21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

An Economic Evaluation Framework for Sustainable Community Microgrids

A. ARAB, A. KHODAEI
University of Denver
USA

SUMMARY

An economic viability assessment framework for capital projects on sustainable community microgrids is proposed in this paper. A set of evaluation considerations with a common performance metric, i.e., the monetary value of each area of concern, is introduced to facilitate an efficient economic assessment of these capital projects. The evaluation considerations include reliability, resiliency, carbon emission cost, recurring system upgrade cost, energy efficiency, power quality, and generation cost. Among established engineering economics models, the benefit-cost ratio (BCR) method is shown to be a more advantageous approach to analyzing the economic viability of sustainable community microgrid projects.

KEYWORDS

Capital projects, distributed energy resources (DERs), engineering economics, sustainable microgrids.

ali.arab@du.edu

1. INTRODUCTION

Microgrids, as enablers of distributed generation, improved grid performance, and the green energy economy, have been deployed on a large scale over the past decade [1] and are expected to continue their growth for the foreseeable future [2]. A significant amount of research has been devoted to study microgrids and to facilitate their development and implementation efforts [3]. The number of published articles in recent years focused on microgrids has increased by multiple folds and microgrid deployments have been federally supported in the United States, where it has been playing a major role in advancing the nation's energy system [4]. As of May of 2021, there have been over 460 operational microgrids in the United States that provide a total of 3.1 gigawatts of reliable electricity [5]. The global microgrid market size is estimated to grow from USD 24.6 billion in 2021 to USD 42.3 billion by 2026 at a compound annual growth rate (CAGR) of 11.4% during this period [8]. The expected growth is primarily driven by the decarbonization trend, demand for higher grid resilience, and electrification economics in rural and remote areas.

A wide range of applications has been identified for microgrids. The very first modern microgrids were deployed in university campuses, primarily due to the availability of funding for research initiatives and internal expertise in science and engineering [6,7]. Microgrid deployment has become an increasingly attractive solution for commercial and industrial consumers who require premium reliability and power quality levels and are interested in realizing cost savings and economic benefits from strategic dispatching of their DERs. An example includes prosumers who want to take advantage of available incentives and utilize idle capacity from backup generation to export power to the grid. Moreover, there is a growing number of microgrid deployments in remote locations, as they can be a more efficient, viable alternative for providing electricity services than other solutions such as upgrading or building new transmission and distribution (T&D) infrastructure. For instance, microgrids can be operated in *interconnected* mode to provide peak shaving and defer capacity investments that otherwise would be needed in remote areas, or they can be operated in *islanded* mode to supply electricity to isolated areas. The latter approach has been used extensively to provide service to remote rural areas, traditionally via conventional generation (e.g., reciprocating engines, small hydro generation, etc.), and more recently via combined dispatch of conventional and renewable DERs. Military microgrids have also received significant traction in recent years, primarily due to support provided by the U.S. Department of Defense. Military microgrids consist of self-sustaining small power grids which are required to address the mission-critical energy needs of military bases.

More recently, *sustainable community microgrids* have emerged as an alternative to address the rising societal demands for sustainable electric infrastructure that is capable of providing high level of reliability and power quality for communities while being economically viable and environmental-friendly. Sustainable community microgrids aim primarily at supplying electricity from renewable resources for a group of consumers in a neighborhood or several connected neighborhoods in close proximity. Despite extensive studies on sustainable microgrids, little literature is dedicated to their engineering economics. This paper discusses sustainable microgrids and elaborates on different components and anticipated outcomes of these viable deployments. Sustainable community microgrids are emerging as a potential solution to address the following trends: 1) residential consumers, who use more than one third of the electric energy produced in the United States [6], are demanding higher levels of reliability and power quality, 2) utility grids are experiencing an unprecedented proliferation of intermittent renewable DERs, which is motivated by the availability of attractive incentives and regulations designed to address socioeconomic and environmental concerns, 3) the commercial and industrial consumers' needs to high reliability and quality premium power is growing due to their dependence on sensitive loads, and 4) the society is demanding more resilient power delivery infrastructure due to the growing dependence on electric service for vital activities such as transportation, e.g., proliferation of Electric Vehicles (EVs), and the well-documented grid vulnerability issues exposed in recent natural disasters.

The transition from the conventional utility grid to integration with sustainable community microgrids and the enhanced utilization of DERs and controllable loads are anticipated to extensively change the way communities use electricity by increasing energy efficiency, enhancing conservation levels, and lowering greenhouse gas emissions, while lowering the stress level on congested transmission and distribution lines. Several obstacles, however, exist in a rapid and widespread deployment of sustainable microgrids, as follows: 1) high capital expenditure requirement for microgrid deployment, 2) lack of consumer knowledge on potential impacts of DERs and load scheduling strategies, and particularly 3) ownership and governance structure and regulatory issues.

This paper intends to provide a decision-making framework for economic viability analysis of sustainable microgrid projects. The rest of the paper is organized as follows. Section 2 provides a brief start of the art review. Section 3 describes the proposed framework for assessment of the economic viability of sustainable community microgrids. The paper is concluded in Section 4.

2. STATE OF THE ART

There is extensive research work on short-term microgrid operations [9]-[20]; however, few papers have studied the long-term microgrid economics and offered proper models for microgrid operations for long-term planning horizon. In [21] an operational and planning case study of a hybrid system is carried out to find the best combination of renewable and conventional resources in a microgrid. It identifies the need to account for various combinations of microgrid components to evaluate the optimal operating configurations using advanced planning technologies. In [22] the best location of renewable energy resources within the microgrid is identified using a probabilistic load flow model. In [23] an optimization model for microgrid power generation expansion planning considering lower carbon economy is proposed. An improved matrix real-coded genetic algorithm is employed to solve the planning problem. The results show that clean energy resources, such as solar and wind, are effective to achieve the targets for CO2 emission reduction that should be advocated and applied more broadly, especially in microgrids. In [24] design, management, and planning of a hydrogen-based microgrid is presented. Experiments are performed on a testbed; however, the long-term planning economics were not taken into account. A model that investigates the planning of microgrids along with traditional power system expansion planning is proposed in [25]. In [25] the economic and reliability benefits of a microgrid from a system operator's perspective is examined and the interactions of microgrid installations with main grid generation and transmission expansion in a long-term horizon are studied. The economic and reliability advantages of microgrid investments from the operator's perspective are exhibited through a microgrid-based co-optimization of the generation and transmission planning. A comprehensive review on the state of the art in research on microgrids can be found in [3]. Reference [3] highlights the relevant research work on distributed generation, microgrid value propositions, applications of power electronics, economics, operations, control, microgrid clusters, protection, and communication issues. A review on the impact of policy on the economics of microgrid projects can be found in [26].

3. ECONOMIC VIABILITY ASSESSMENT

Microgrid development is economically justified when the expected benefits of their deployment exceed the required capital expenditure. The microgrid benefits must be comprehensively evaluated and compared with the cost of capital to ensure a complete return on investment to economically justify a microgrid deployment capital project. An accurate assessment of microgrid economic benefits is a challenging task due to deep uncertainty involved in the data required for its assessment. Moreover, some of the assessment results such as reliability improvements are difficult to comprehend for consumers when represented in supply availability terms. Two well-established methods from engineering economics literature for economic evaluation of capital projects that can be applied to sustainable community microgrid investments include the net present value (NPV) and benefit-cost ratio (BCR) methods. Both methods are related to the concept of net cash flow, i.e., the algebraic sum of expected cash inflows and outflows over a given investment horizon (project's life) for a particular microgrid project. While NPV method generally provides a more straightforward approach to economically evaluate the projects, BCR method is more desirable for sustainable community microgrid projects. That is due to that fact that BCR methods would allow ranking of various investment alternatives which is often required when there is a constraint on allocation of resources in capital budgeting process. The basic form of BCR for a given microgrid project can be defined, as follows [27]:

$$B/C = \frac{\sum_{j=0}^{n} B_j (1+k)^{-j}}{\sum_{j=0}^{n} C_j (1+k)^{-j}} \tag{1}$$

where B_j is the microgrid project benefits in year j, C_j is project costs in year j, and k is the minimum acceptable rate of return (MARR) for the investment. In general, if project's rate of return is greater than MARR, the project is economically desirable. Thus, efficient planning models are required for ensuring the economic viability of microgrid deployments and further justifying investments based on cost-benefit analyses under conditions of uncertainty. These benefits, however, must be validated and benchmarked with the microgrid investment cost to ensure the required return on investment to justify their deployment.

The fundamental step in assessing economic viability of microgrid capital projects is to identify the cost and benefit value streams. The benefit value streams for a sustainable community microgrid project can incorporate a list of variables, as follows:

Reliability: One of the most important benefits of sustainable microgrids is to increase the power supply reliability. Electric utilities constantly monitor the reliability levels and perform required system upgrades to improve supply availability and to reach and maintain desired performance. Consumer reliability is typically evaluated in terms of system and customer average interruption frequency and/or duration (e.g., SAIFI, SAIDI, CAIFI, and CAIDI indices, among others). Outages due to storms, equipment failure, and other risk factors, impact reliability levels by increasing the average frequency and duration of interruptions. However, when a sustainable microgrid is deployed, these metrics can be significantly improved. This is due to the increased redundancy and intrinsic intelligence (control and automation systems) of sustainable community microgrids and the utilization of DERs that allow islanded operations from the grid. Since generation in sustainable community microgrids is located in close proximity to consumer loads, it is less prone to being affected by grid disturbances and infrastructure issues. Additional flexibility to provide service under these conditions is provided by the ability to adjust loads (e.g., demand response) via building and/or microgrid master controllers. Improved reliability can be translated into economic benefits for consumers and utility due to a reduction in interruptions costs and energy not supplied (ENS) considering value of lost load (VOLL). The reliability cost is the amount of ENS multiplied by VOLL during planning horizon. VOLL is an important measure in power utilities' microeconomics which represents the willingness of customers to pay for their electricity service to avoid curtailment. Valuation of VOLL, which is usually measured in dollars per MWh, can either be based on the marginal value of the next unit of interrupted electricity load or the average value of interrupted load. However, it varies depending on the type of usage and outage [28]. From economics point of view, the load interruption cost is considered as an opportunity cost. The magnitude of these benefits is depended upon load criticality and value of lost load, and also the availability of other alternatives such as backup generation or automatic load transfer trips.

Resiliency: Resiliency refers to the capability of the energy systems to withstand low-probability high-impact events by minimizing possible power outages and quickly returning to normal operating state with minimum cost. These events typically include extreme weather events and natural and manmade disasters, such as hurricanes, tornados, earthquakes, snow, floods, cyber and physical attacks, among others. Recent hurricanes in the United States as well as a documented attack on a California substation [29] and the potential significant social disruptions have spawned a great deal of discussion in the power and energy industry about the value and application of microgrids. If the power system is impacted by these events and critical components are severely damaged (e.g., generating facilities and/or transmission and distribution infrastructure), service may be disrupted for days or even weeks. The impact of these events on consumers could be mitigated by deployment of sustainable community microgrids which allow the local supply of loads even when the supply of power from the utility grid is not available. The increased resilience of the system can be economically quantified through various methods as part of microgrid project benefits and incorporated in BCR analysis.

Carbon emission reduction: Community microgrids could be accredited as rapid enablers of renewable energy integration to distribution networks. Renewable energy resources may cause significant technical challenges when integrated to a distribution network as they generate a variable supply of energy. Seamless integration of these resources may only be accomplished through the implementation of mitigation measures. Utilities may need to upgrade their distribution network, utilize advanced Volt-VAR control practices, smart inverters, or energy storage to address the rapid deployment of renewable energy resources. Sustainable community microgrids utilize the coordinated control of a combination of dispatchable DERs, DES, and controllable loads to "smooth down" the intermittent output of renewable energy resources. This allows increased penetration of renewable energy and diversification of resources, allows utilities to meet goals set by Renewable Portfolio Standards (RPS), and helps reduce greenhouse gas emissions to combat climate change. Through an in internal carbon pricing method, the monetary value of reduction in carbon emission can be calculated and incorporated in long-term economic viability assessment of sustainable community microgrid projects. That includes internal carbon fee, shadow carbon price, and implicit carbon price methods, among other approaches.

Reduced costs of recurring system upgrades: As the demand for electricity increases, today's power system must be reinforced by the addition of new generation, transmission, and distribution facilities. Sustainable community microgrids deploy DERs to supply local loads, including conventional and renewable DERs, and implement load control to facilitate local grid management. Therefore, while operating in interconnected mode the additional generating capacity from sustainable community microgrids decreases the average and peak system load, effectively deferring capacity increase or generation investments. This benefit, however, is contingent upon a large penetration of microgrids in distribution networks which could accordingly contribute to mitigate congestion issues. Sustainable community microgrids can also provide utilities with additional operational flexibility (increased reserve) to handle load transfers during restoration or system reconfiguration. These aspects need to be evaluated when considering microgrid deployment as part of system expansion plans, along with investments in conventional transmission, distribution, and generation infrastructure.

Energy efficiency: Sustainable community microgrids can help improve overall energy efficiency by reducing transmission and distribution losses and allowing the implementation of optimal load control and resource dispatch. The former is a direct consequence of supplying consumer loads with local generating facilities, and the latter can be accomplished by intelligent control and dispatch of consumer loads. For instance, the microgrid controller can interact with consumer controllers to curtail or dispatch loads to accomplish overall system efficiency goals. Similarly, this objective could be adjusted to respond to real-time price, operational security, power quality, or reliability signals. Evidently, this requires having the adequate regulatory framework and consumer incentives in place. FERC Order No. 2222 in the United States to a large extent has facilitated the regulatory requirements that enables higher energy efficiency by deployment of DERs through microgrids [30].

Power quality: Consumers' needs for higher power quality have significantly increased during past decade due to growing application of voltage sensitive loads, including a large number and variety of electronic loads and LEDs. Utilities are always seeking efficient ways of improving power quality issues by addressing prevailing concerns stemmed from harmonics and voltage. Sustainable community microgrids provide an efficient answer to address power quality needs by enabling local control of frequency, voltage, load, and the rapid response from DES. The financial incentives set by system operators to assure power quality should be incorporated in analysis of economic viability of sustainable microgrids.

Lowered energy costs: Financial incentives offered to consumers within a sustainable community microgrid, who would consider load scheduling strategies according to electricity prices and benefit from locally generated power, is a significant driver in the economic deployment of microgrids. Although it can still be more economical to purchase power from the utilities due to their economies of scale, microgrids can provide benefits by reducing transmission and distribution costs. The lowered energy costs impact each individual consumer within the sustainable community microgrid ecosystem. However, the microgrid local generation not only has the potential to lower energy costs for local consumers (which will be more significant as DER technologies become less expensive), but it could potentially benefit the entire system by reducing the transmission and distribution network congestion levels (when the community microgrids penetration is high) and enabling a more economic dispatch of available energy resources in the utility grid.

On the other hand, the project cost stream for a sustainable community microgrid project should include the required initial capital expenditure (CapEx) to implement the project, the expected cost of operations and maintenance (O&M) during the lifecycle of the project, and the final disposal cost of the microgrid at the end of its lifecycle. Figure 1 the proposed framework for economic viability assessment and ranking of sustainable community microgrid capital projects.

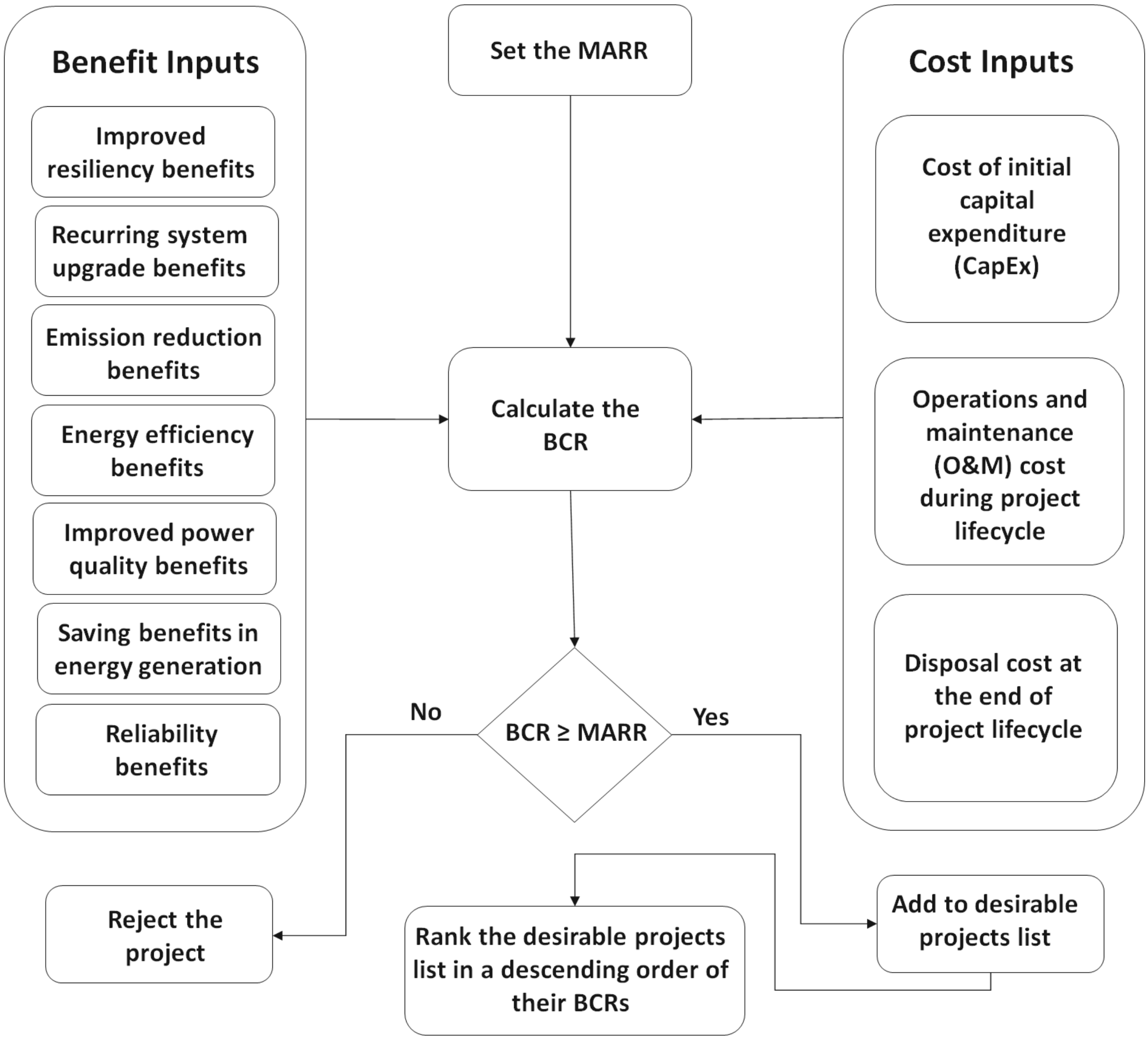

Figure 1. The proposed economic evaluation framework for sustainable community microgrids

4. CONCLUSIONS

A framework was proposed to assess the economic viability of sustainable community microgrids. Benefit-cost ratio model was proposed to be used as a preferred model due to its ability to rank various investment alternatives. A set of relevant evaluation considerations to be used as an input to BCR model were discussed. The proposed framework intends to simplify the economic assessment of capital projects for microgrid deployment considering financial restrictions.

BIBLIOGRAPHY

[1] M. Shahidehpour and J. Clair, “A functional microgrid for enhancing reliability, sustainability, and energy efficiency,” *Electricity Journal*, Oct. 2012.

[2] S. Pandey, J. Han, N. Gurung, H. Chen, E.A. Paaso, Z. Li, and A. Khodaei, “Multi-Criteria Decision-Making and Robust Optimization Methodology for Generator Sizing of a Microgrid,” *IEEE Access*, vol. 9, pp. 142264-142275, 2021.

[3] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, “State of the art in research on microgrids: A review,” *IEEE Access*, vol. 3, pp. 890-925, 2015.

[4] The Role of Microgrids in Helping to Advance the Nation’s Energy System, May 2022 [Online]. Available: https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/role-microgrids-helping.

[5] The Microgrid Installation Database , May 2021 [Online]. https://doe.icfwebservices.com/microgrid

[6] Business Wire, $42.3 Bn Microgrid Markets by Connectivity, Offering, End Use, Pattern, Type - Global Forecast to 2026, May 2021 [Online]. Available: http://www.ResearchAndMarkets.com

[7] IIT Microgrid, Available [Online:] http://www.iitmicrogrid.net/microgrid.aspx

[8] E. Krapels, “Microgrid development: Good for society and utilities,” *IEEE Power and Energy Mag.*, vol. 11, no .4, pp. 96-94, 2013.

[9] C. Marnay, F. Rubio, and A. Siddiqui, “Shape of the microgrid,” *IEEE Power Eng. Soc. Winter Meeting*, vol. 1, pp. 150–153, 2001.

[10] A. Meliopoulos, “Challenges in simulation and design of μgrids,” IEEE Power Eng. Soc. Winter Meeting, vol. 1, pp. 309–314, 2002.

[11] R. Lasseter, “Microgrids,” *IEEE Power Eng. Soc. Winter Meeting*, vol. 1, pp. 305–308, 2002.

[12] Y. Li, D. Vilathgamuwa, and P. Loh, “Design, analysis, and real-time testing of a controller for multibus microgrid system,” *IEEE Trans. Power Elect.*, vol. 19, no. 5, pp. 1195–1204, 2004.

[13] A. Khodaei, “Microgrid optimal scheduling with multi-period islanding constraints,” *IEEE Trans. Power Syst.*, vol. 29, no. 3, 1383-1392 , 2013.

[14] C. Hernandez-Aramburo, T. Green, and N. Mugniot, “Fuel consumption minimization of a microgrid,” *IEEE Trans. Ind. App.*, vol. 41, no. 3, pp. 673–681, 2005.

[15] A. Dimeas and N. Hatziargyriou, “Operation of a multiagent system for microgrid control,” *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, 2005.

[16] S. Patra, J. Mitra, and S. Ranade, “Microgrid architecture: a reliability constrained approach*,” IEEE Power Eng. Soc. General Meeting*, pp. 2372–2377, 2005.

[17] F. Katiraei and M. Iravani, “Power management strategies for a microgrid with multiple distributed generation units,” *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1821–1831, 2006.

[18] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. Green, “Energy management in autonomous microgrid using stability constrained droop control of inverters,” *IEEE Trans. Power Elect.*, vol. 23, no. 5, pp. 2346–2352, 2008.

[19] I. Maity and S. Rao, “Simulation and pricing mechanism analysis of a solar powered electrical microgrid,” IEEE Syst. Journal, vol. 4, no. 3, pp. 275–284, 2010.

[20] I. Bae and J. Kim, “Reliability evaluation of customers in a microgrid,” *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1416–1422, 2008.

[21] W. Su, Z. Yuan, and M. Y. Chow, “Microgrid planning and operation: Solar energy and wind energy,” *IEEE Power Energy Soc. Gen. Meeting*, 2010.

[22] O. A. Oke, D. W. P. Thomas, “Probabilistic load flow in microgrid assessment and planning studies,” *IEEE Elect. Power Energy Conf.*, 2012.

[23] X. Yang, W. Tian, “Microgrid's generation expansion planning considering lower carbon economy,” *Power Energy Eng. Conf.*, 2012.

[24] L. Valverde, F. Rosa, C. Bordons, “Design, planning and management of a hydrogen-based microgrid,” *IEEE Trans. Ind. Inf.*, vol. 9, no. 3, pp. 1398-1404, 2013.

[25] A. Khodaei, M. Shahidehpour, “Microgrid-based co-optimization of generation and transmission planning in power systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1582-1590, 2013.

[26] K. Milis, H. Peremans, and S. Van Passel, “The impact of policy on microgrid economics: A review,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp.3111-3119, 2018.

[27] G.T. Stevens, The economic analysis of capital expenditures for managers and engineers. Simon & Schuster Custom Pub., 1994.

[28] *Estimating the Value of Lost Load*, London Econ. Int. LLC, Boston, MA, USA, 2013.

[29] R. Smith, US risks national blackout from small-scale attack. *Wall Street Journal*, 12, 2014.

[30] E.D. Cartwright, FERC order 2222 gives boost to DERs. *Climate and Energy*, 37(5), 22-22, 2020.