utility control.

b) Incentive-based DR (explicit DR): Programs such as direct load control, interruptible/curtailable rates, capacity/ancillary services, or emergency demand response offer direct financial incentives (payments or bill credits) for consumers to curtail load when called upon by the utility, often during reliability events or high system demand.

These mechanisms improve key reliability indices:

a) SAIFI (System Average Interruption Frequency Index): Measures the average number of interruptions per customer over a period (typically SAIFI = total customer interruptions / total customers served). By reducing peak loads and preventing overload-induced outages, DR lowers the frequency of interruptions.

b) SAIDI (System Average Interruption Duration Index): Quantifies the average outage duration per customer (SAIDI = sum of customer interruption durations / total customers served). Load curtailment during faults or maintenance can accelerate restoration or prevent cascading failures, shortening durations.

c) ENS (Energy Not Supplied): Represents the total energy unserved due to interruptions (often linked to AENS, average ENS per customer). DR mitigates ENS by shedding non-critical loads, preserving supply to essential services, and reducing overall unserved energy during contingencies.

Studies demonstrate these benefits quantitatively. For instance, DR programs in distribution systems have achieved improvements such in SAIFI and in SAIDI through load reduction and optimal operation. Other research shows DR's sensitivity to load variations, particularly impacting ENS, with reductions in expected energy not supplied and enhanced reliability in automated systems. Innovative pricing schemes, like instantaneous pricing, further optimize operation and reliability in distribution networks.

Smart consumers, equipped with advanced technologies, amplify DR's contributions to grid resilience. Prosumers with energy storage systems (ESS), such as home batteries, can store excess energy during low-demand periods and discharge during peaks or outages, acting as distributed resources to support local reliability and reduce reliance on the main grid. Electric vehicles (EVs), especially through vehicle-to-grid (V2G) technology, transform EVs into mobile energy storage units. In V2G mode, EVs discharge stored battery energy back to the grid during high demand or emergencies (bidirectional flow), while grid-to-vehicle (G2V) enables smart charging to avoid peaks. This provides ancillary services like frequency regulation, peak shaving, and reserve capacity. Studies highlight V2G and smart EV integration's positive effects. V2G improves reliability indices (e.g., SAIFI, SAIDI, ASAI, and ENS) by enhancing load balancing and supporting the grid during faults. Integration of EVs with demand response and distributed generation reduces network losses, load fluctuations, and unserved energy while boosting resilience. Aggregated EVs in V2G setups act as flexible resources, lowering ENS and improving overall system well-being under uncertainties like renewables variability. Case studies show combined ESS, EVs, and DR yield better performance in radial distribution systems, with EVs preventing outages and supporting restoration [152-159].

By empowering consumers as active participants, via smart meters, home energy management systems, and bidirectional capabilities, DR fosters a more resilient grid. This is especially vital with increasing renewable penetration and electrification, where consumer-side flexibility mitigates intermittency and enhances reliability metrics. Ongoing research and pilots continue to validate these benefits, underscoring the shift toward consumer-centric, demand-flexible power systems [160-162].

6. Conclusion

Energy is one of the fundamental pillars for the survival of modern societies and the proper functioning of power systems. Reliability in power systems is the key factor that guarantees the continuous and stable supply of electricity to end-users. This directly supports economic prosperity (by preventing financial losses in industries and businesses due to blackouts), environmental sustainability (through better integration of renewable energy sources and reduced reliance on fossil fuels), and social well-being (ensuring electricity for hospitals, households, emergency services, and daily life).

Reliability in power systems refers to the ability of the grid to supply electricity continuously with minimal interruptions and disturbances, even under varying conditions such as fluctuating demand, equipment failures, extreme weather events, or sudden generation losses. This concept remains one of the most critical aspects of power system planning,

operation, and maintenance, as its primary goal is to ensure that generation and transmission capacity always match demand under a wide range of possible scenarios.

This paper provides a comprehensive overview of the key concepts and major challenges related to reliability in restructured (deregulated) power systems. In restructured electricity markets, the traditional vertically integrated utility model has been replaced by competitive markets, functional unbundling of generation, transmission, and distribution activities, and the participation of multiple independent actors (independent power producers, retail suppliers, large consumers, etc.). While this market-oriented structure can significantly improve economic efficiency (through competition and cost reduction), it simultaneously introduces substantial new complexities and risks to system reliability.

Empirical evidence from California (2020) and Texas (2021) demonstrates that restructuring can exacerbate reliability risks during extreme weather events if market design and regulatory oversight do not adequately address resource adequacy and infrastructure resilience.

In such decentralized and market-driven environments, reliability can no longer rely solely on centralized control. Instead, it must ensure three main pillars:

- Resource Adequacy (sufficient installed capacity and reserves to meet demand over the long term)
- Operational Reliability (ability to maintain frequency, voltage, and stability in real time)
- Resilience (capacity to withstand and recover from high-impact, low-probability events)

Major challenges include:

- Integration of intermittent renewable energy sources (wind and solar), whose output is highly variable and only partially predictable due to weather dependence
- Significant reduction in system inertia caused by the replacement of traditional synchronous generators (with high rotating inertia) by inverter-based resources (IBRs — solar PV, wind turbines, batteries), which provide little or no natural inertia → leading to faster frequency changes and greater difficulty in frequency control
- Poor coordination among diverse market participants (generators, transmission system operators, distribution companies, retailers, demand-response providers), who often have conflicting short-term economic incentives

Addressing these challenges requires innovative solutions, including:

- Advanced technologies: large-scale energy storage (batteries), smart grids, Flexible AC Transmission Systems (FACTS), High-Voltage Direct Current (HVDC) links, grid-forming inverters, synthetic inertia solutions
- Stronger market mechanisms: capacity markets, ancillary services markets, scarcity pricing, real-time pricing, demand-side participation
- Tight regulatory oversight to prevent market abuse, ensure adequate investment in reliability-enhancing infrastructure, and enforce minimum reliability standards

Recent advances in probabilistic modeling, advanced optimization techniques, and the application of artificial intelligence / machine learning for real-time forecasting, risk assessment, and decision support have substantially improved reliability evaluation capabilities. Nevertheless, critical issues persist, such as:

- Rapid loss of system inertia
- Compounding effects of extreme weather events (which simultaneously affect both renewable generation and electricity demand)
- Growing cybersecurity vulnerabilities in increasingly digitized and interconnected systems
- Accurate spatio-temporal modeling of variable renewable output
- Ensuring fair and non-discriminatory reliability assessment across competing market players

Current trends clearly point toward probabilistic and simulation-based approaches, combined with heavy integration of AI for real-time situational awareness, contingency analysis, and automated corrective actions.

6.1. Reliability Indices

Power system reliability is typically evaluated using two broad categories of indices:

a) Distribution-level reliability indicators (customer-oriented metrics), such as:

* SAIFI (System Average Interruption Frequency Index)- average number of interruptions per customer per year
* SAIDI (System Average Interruption Duration Index)- average duration of interruptions per customer per year (usually in minutes or hours)
* CAIDI (Customer Average Interruption Duration Index)- average time to restore service after an interruption (SAIDI ÷ SAIFI)

These metrics primarily capture local distribution-level outages (caused by equipment failure, vegetation, animals, traffic accidents, etc.) and fall under the responsibility of distribution system operators/companies.

b) Bulk/system-level (aggregate) reliability indicators, such as:

* LOLE (Loss of Load Expectation), expected number of hours per year when load will exceed available generation
* LOLP (Loss of Load Probability), probability that load will exceed available generation at a given moment
* EENS (Expected Energy Not Supplied), expected amount of energy (MWh) that will not be supplied per year
* Occasionally LOLH (Loss of Load Hours) or similar metrics

These indices focus on generation and transmission adequacy and operational security against major disturbances (large generator outages, transmission contingencies, extreme load events), and are typically the responsibility of the system operator (TSO/ISO) and/or capacity planning authorities.

These two groups of indices operate at different layers of the electricity supply chain, address different causes of interruptions, and align with the divided responsibilities that exist in restructured electricity markets.

6.2. Critical Analysis

While the original text provides a solid general overview, several important shortcomings and limitations should be noted:

* Excessive optimism regarding the benefits of restructuring and new technologies: Although deregulation and high renewable penetration offer efficiency gains, real-

world evidence (e.g., NERC reports, Texas 2021 blackout, Odessa 2021 events, multiple UK and Australian frequency incidents) clearly shows that reliability risk has increased during the transition to low-inertia systems dominated by inverter-based resources.

* Insufficient emphasis on the fundamental tension between short-term economic incentives and long-term reliability: In competitive markets, many participants prioritize short-term profit maximization, which can lead to under-investment in reserves, inertia support, storage, or backup capacity. The text does not sufficiently address this structural conflict of interest.

* Limited discussion of critical mitigation technologies: The rapid decline in system inertia is one of the most serious threats to frequency stability, yet the text mentions it only superficially without adequately highlighting practical large-scale countermeasures (utility-scale batteries with grid-forming capability, synchronous condensers, flywheels, etc.).

* Inadequate treatment of climate change impacts: Extreme weather is not merely a "challenge" — it is becoming more frequent and severe due to global warming, often simultaneously reducing renewable output and driving record demand (e.g., heatwaves, cold snaps). The text underplays this dual impact on both supply and demand sides.

* Limitations of conventional indices: While the indices are well explained, the text could have better addressed their weaknesses, for example, their focus on average values often masks worst-case impacts on specific customers (metrics such as CEMI, CELID, or customers with long-duration outages are rarely discussed). Also, in restructured markets, the separation of responsibilities between distribution and system-level indices sometimes results in no single entity accepting full accountability for combined or cascading failures.

6.3. Future Research Directions

Despite significant progress in conceptualizing and classifying reliability in restructured power systems, as well as in identifying key technical, economic, and institutional challenges, several critical areas remain underexplored or require deeper investigation to ensure secure and economically efficient operation in increasingly complex electricity markets.

First, the development of hybrid reliability assessment frameworks that simultaneously incorporate physical system adequacy (HL I, HL II, HL III levels) and market performance indicators remains limited. Future studies should focus on integrated models that quantify the interaction between market clearing outcomes, participant strategic behavior, and long-term resource adequacy under high uncertainty. In particular, incorporating game-theoretic approaches and agent-based modeling to simulate realistic market participant decisions (including risk-averse GenCos, demand response aggregators, and storage operators) can provide more realistic reliability risk profiles in competitive environments.

Second, with the rapid transition toward inverter-based resources (IBRs), variable renewable energy sources (VRES), and distributed energy resources (DERs), traditional deterministic and probabilistic reliability metrics are becoming insufficient. There is a pressing need to develop next-generation reliability indices and standards tailored to low-inertia systems, such as frequency nadir-based metrics, operating reserve products for fast frequency response, and energy-limited resource adequacy evaluation methods. Research should also explore how market design (e.g., scarcity pricing, performance-based capacity mechanisms, or forward reliability markets) can properly incentivize flexibility attributes that enhance system reliability under deep de-carbonization scenarios.

Third, the coordination problem between system operators, market operators, transmission owners, and distribution system operators in restructured environments requires more attention. Hierarchical and distributed optimization frameworks, potentially leveraging ADMM (Alternating Direction Method of Multipliers), block chain-enabled transparent data sharing, or federated learning, could improve real-time reliability management while preserving commercial confidentiality. Special emphasis should be placed on multi-timescale reliability assessment that bridges short-term security-constrained unit commitment with long-term generation and transmission expansion planning under uncertainty.

Fourth, resilience-oriented reliability analysis, which extends beyond conventional N-1/N-k contingency analysis to account for extreme weather events, cyber-physical threats, and cascading failures, has received growing interest but remains fragmented in the context of deregulated systems. Future work should investigate resilience-constrained market clearing models, the value of grid-enhancing technologies (advanced conductors, dynamic line rating, topology control), and incentive mechanisms that encourage private investment in resilience-enhancing assets.

Fifth, the role of emerging technologies such as large-scale energy storage, green hydrogen, vehicle-to-grid (V2G), demand-side flexibility platforms, and AI/ML-driven predictive maintenance and anomaly detection needs systematic reliability impact assessment in market-based settings. In particular, research should quantify how these technologies can be co-optimized in joint energy-reserve-flexibility markets and how regulatory frameworks should evolve to remove barriers to their participation.

Finally, from a methodological perspective, there is a need for benchmarking datasets, standardized test systems, and open-source tools specifically designed for reliability studies in restructured environments (extending beyond classical RTS-79/RTS-96 cases). Comparative studies across different market designs (pool vs. bilateral, nodal vs. zonal pricing, capacity market vs. energy-only market) would help draw generalizable conclusions.

Addressing these directions will require interdisciplinary collaboration among power engineers, economists, data scientists, and policy researchers. Ultimately, advancing reliability science in restructured power systems is essential not only for maintaining acceptable service quality during the energy transition, but also for enabling competitive, low-carbon, and resilient electricity supply well into the future.

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