Current Sustainable/Renewable Energy Reports
https://doi.org/10.1007/s40518-021-00194-4

ENERGY MARKET (R SIOSHANSI AND A MOUSAVIAN, SECTION EDITORS)

Electricity Markets and Power Supply Resilience: an Incisive Review

Ekundayo Shittu[1] · **Joost Reyes Santos**[1]

Accepted: 5 August 2021

Abstract

Purpose of Review This paper focuses on the advances in the resilience of electricity systems and energy markets. The objective is to identify how the progress on system resilience may influence market rules while uncovering the gaps in the literature.

Recent Findings This review distills three findings. First, significant advances have been achieved both in the design and configuration of power systems for resilience. Second, topological and architectural advances appear isolated from market operations. Third, there is room to integrate self-healing resilience into power systems and bridge the bifurcation between increasing network resilience and having the market adequately value resilience.

Summary Evidently, the incidences of disruptions to electricity networks are on the rise, making a change from having a merely reliable electricity network to one that is resilient and adaptive a necessity. This review showcases the qualitative value inherent in processes to enhance adaptive resilience while promoting the requisite signals for power market integration.

Keywords Disruptions · Electricity · Market · Reliability · Resilience · Self-healing

Introduction

Today, electricity transactions and services vary across different regions of the USA. Different markets also value carbon-free power differently [1]. In centralized wholesale markets, transactions occur through Regional Transmission Organizations (RTOs) with operational oversight by the Federal Electricity Regulatory Commission (FERC). The characteristics of these RTOs include real-time, day-ahead, and capacity transactions. To a large extent, RTOs have provided a good platform for electricity transactions between generators and bulk power purchasers. However, there is a widening gap between the advancements in electricity generating technologies, the increasing scale of renewable penetration, and the market structures in which electricity is traded as a commodity. The increases in disruptions to the power supply further exacerbate the gap. This paper aims to shed lights on the literature underlying advancements in electricity systems with emphasis on the interaction between resilience and energy markets. In the context of this paper, "resilience is the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents" [2]. An intermediate outcome of this examination is to uncover the gaps at the intersection of the market and power systems resilience.

The motivation is underscored by the recent power outages across the state of Texas for 4 days in February 2021 due to unexpected significant drops in temperatures. Specifically, the sudden rise in the demand for electricity for heating needs and the sudden drop in supply, especially in thermal resources, inundated power plants as demand significantly exceeded supply. Consequently, many power plants shut down [3]. It is predicated on the physics of electricity that disallows a mismatch between supply and demand as a prerequisite for frequency and voltage to be within limited tolerances. The system failure resulted in the loss of more than eighty lives and billions of dollars of property damages. Though access to electricity is significantly dependable, the market where it trades is predominantly sophisticated. The mismatch between the market operations and the changing grid is a classic example of the clock speed hypothesis, i.e., the system must

This article is part of the Topical Collection on *Energy Markets*

✉ Ekundayo Shittu
eshittu@gwu.edu

Joost Reyes Santos
joost@gwu.edu

[1] Engineering Management and Systems Engineering, George Washington University, Washington, D.C., US

Published online: 31 August 2021

concurrently align new processes (emerging technologies) and redesign supply chains (existing markets) [4, 5].

The Texas debacle is reminiscent of prior disruptions that litter recent history on the magnified value of a resilient electricity system especially when the cascading consequences of the failures are considered. The outage of power leaves millions of customers with economic losses, pose threats to health and public safety, and holds the potential to compromise national security [6]. For example, the New England/Eastern Canada Ice Storm that occurred between January 4 and January 10, 1998, left more than 5.2 million customers without power. The absence of a resilient system meant that a month after the storm, hundreds of thousands of customers still had no power with economic losses to the tune of $4 billion [7]. The Northeast Blackout in August 2003 caused by a confluence of factors including market operator errors led to a cascading collapse of the bulk power system across eight states and two Canadian provinces. The cascading failure affected more than 50 million people with power outages that lasted more than four days with economic cost estimated to be up to $10 billion and 11 deaths [8]. Others such as hurricane Katrina in 2005 [9] and Superstorm Sandy in 2012 [10] further reiterate the value of designing electricity markets for enhanced resilience. It is clear that in every incident, the magnitude of the losses is an exponentially increasing function of the restoration time. Thus, there is an urgent need for market redesigns that accommodate resilience.

The market redesigns that are cognizant of the fast and vast changes in energy portfolios may minimize the vulnerability of the system. This literature survey spanning mainly 2015 through 2020 shows that significant advances have been achieved both in the design of power systems and their optimal configurations for resilience. Conversely, gaps are highlighting the role of autonomous or self-healing systems and the inadequacies of the markets at recognizing or valuing them. Thus, the exploration suggests an opportunity to fortify the power system's resilience by bridging the bifurcation between the efforts at network reconfiguration for resilience and having the market adequately value the improvements in resilience. Thus, the contribution of this review is on the qualitative value inherent in adaptive resilience while promoting the requisite signals to optimize market operation. This value proposition also encourages trading forward electricity more efficiently.

Methodology

The bibliometric analysis draws from related literature from databases including Google Scholar and Web of Science emphasizing papers mainly between 2015 and 2020. The search criteria include keywords such as electricity markets, resilience, restoration, disaster mitigation, emerging electricity technology, self-healing, and autonomous power systems. Full articles based on these terms were downloaded for analysis in consistence with related methods in literature [11].

Figure 1 of the bibliometric network map was developed with the aid of VOSViewer [12], a visualization software. The major keyword nodes, made significant by dimension and relative count, in Fig. 1 provide the bases for establishing the central themes for this review with the lines showing how the nodes are related or connected. The figure also shows the colors indicating averaged aggregated publication by year with a scale at the bottom. Finally, NVIVO, a qualitative data analysis software, was used to deductively code the gaps [13, 14].

The figure shows several keywords and linkages that have been integrated into the following themes: (i) the evolution of electricity markets and trading, (ii) disruptions in electricity supply, (iii) policies and metrics for resilience, (iv) self-healing or bio-inspired networks, and (v) implications for a market redesign. These form the main sections of the review. The figure also shows that control, market designs, and self-healing power systems have not received significant attention in recent times as much as issues of vulnerability, trading, environmental performance, and enhanced resilience have. The following sections review the literature and identify gaps that demand research attention. Each section concludes with a box highlighting a deduced summary.

Electricity Markets, Cyberattacks and Trading

Energy markets have evolved considerably with the advent, and increasing penetration, of renewable generation capacities [15]. Integrated energy systems (IES) made up of subsystems including electricity, natural gas, heat/cooling, industrial processes, and hydrogen have offered the promise of reducing the dependence of the economy on fossil fuels. However, studies on these systems, particularly on their resilience, are still conducted not only independent of the other subsystems but also of the market [16, 17•]. The need for increased interconnectivity to match demand and supply has led some to coin the term, "Internet of Energy," i.e., a system that is inclusive of digitizing interdependence and cybersecurity [18•] or internet of things, IoT-enabled electricity network [19].

Nonetheless, there are still some considerable challenges related to how resilient the system may be to Cybersecurity risks [20, 21] compared with conventional centralized electricity system [22] and to what extent is the resilience

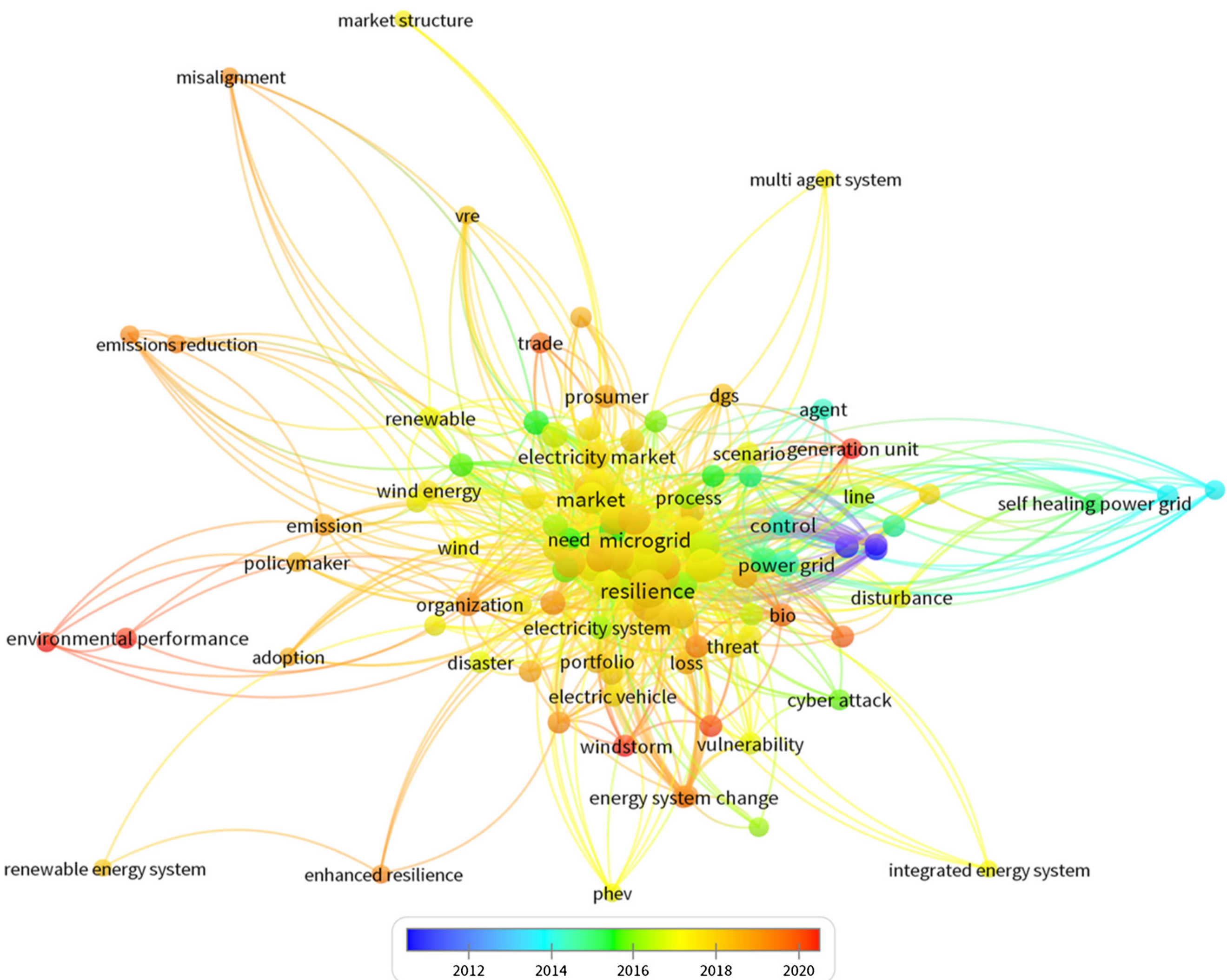

Fig. 1 Time-sequenced bibliometric network of keywords and themes

priced in the market. Cyberattack risks could manifest in the combination of high-wattage demand-side appliances with public information for attacks on the power grid through electric vehicle charging stations with smartphone application and the power grid data [23–25]. The value of resilience, if captured, may also vary by the geographical location of the market.

Beyond peradventure, evidence suggests that restructuring of electric utilities promotes competitive markets despite institutional and policy heterogeneity [6], and often leads to serious effects on market pricing. By the same token, electricity-intensive industries may be dependent on countries' power system resilience [26]. To illustrate, assessing electricity market integration in Europe, factors such as new interconnection, market coupling, and the share of intermittent generation have effects on spot and forward markets, especially on their resilience to shocks [27, 28••]. As systems integrally connect to electricity, such as transportation systems, grid-to-vehicle integration, and markets for ancillary grid services may be prerequisites for resilience and decarbonization [29]. The reducing costs due to technological learning may also influence market signals [30].

Researchers develop optimization-based routines to carve out market structures specific to locational marginal prices to determine optimal market clearing conditions. For instance, an application of inverse optimization to the Midcontinent ISO (MISO) market shows the correlation of optimal prices to the actual MISO prices under different market conditions [31]. Complexity science algorithms, when applied to energy systems, integrate themes related to transportation, energy behavior, and physical infrastructure [32]. Unfortunately, such modeling frameworks are either difficult to communicate or have no direct bearing on the market dynamics. Multi-agent systems have been proposed with the premise of their suitability across multiple domains [33] to address these limitations.

Primal-dual gradient methods that incorporate line constraints to avoid congestion in bilateral trading have been proposed for clearing the market [34] to promote active market participation. Yet, these systems are limited at offering electricity markets the capability to respond to a consumer-centric generation that is bound to be a feature of future electricity markets [35].

The emergence of prosumers, agents that both consume and produce electricity through solar panels [36], plug-in hybrid electric vehicles (PHEVs) [37], battery storage [38–41], the value of flexibility [42], not only introduces risks for the market but also poses challenges to integrate them into competitive markets [43, 44]. Empirical analysis exquisitely demonstrates that peer-to-peer (P2P) prosumer electricity markets require the active contribution of intermediaries [45, 46]. However, it is unpersuasive how the system values such intermediaries in day-ahead or in real-time pricing or what their marginal economic benefits are [47, 48].

Evidently, the emergence of prosumers may dilute the concentration of supply bulks as their increasing presence offers avenues for multi-spatial supplies. There are three potential effects of their increasing emergence. First, the dilution of market power will have impacts on the level of the price that the market clears at. Second, the exogenous consequence could lead to bulk producers reconsidering their business models. For example, there could be an increase in the trend of major utilities investing in community solar projects. Third, in areas where net-metering is an option in the market, the greening of the electricity supply chain could be accelerated.

Deduction 1: Market Gap

Electricity markets are to supply minimum cost, reliable (and now resilient) electricity. Resource portfolio transition from mainly conventional to renewable options and the emergence of prosumers portend significant challenges. Though battery storage to address intermittent outputs and improved demand response have been touted as solutions, the absence of marginal costs coupled with rent-seeking prosumers suggests that new and responsive market rules are required.

Disruptions in Electricity Supply

Unfortunately, exposure of energy systems to disruptions range from climate change-induced hurricanes and floods, artificial disasters such as cyber-attacks, ransomeware, earthquakes to intermittent energy sources [20, 21, 49, 50]. These high-impact, low-probability (HILP) events are challenging the operation and resilience of power networks [51, 52]. The literature is replete with models that consider microgrids [53] to offer resilience enhancements because they are decentralized. For example, stochastic programming is used to evaluate microgrids by including uncertainties in the wind and real-time market prices to mitigate disruptions [54]. Models of mixed-integer linear programming and utilizing IEEE test systems have been considered for the resiliency of distribution systems given the rising levels of the renewable energy [55] or disruptions due to disasters such as earthquakes [41] or HILP events in general [56, 57]. Chaotic failure models for nodal resilience under windstorms have been proposed with promising insulation to disruption outputs [58]. Artificial Intelligence (AI) and machine learning methods [59] have been employed to identify network risks [60, 61] for emerging electricity systems. An incremental cost consensus algorithm examines three different network topologies of microgrids in emergency modes to decipher alternative ways to alleviate demand-supply mismatch [62].

The examples mentioned above illustrate significant advances that offer the preface to more integrated approaches for including disasters and disruptions into technology combination scenarios. Perhaps examining a unifying framework of these methods with the extant rules in power markets could help to reaffirm advances that could prevent the Texas debacle. While the acknowledgment of disruptions is inherently motivating, their effects can be magnified by power system planning that unconsciously ignores their cascading impacts [8].

Deduction 2: Lessons from Disruptions

The lesson from the literature is that disruptions have the unintended consequence of offering rationales for system redesign that may be agnostic of disaster type. Undoubtedly, the dearth of an integrated system of systems analysis implies that as the density of disruptions continues to transform into one with fat tails, the effects cascade and magnify. This dearth is not a deficiency of the extant literature taking disasters as exogenous to power network configurations. Rather, it is an aberration that future research must address.

Policies and Metrics for Resilience

It is essential to delineate how resilience is measured, given that only measurable parameters can be controlled. Earlier in 2013, the US government proposed steps to strengthen critical infrastructure resilience emphasizing energy infrastructures as being uniquely critical. The guiding principles on resilience metrics include: (i) usefulness — metrics must be relevant for decision making in contexts such as system planning, real-time operations, and policy decisions [56]; (ii) offer a mechanism for comparison — applicable across multiple systems and capable of differentiating enhanced systems from weak ones; (iii) extensibility — metrics must be scalable in time and geography; and (iv) quantitative and qualitative [2].

Independent of the research domain, resilience will minimize the effects of a catastrophic event across four functions, including resist, restabilize, rebuild, and reconfigure [63]. The criticality of having a resilient system has been orchestrated to improve equity in environmental and urban services. For instance, closeness to essential services, such as health care facilities, influences resilience benefits [64]. Nonetheless, indicators and metrics for resilience such as proximity to a critical resource or service are prerequisites for investments [65] and costs [66]. This example illustrates how policy could be influenced, as noted in Japan after the 2011 Fukushima nuclear disaster [67]. In response to Japan's earthquake propensity, the country evaluated the possibility of having all electricity supply from renewables and demonstrated even higher levels of resilience [68]. The value of examining resilience beyond electricity generation into social and environmental considerations is crucial for a system of systems integration, and for the recovery of complex systems after a disaster [69].

While existing efforts at distributed resources offer promises of increased resilience, the calls for accelerated and expanded progress are growing louder such that a new technology consideration for resilience enhancement is distributed nuclear [70] to complement others. In the context of multi-energy systems, enhanced resilience with solar photovoltaic coupled with Lithium-ion batteries demonstrate how homes, companies, and regions may use renewable resources for their energy supply [71]. However, the pace requires policies that promote democratizing energy access [72]. Such policies could aid efficient building designs, and passive cooling devices [73, 74]. From the lens of a policymaker, microgrids offer a strategic role, particularly in the design of ancillary services markets for resilience [75]. One such examination considers resilience-constrained unit commitment (RCUC) in a proportional hazard model that simulates line forced outage to highlight the cost implications of preparedness [76].

The increasing enactment of renewable portfolio standard (RPS), a regulatory tool prescribing that a specific percentage of electricity generation be from renewables, correlates with the rise of strategic behavior (by firms that hold market power) in the market for renewable energy credit (REC). This observation has significant impacts on REC and electricity prices [77]. While behavior is strictly in the context of declining dispatchability, it is arguable to be more pronounced when the need for resilience of supplies in these markets is factored in. In sum, isolating RPS regimes from the market structure may have significant impacts such as welfare losses [78], and the ambivalence of policy could impact portfolios' capacity expansions [79, 80].

Deduction 3: Bridging the Metrics–Policy Gap

The failure of critical infrastructure systems in the event of a disaster is exacerbated by the inability of the systems to recover in "good" time in what some scholars call the *resilience triangle*. The demonstrated opportunity for research is how to harness the diversity of the characteristics of metrics to inform resilience policies. A second and more critical element is how the market may be bilaterally influenced by policies, and vice-versa.

Self-healing and Bio-inspired Networks

There is a growing emergence of power systems capable of self-healing in the event of a fault or disruption. Such systems may include advanced control schemes ranging from test demonstrations of fault location, isolation and service restoration (FLISR) [81, 82], two-layer algorithms with storage in an energy management system [83], phasor measurement unit (PMU) [84, 85], large-scale measurement with information-based control strategy [86], distributed communication protocols [87], maintaining the stability of the synchronous state of the grid [88], or adaptive restoration decision support system [89, 90]. At the minimum, local microgrid capacities may support an isolated part of a disrupted network [9]. For example, the distribution of power for contingency purposes use consensus algorithms [91].

In a bid to adopt self-healing lessons from nature, bio-inspired power system network designs have been modeled for system reliability, and resilience against disturbances [92]. Inspired by ecological robustness, transmission networks have been modeled in mixed-integer nonlinear programming to demonstrate improvements in optimized robustness, reliability, and resilience in the face of synthetic contingencies [93, 94]. One of the benefits of adopting the architecture of biological systems is the way such systems strike a balance between redundancy and efficiency [95]. This balance motivates how a bio-inspired design of a supply chain network offers better resilience performance than one based on minimum cost [96]. Despite these advances, there is a striking disconnection between the proposed enhancements to power systems through self-healing systems and how the market either responds to the improvements or whether such are adequately valued.

Smartening the grid through self-healing strategies such as automatic switching plans dependent on network topology and load characteristics continue to aim at the dual goals of minimizing both the count of switching operations and the time to autonomous recovery [97]. Another bio-inspired approach is self-optimized butterfly mating optimization that shows improvements over existing routing schemes in power network communication [98]. While these efforts produce efficiency gains, the isolation of the grid from other systems abstracts it from systems interdependence [99]. One attempt to integrate electric and gas networks is a model that determines grid topology in the presence of gas constraints while minimizing the demand or load to be isolated from the network [100]. The benefits of this system integration through restrictions governed by interdependence demonstrate the potential for a system of systems analysis over and above gas and electricity networks [101]. Note that real-time responses to disruptions ought not to be strictly based on sectional isolation, the provision of redundancy or standby capacity [102], or insulation to avoid cascading impacts [103]. There should be coordination on pre-disruption plans for critical infrastructure systems with the system of systems interdependency [104].

Deduction 4: Valuing Resilience Autonomy

It is a paradox that the advances in the use of communication technologies in electricity systems and self-healing strategies to smartening the grid have not been directly integrated into market designs. Perhaps there is room for inserting the value of quality-of-service enhanced by self-healing in episodes of disruption into how the market rules are designed.

Market Redesign and the Cost of Resilience

While a number of electricity markets have explicit mechanisms for pricing reliability, it is not evident if there are explicit approaches for pricing resilience. For example, Texas and Australia use scarcity pricing in an energy-only design [105, 106] and PJM uses an explicit capacity auction [107, 108]. Nonetheless, it is arguable that any policies or actions that improve reliability also tend to improve resilience. Yet, the value of resilience warrants that markets need to have new metrics that may be enhancements to those for reliability.

Although the rules in current markets require updating, the rise of non-dispatchable generation coupled with disruptions to the network exacerbates the challenges for restructuring [109••]. Resilience enhancement, in any of its ramifications, is not free. Nonetheless, it is crucial to note that investments into electricity system resilience are only feasible when the economic benefits of such investments outweigh the costs [110]. Subsequently, resilience implemented by islanding whereby a microgrid is used to power critical loads raises the issue of the best approach to price the contingency power. This issue is addressed in a variety of methods including: the use of models of load dispatch in a single-bid auction market with outcomes showing lower than on-grid market-clearing price of electricity in the island mode [111]; the use of HOMER to model a smart municipal grid with real-time prices in a system requiring resilience due to the mix of combined heat and power and variable renewable energy; indicates flexibility reduces levelized costs in the municipal grid when compared with market prices [112].

Justifying these models is complicated by the efficiency in market designs where, for instance, agreements are made at day-ahead prices, but are settled in real-time. To illustrate, PJM market rules highlight imbalances in how virtual transactions are settled [113]. Thus, considerations for wholesale market designs that include demand response, distributed generation, and storage are required [114]. Specifically, increasing variable renewable options in the market might minimize integration costs, but the electricity market, e.g., in Europe, is not optimized for this opportunity [115] because of market coupling issues and the EU emissions trading system [116, 117]. The equilibrium of peer-to-peer prosumer networks in market design with privacy issues also becomes important [44]. Though a summary of the relation between transactive energy and marginal distribution pricing has been provided [118], it is yet to be seen the extent of resilience in the consideration. There is room also to understand how the equity market values firms that invest in resilience [1].

It is arguable that pricing resilience might lead to the unintended consequence of inequitable access to supply. This implies that the market redesign may lead to a future where the "haves" have access to resilient electricity supply and the "have-nots" or low- and middle-income (LMI) households who do not have the financial means do not have such access. This notion is viewed in a different lens from the observation on the access to renewable electricity such as rooftop solar panels. Specifically, a market design that incorporates the value of resilience would be integral to the electricity supply infrastructure just as existing markets value reliability and capacity. Such redesign would be no different from the modalities governing the current grid supplies. In other words, factoring the value of resilience would be sine qua non to the operation of the grid. In the same vein, it is critical for future market designs to implement such pricing changes without creating inequitable accessibility to resilient supply.

Deduction 5: Tranches of Market Redesign

Despite updates in market-clearing rules, the load curtailment penalty is weak. This weak penalty implies that resilience valuation either from the lens of market coupling or proliferating prosumer networks or financial markets is required to address price imbalances and incentivize resilience. Market redesigns for resilience must be void of inequity that may alienate certain income groups.

Conclusion

This paper presents an incisive review of the recent literature on electricity markets and resilience to shed light on market redesign opportunities. The increasing penetration of renewable generation options, the emergence of prosumers, the rising incidences of disasters combine to suggest that new and responsive market rules are required. Though the literature eloquently demonstrates that disasters call for increasing resilience, the absence of an integrated system of systems analysis implies that isolated efforts will not arrest cascading impacts of disruptions. The continued prolonged restoration time after every disaster to power networks shows that it is imperative for the market to harness a multi-metric approach to measuring resilience and, in turn, inform policy. The same argument holds for the market appreciation of communication technologies for a smarter grid, i.e., their direct integration into market redesigns through a measure of quality-of-service especially for intermittent renewables [119] and as may be induced by self-healing processes. In sum, this article calls for optimizing the market incentives for resilience-enhancing initiatives in power networks that not only preserves equitable access to electricity but also is robust to the rising potentials of cyberattacks.

Acknowledgements The authors would like to thank the reviewers and the Energy Market Editors, Dr. R. Sioshansi and Dr. S. Mousavian, for their submission invitation and helpful suggestions to improve the article.

Funding This work was supported by the National Science Foundation (NSF) under Grant 1847077. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the NSF.

Declarations

Conflict of Interest The author declares no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Ogunrinde O, Shittu E, Dhanda KK. Investing in renewable energy: Reconciling regional policy with renewable energy growth. IEEE Eng Manag Rev. 2018;46(4):103–111.
2. Watson JP, Guttromson R, Silva-Monroy C, Jeffers R, Jones K, Ellison J, et al. Conceptual framework for developing resilience metrics for the electricity oil and gas sectors in the United States. US: Sandia National Lab; 2014.
3. Traywick C, Chediak M, Malik NS, Saul J. The two hours that nearly destroyed Texas's electric grid. Bloomberg Green. Https://tinyurl.com/53ttxey6. 2021.
4. Pollitt MG, Georgiopoulos S. The impact of new technology on electricity network operators. Cambridge: University of Cambridge; 2019.
5. Fine CH. Clockspeed: Winning industry control in the age of temporary advantage. ReadHowYouWant com. 2010.
6. National Academies of Sciences, Engineering, Medicine, et al. Enhancing the resilience of the nation's electricity system. National Academies Press. 2017.
7. Jones KF, Mulherin ND. An evaluation of the severity of the January 1998 ice storm in northern New England. Hanover NH: Cold Regions Research and Engineering Lab; 1998.
8. Anderson CW, Santos JR, Haimes YY. A risk-based input–output methodology for measuring the effects of the August 2003 northeast blackout. Econ Syst Res. 2007;19(2):183–204.
9. Shittu E, Parker G, Mock N. Improving communication resilience for effective disaster relief operations. Environ Syst Dec. 2018;38(3):379–397.
10. Tompson T, Benz J, Agiesta J, Cagney K, Meit M. Resilience in the wake of Superstorm. Sandy Associated Press-NORC Center for Public Affairs Research. 2013.
11. Barra P, Coury D, Fernandes R. A survey on adaptive protection of microgrids and distribution systems with distributed generators. Renew Sustain Energy Rev. 2020;118:109524.
12. Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010;84(2):523–538.
13. QSR. QSR NVivo (Version 12) International Pty Ltd. Https://tinyurl.com/sr2vnds. 2018.

14. Edhlund B, McDougall A. NVIVO 12 essentials. Lulu. com. 2019.
15. Cramton P. Electricity market design. Oxford Review of Economic Policy. 33(4). 2017.
16. Lin Y, Bie Z. Study on the resilience of the integrated energy system. Energy Procedia. 2016;103:171–176.
17.• Yan M, He Y, Shahidehpour M, Ai X, Li Z, Wen J. Coordinated regional-district operation of integrated energy systems for resilience enhancement in natural disasters. IEEE Trans Smart Grid. 2018;10(5):4881–4892. **This paper proposes a coordinated operation of energy units to enhance resilience in extreme conditions by modeling random outages caused by disasters to interdependent systems**.
18.• Mehrdad S, Mousavian S, Madraki G, Dvorkin Y. Cyber-physical resilience of electrical power systems against malicious attacks: A review. Current Sustainable/Renewable Energy Reports. 2018;5(1):14–22. **This paper examines the research on cyber-physical security of electrical power systems with emphasis on the strengths and weaknesses of electrical systems against malicious attacks; used as current paper's template**.
19. Dvorkin Y, Garg S. IoT-enabled distributed cyber-attacks on transmission and distribution grids. In: 2017 North American Power Symposium (NAPS). IEEE. p 1–6; 2017.
20. Baggott SS, Santos JR. A risk analysis framework for cyber security and critical infrastructure protection of the US electric power grid. Risk Anal. 2020;40(9):1744–1761.
21. Mieth R, Acharya S, Hassan A, Dvorkin Y. Learning-enabled residential demand response: Automation and security of cyberphysical demand response systems. IEEE Electrif Magaz. 2021;9(1):36–44.
22. Ratnam EL, Baldwin KG, Mancarella P, Howden M, Seebeck L. Electricity system resilience in a world of increased climate change and cybersecurity risk; 2020. p. 106833.
23. Acharya S, Dvorkin Y, Karri R. Public plug-in electric vehicles+ grid data: Is a new cyberattack vector viable? IEEE Trans Smart Grid. 2020;11(6):5099–5113.
24. Acharya S, Mieth R, Konstantinou C, Karri R, Dvorkin Y. Cyber Insurance Against Cyberattacks on Electric Vehicle Charging Stations. arXiv:210703954. 2021.
25. Nguyen T, Wang S, Alhazmi M, Nazemi M, Estebsari A, Dehghanian P. Electric power grid resilience to cyber adversaries: State of the art. IEEE Access. 2020;8:87592–87608.
26. Molyneaux L, Wagner L, Froome C, Foster J. Resilience and electricity systems: A comparative analysis. Energy Policy. 2012;47:188–201.
27. de Menezes LM, Houllier MA. Reassessing the integration of European electricity markets: A fractional cointegration analysis. Energy Econ. 2016;53:132–150.
28.•• Bublitz A, Keles D, Zimmermann F, Fraunholz C, Fichtner W. A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms. Energy Econ. 2019;80:1059–1078. **This paper presents findings in the literature based on economic implications of growing renewables in electricity markets and offers shortcomings in existing research with questions to be addressed**.
29. Brown MA, Soni A. Expert perceptions of enhancing grid resilience with electric vehicles in the United States. Energy Res Social Sci. 2019;57:101241.
30. Shittu E, Kamdem BG, Weigelt C. Heterogeneities in energy technological learning: Evidence from the U.S. electricity industry. Energy Policy. 2019;132:1034–1049.
31. Birge JR, Hortaçsu A, Pavlin JM. Inverse optimization for the recovery of market structure from market outcomes: An application to the MISO electricity market. Operations Res. 2017;65(4):837–855.
32. Bale CS, Varga L, Foxon TJ. Energy: complexity New ways forward. Appl Energy. 2015;138:150–159.
33. Coelho VN, Cohen MW, Coelho IM, Liu N, Guimaraes FG. Multi-agent systems applied for energy systems integration: State-of-the-art applications and trends in microgrids. Appl Energy. 2017;187:820–832.
34. Khorasany M, Mishra Y, Ledwich G. A decentralized bilateral energy trading system for peer-to-peer electricity markets. IEEE Trans Ind Electron. 2019;67(6):4646–4657.
35. Pinson P, Baroche T, Moret F, Sousa T, Sorin E, You S. The emergence of consumer-centric electricity markets. Distrib Utiliz. 2017;34(12):27–31.
36. Barna SM, Deason JP, Shittu E. Solar energy prosumer decision-making: Developing a simulation framework for enabling cognitive learning in energy management. In: IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE). p 61A–66A; 2020.
37. Kang J, Yu R, Huang X, Maharjan S, Zhang Y, Hossain E. Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains. IEEE Trans Ind Inform. 2017;13(6):3154–3164.
38. Luo F, Dong ZY, Liang G, Murata J, Xu Z. A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain. IEEE Trans Power Syst. 2018;34(5):4097–4108.
39. Baker T, Shittu E, Greenwood S. Valuing the capacity contribution of renewable energy systems with storage. IISE transactions. 2020.
40. Arbabzadeh M, Sioshansi R, Johnson JX, Keoleian GA. The role of energy storage in deep decarbonization of electricity production. Nature Commun. 2019;10(1):1–11.
41. Nazemi M, Moeini-Aghtaie M, Fotuhi-Firuzabad M, Dehghanian P. Energy storage planning for enhanced resilience of power distribution networks against earthquakes. IEEE Trans Sustain Energy. 2019;11(2):795–806.
42. Munoz FD, Wogrin S, Oren SS, Hobbs BF. Economic inefficiencies of cost-based electricity market designs. The Energy Journal 39(3) 51–68. 2018.
43. Parag Y, Sovacool BK. Electricity market design for prosumer era. Nat Energy. 2016;1(4):1–6.
44. Le Cadre H, Jacquot P, Wan C, Alasseur C. Peer-to-peer electricity market analysis: From variational to generalized nash equilibrium. European J Operat Res. 2020;282(2):753–771.
45. Wilkinson S, Hojckova K, Eon C, Morrison GM, Sandén B. Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. Energy Res Social Sci. 2020;101500:66.
46. Kim J, Dvorkin Y. A P2P-dominant distribution system architecture. IEEE Trans Power Syst. 2019;35(4):2716–2725.
47. Rao BH, Arun SL, Selvan MP. Framework of locality electricity trading system for profitable peer-to-peer power transaction in locality electricity market. IET Smart Grid. 2020;3(3):318–330.
48. Newbery D, Strbac G, Viehoff I. The benefits of integrating European electricity markets. Energy Policy. 2016;94:253–263.

49. Clarion Energy Content Directors. DOE head Granholm warns cyber criminals could shut down U.S. power grid. Power Engineering. Shorturl.at/ijCP3. 2021.
50. Jesse BJ, Heinrichs HU, Kuckshinrichs W. Adapting the theory of resilience to energy systems: a review and outlook. Energy Sustain Soc. 2019;9(1):1–19.
51. Nazemi M, Dehghanian P. Seismic-resilient bulk power grids: Hazard characterization, modeling, and mitigation. IEEE Trans Eng Manag. 2019;67(3):614–630.
52. Yang Z, Dehghanian P, Nazemi M. Seismic-resilient electric power distribution systems: Harnessing the mobility of power sources. IEEE Trans Ind Appl. 2020;56(3):2304–2313.
53. Vine D, Attanasio D, Shittu E. Microgrid momentum: Building efficient, resilient power. Center for Climate and Energy Solutions. 2017.
54. Gholami A, Shekari T, Aminifar F, Shahidehpour M. Microgrid scheduling with uncertainty: The quest for resilience. IEEE Trans Smart Grid. 2016;7(6):2849–2858.
55. Mousavizadeh S, Haghifam MR, Shariatkhah MH. A linear two-stage method for resiliency analysis in distribution systems considering renewable energy and demand response resources. Appl Energy. 2018;211:443–460.
56. Dehghanian P, Zhang B, Dokic T, Kezunovic M. Predictive risk analytics for weather-resilient operation of electric power systems. IEEE Trans Sustain Energy. 2018;10(1):3–15.
57. Dehghanian P, Aslan S, Dehghanian P. Maintaining electric system safety through an enhanced network resilience. IEEE Trans Ind Appl. 2018;54(5):4927–4937.
58. Bao M, Ding Y, Sang M, Li D, Shao C, Yan J. Modeling and evaluating nodal resilience of multi-energy systems under windstorms. Appl Energy. 2020;115136:270.
59. Yamangil E, Bent R, Backhaus S. Resilient upgrade of electrical distribution grids. In: Proc. of the AAAI Confab on Artificial Intelligence; 2015.
60. Fu G, Wilkinson S, Dawson RJ, Fowler HJ, Kilsby C, Panteli M, et al. Integrated approach to assess the resilience of future electricity infrastructure networks to climate hazards. IEEE Syst J. 2017;12(4):3169–3180.
61. Chinmoy L, Iniyan S, Goic R. Modeling wind power investments, policies and social benefits for deregulated electricity market–A review. Appl Energy. 2019;242:364–377.
62. Hussain A, Bui VH, Kim HM. Resilience-oriented optimal operation of networked hybrid microgrids. IEEE Trans Smart Grid. 2017;10(1):204–215.
63. Gasser P, Lustenberger P, Cinelli M, Kim W, Spada M, Burgherr P, et al. A review on resilience assessment of energy systems. Sustainable and Resilient Infrastructure 1–27. 2019.
64. Liévanos RS, Horne C. Unequal resilience: The duration of electricity outages. Energy Policy. 2017;108:201–211.
65. Gößling-Reisemann S. Resilience–preparing energy systems for the unexpected. An edited collection of authored pieces comparing, contrasting, and integrating risk and resilience with an emphasis on ways to measure resilience 73. 2016.
66. Pourahmadi F, Hosseini SH, Dehghanian P, Shittu E, Fotuhi-Firuzabad M. Uncertainty cost of stochastic producers: Metrics and impacts on power grid flexibility. IEEE Transactions on Engineering Management. 2020.
67. Goto M, Sueyoshi T. Electric power market reform in Japan after Fukushima Daiichi nuclear plant disaster. Int'l Journal of Energy Sector Management. 2015.
68. Esteban M, Portugal-Pereira J. Post-disaster resilience of a 100% renewable energy system in Japan. Energy. 2014;68:756–764.
69. Santos J, Yip C, Thekdi S, Pagsuyoin S. Workforce/population, economy, infrastructure, geography, hierarchy, and time (WEIGHT): reflections on the plural dimensions of disaster resilience. Risk Anal. 2020;40(1):43–67.
70. Gilbert AQ, Bazilian MD. Can distributed nuclear power address energy resilience and energy poverty? Joule. 2020;4(9):1839–1843.
71. Pagliaro M. Renewable energy systems: Enhanced resilience, lower costs. Energy Technol. 2019;7(11):1900791.
72. Stephens JC. Assessing resilience in energy system change through an energy democracy lens. Edward Elgar Publishing. 2019.
73. Totschnig G, Hirner R, Müller A, Kranzl L, Hummel M, Nachtnebel HP, et al. Climate change impact and resilience in the electricity sector: the example of Austria and Germany. Energy Policy. 2017;103:238–248.
74. Newell B, Marsh DM, Sharma D. Enhancing the resilience of the Australian national electricity market: Taking a systems approach in policy development. Ecology and Society. 16(2):1–22. 2011.
75. Zhou Y, Panteli M, Moreno R, Mancarella P. System-level assessment of reliability and resilience provision from microgrids. Appl Energy. 2018;230:374–392.
76. Wang Y, Huang L, Shahidehpour M, Lai LL, Yuan H, Xu FY. Resilience-constrained hourly unit commitment in electricity grids. IEEE Trans Power Syst. 2018;33(5):5604–5614.
77. Tanaka M, Chen Y. Market power in renewable portfolio standards. Energy Econ. 2013;39:187–196.
78. Siddiqui AS, Tanaka M, Chen Y. Are targets for renewable portfolio standards too low? The impact of market structure on energy policy. Eur J Oper Res. 2016;250(1):328–341.
79. DeLuque I, Shittu E. Generation capacity expansion under demand, capacity factor and environmental policy uncertainties. Comput Ind Eng. 2019;127:601–613.
80. Deluque I, Shittu E, Deason J. Evaluating the reliability of efficient energy technology portfolios. EURO J Decis Process. 2018;6(1-2):115–138.
81. Eriksson M, Armendariz M, Vasilenko OO, Saleem A, Nordström L. Multiagent-based distribution automation solution for self-healing grids. IEEE Trans Ind Electron. 2014;62(4):2620–2628.
82. Shirazi E, Jadid S. Autonomous self-healing in smart distribution grids using agent systems. IEEE Trans Ind Inform. 2018;15(12):6291–6301.
83. Zadsar M, Haghifam M, Larimi S. Approach for self-healing resilient operation of active distribution network with microgrid. IET Gener Trans Distrib. 2017;11(18):4633–4643.
84. Lin H, Chen C, Wang J, Qi J, Jin D, Kalbarczyk ZT, et al. Self-healing attack-resilient PMU network for power system operation. IEEE Trans Smart Grid. 2016;9(3):1551–1565.
85. Mousavian S, Valenzuela J, Wang J. A probabilistic risk mitigation model for cyber-attacks to PMU networks. IEEE Trans Power Syst. 2014;30(1):156–165.
86. Jiao Z, Wang X, Gong H. Wide area measurement/wide area information-based control strategy to fast relieve overloads in a self-healing power grid. IET Gener Trans Distrib. 2014;8(6):1168–1176.
87. Quattrociocchi W, Caldarelli G, Scala A. Self-healing networks: redundancy and structure. PloS one. 2014;9(2):e87986.
88. Motter AE, Myers SA, Anghel M, Nishikawa T. Spontaneous synchrony in power-grid networks. Nat Phys. 2013;9(3):191–197.

89. Golshani A, Sun W, Zhou Q, Zheng QP, Tong J. Two-stage adaptive restoration decision support system for a self-healing power grid. IEEE Trans Ind Inform. 2017;13(6):2802–2812.
90. Molyneaux L, Brown C, Wagner L, Foster J. Measuring resilience in energy systems: Insights from a range of disciplines. Renew Sustain Energy Rev. 2016;59:1068–1079.
91. Wang Z, Chen B, Wang J, Chen C. Networked microgrids for self-healing power systems. IEEE Trans Smart Grid. 2015;7(1):310–319.
92. Shittu E, Tibrewala A, Kalla S, Wang X. Meta-Analysis of the Strategies for Self-healing and Resilience in Power Systems. Advances in Applied Energy. 100036. 2021.
93. Huang H, Panyam V, Narimani MR, Layton A, Davis KR. Mixed-integer optimization for bio-inspired robust power network design. arXiv:201016033. 2020.
94. Panyam V, Huang H, Davis K, Layton A. Bio-inspired design for robust power grid networks. Appl Energy. 2019;113349:251.
95. Dehghanpour K, Colson C, Nehrir H. A survey on smart agent-based microgrids for resilient/self-healing grids. Energies. 2017;10(5):620.
96. Chatterjee A, Layton A. Mimicking nature for resilient resource and infrastructure network design. Reliab Eng Syst Safety. 2020;204:107142.
97. Leite JB, Mantovani JRS. Development of a self-healing strategy with multiagent systems for distribution networks. IEEE Trans Smart Grid. 2016;8(5):2198–2206.
98. Faheem M, Butt RA, Raza B, Ashraf MW, Begum S, Ngadi MA, et al. Bio-inspired routing protocol for WSN-based smart grid applications in the context of Industry 4.0. Trans Emerg Telecommun Technol. 2019;30(8):e3503.
99. Santos JR. Inoperability input-output modeling of disruptions to interdependent economic systems. Syst Eng. 2006;9(1):20–34.
100. Vazinram F, Hedayati M, Effatnejad R, Hajihosseini P. Self-healing model for gas-electricity distribution network with consideration of various types of generation units and demand response capability. Energy Convers Manag. 2020;206:112487.
101. He C, Zhang X, Liu T, Wu L, Shahidehpour M. Coordination of interdependent electricity grid and natural gas network—a review. Current Sustain Renew Energy Rep. 2018;5(1):23–36.
102. Duggan JE. Capacity market mechanism analyses: a literature review. Current Sustain Renew Energy Rep 1–7. 2020.
103. Khalili T, Hagh MT, Zadeh SG, Maleki S. Optimal reliable and resilient construction of dynamic self-adequate multi-microgrids under large-scale events. IET Renew Power Gener. 2019;13(10):1750–1760.
104. Fang YP, Zio E. An adaptive robust framework for the optimization of the resilience of interdependent infrastructures under natural hazards. European J Oper Res. 2019;276(3):1119–1136.
105. Schubert ES, Hurlbut D, Adib P, Oren S. The Texas energy-only resource adequacy mechanism. Electric J. 2006;19(10):39–49.
106. Hogan W, et al. Electricity scarcity pricing through operating reserves: An ERCOT window of opportunity. Harvard University Cambridge (MA). 2012.
107. Bowring J. Capacity markets in PJM. Econ Energy Environ Policy. 2013;2(2):47–64.
108. Pfeifenberger J, Spees K, Schumacher A. A comparison of PJM's RPM with alternative energy and capacity market designs. Prepared for PJM Interconnection, Inc September. 2009.
109.•• Conejo AJ, Sioshansi R. Rethinking restructured electricity market design: Lessons learned and future needs. Int J Electr Power Energy Syst. 2018;98:520–530. **This paper discusses the lessons learned from market designs and suggests key reforms in electricity market designs**.
110. Zamuda CD, Larsen PH, Collins MT, Bieler S, Schellenberg J, Hees S. Monetization methods for evaluating investments in electricity system resilience to extreme weather and climate change. Electr J. 2019;32(9):106641.
111. Shang DR. Pricing of emergency dynamic microgrid power service for distribution resilience enhancement. Energy Policy. 2017;111:321–335.
112. Batas-Bjelic I, Rajakovic N, Duic N. Smart municipal energy grid within electricity market. Energy. 2017;137:1277–1285.
113. Hogan WW. Virtual bidding and electric. market design. Electr J. 2016;29(5):33–47.
114. Cochran J, Miller M, Milligan M, Ela E, Arent D, Bloom A, et al. Market evolution: Wholesale electricity market design for 21st century power systems. NREL, Golden, CO U.S. 2013.
115. Hu J, Harmsen R, Crijns-Graus W, Worrell E, van den Broek M. Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. Renew Sustain Energy Rev. 2018;81:2181–2195.
116. Peng D, Poudineh R. Electricity market design under increasing renewable energy penetration: Misalignments observed in the European Union. Util Policy. 2019;61:100970.
117. Peng D, Poudineh R. Electricity market design for a decarbonised future: An integrated approach. Oxford Institute for Energy Studies. 2017.
118. Yin S, Wang J, Qiu F. Decentralized electricity market with transactive energy–a path forward. Electr J. 2019;32(4):7–13.
119. Jiang X, Parker G, Shittu E. Envelope modeling of renewable resource variability and capacity. Comput Oper Res. 2016;66:272–283.