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Krzysztof Waśniewski

PhD, Andrzej Frycz Modrzewski Krakow University
https://orcid.org/0000-0003-0076-4804

The management of distributed energy resources for national security

Introduction

Today, just as it used to be in the past, innovation and technological change are key issues for national security.[1] As a civilization, we seem to be experiencing, right now, an episode of technological breakthrough and social discontinuity. New technologies become new targets, new weapons, and new fields of vulnerability, which is reflected, among others, in the concept of systemic war.[2]

National energy systems can be targets and are vulnerable. When the critical infrastructure of energy systems is under imminent threat of systemic failure due to the projection of military force, managing energy security means finding ways of assuring maximum resilience. Different spatial distributions of power-generating and energy-storing facilities are conducive to different exposures of the national energy system to exogenous risks such as war. That kept in mind, technological advancements as regards energy resources have been creating new areas of international conflict since at least 2014; e.g. new geotechnologies bring the discovery of new offshore oil and gas fields, which, in turn, brings new international tensions as regards the actual control over those reserves.[3]

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[1] V. Levchenko, A. Boiko, T. Savchenko *et al.*, "State regulation of the economic security by applying the innovative approach to its assessment", *Marketing and Management of Innovations*, vol. 10, no. 4, 2019, pp. 364–372.

[2] E.A. Colby, *The Strategy of Denial: American Defense in An Age of Great Power Conflict*, New Haven: Yale University Press, 2021, pp. 23–26.

[3] R. Dannreuther, *Energy security*, Hoboken, NJ: John Wiley & Sons, 2017, pp. 101–122; N. Mazzucchi, *Énergie: Ressources, Technologies et Enjeux de Pouvoir*, Paris: Armand Colin, 2017, pp. 55–134.

Assuring energy security is one of the most basic missions of national governments.[4] Still, it remains the weak spot of most countries. Less than 25% of countries on the planet have national energy systems endowed with high resilience to exogenous shocks and change in that domain is slow because of significant hysteresis.[5] Distributed energy resources (DER) are one of the ways to make the national energy system more resilient. Small power installations distributed across local communities, are unlikely to be all incapacitated at the same moment, whilst one big power plant can be shut down at once, e.g. by an adversary attack.[6]

The purpose of this article is to pass in review the principal angles of scientific approach to the deployment of DER, and therefore to assess the way that scientific research is being done on that topic. Review of literature and meta-analysis are the main conceptual tools used. The expected outcome of that analysis is to define fields, which either require further research or raise doubts as for the practical utility of the research done so far.

The technological state of the art in distributed energy resources

All the essential technologies for DER seem to be available and tested at the industrial scale. DER systems prove to be workable solutions in very different conditions of physical geography.[7] Technological progress goes even as far as allowing self-charging in local power installations by harvesting surpluses of energy.[8] DER systems are complex technologies. Two basic models can be distinguished in literature as for modelling that complexity: the remote island and the virtual power plant. The model of remote island[9] studies DER systems in hypothetical situations, when country-wide disruptions in power supply turn specific areas into de-facto islands, i.e. places either completely cut from external supplies or exposed to severe uncertainty in that respect, both isolation and uncertainty determined essentially by exogenous factors. In such an island-like case, a power system is based on one

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[4] E. Bompard, A. Carpignano, M. Erriquez *et al.*, "National energy security assessment in a geopolitical perspective", *Energy*, vol. 130, 2017, pp. 144–154.

[5] Q. Wang, K. Zhou, "A framework for evaluating global national energy security", *Applied Energy*, vol. 188, 2017, pp. 19–31.

[6] P. Kivimaa, M.H. Sivonen, "Interplay between low-carbon energy transitions and national security: An analysis of policy integration and coherence in Estonia, Finland and Scotland", *Energy Research & Social Science*, vol. 75, 2021, 102024.

[7] N. McIlwaine, A.M. Foley, D.J. Morrow *et al.*, "A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems", *Energy*, vol. 229, 2021, 120461.

[8] X. Pu, Z.L. Wang, "Self-charging power system for distributed energy: Beyond the energy storage unit", *Chemical Science*, vol. 12, no. 1, 2021, pp. 34–49.

[9] L. Feng, X. Zhang, X. Li *et al.*, "Performance analysis of hybrid energy storage integrated with distributed renewable energy", *Energy Reports*, vol. 8, 2022, pp. 1829–1838.

or more microgrids. Distributed installations of renewable energy (mostly photovoltaic and wind) are combined with hybrid energy storage. The latter comprises lithium-ion batteries, super capacitors, and compressed air energy storage (CAES). Adding storage technologies other than just batteries seems to: a) lower the cost of energy for end-users b) improve stability in the system.

The model of virtual power plant (VPP) was brought forth in the late 1990s,[10] and takes a tangent opposite to that of the remote island paradigm: flexible, market-based cooperation between many independent agents with local installations of generation and storage can be studied as one big power plant with many component parts in it. Sikorski et al. demonstrate the working of the VPP framework in a network of 1 MW hydro-electric turbines, coupled with 0,5 MW battery-based energy storage.[11] An interesting finding of that study is that distributed energy systems can be a burden for larger power grids, as they generate rapid changes in voltage. Combining local generation of energy from renewable sources with the technologies of energy storage seems to use the best of both. Local energy storage allows curtailing the inherent volatility of supply in energy from renewable sources, whilst using renewable sources to charge those energy-storage devices solves the problem of secondary load put on a typical power grid when end users start storing energy.[12]

The economics of distributed energy resources

Apparently, distributed networks of energy resources can lead to solutions which are economically far from optimal; e.g., distributed energy storage facilities can destabilize the high-voltage power grid instead of stabilizing it, as individual owners of such installations start arbitering in the market of energy.[13] Market-based solutions, where intelligent devices installed at the level of individual installations, coordinate with each other using monetary value as the baseline semantics for communication, seem promising to optimize economic efficiency of distributed energy systems.[14]

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[10] *The Virtual Utility: Accounting, technology & competitive aspects of the emerging industry*, eds. S. Awerbuch, A. Preston, Boston, MA Springer, 1997.

[11] T. Sikorski, M. Jasiński, E. Ropuszyńska-Surma *et al.*, "A case study on distributed energy resources and energy-storage systems in a virtual power plant concept: Technical aspects", *Energies*, vol. 13, no. 12, 2020, 3086.

[12] W. Zheng, B. Zou, "Evaluation of intermittent-distributed-generation hosting capability of a distribution system with integrated energy-storage systems", *Global Energy Interconnection*, vol. 4, no. 4, 2021, pp. 415–424; C. Silva, P. Faria, A. Fernandes, Z. Vale, "Clustering distributed Energy Storage units for the aggregation of optimized local solar energy", *Energy Reports*, vol. 8, suppl. 3, 2022, pp. 405–410.

[13] B. Zakeri, G.C. Gissey, P.E. Dodds, D. Subkhankulova, "Centralized vs. distributed energy storage: Benefits for residential users", *Energy*, vol. 236, 2021, 121443.

[14] P. Hou, G. Yang, J. Hu *et al.*, "A distributed transactive energy mechanism for integrating PV and storage prosumers in market operation", *Engineering*, vol. 12, 2022, pp. 171–182.

Distributed systems of power installations can be studied as intelligent structures and therefore simulate their collective behaviour with artificial intelligence. There is substantial evidence that DER systems display intelligent learning with reinforcement, which, in turn, allows assuming the importance of market-based incentives in the deployment and current management of such systems.[15]

Intelligent collective learning is a valuable cognitive perspective for understanding the behaviour of DER systems, yet there remains the issue of their linear predictability. We need to predict accurately the aggregate need for investment in capacity of generation and storage. Xia et al.[16] argue that such a system becomes linearly predictable only in the presence of both the positive and the negative behavioural reinforcement: there needs to be a system of rewards for playing fair in the network, and punishments for opportunistic behaviour. On the other hand, Sidnell et al.[17] provide evidence that linear predictability of distributed energy systems is strongly sensitive to the catalogue of technologies on both the demand and the supply side of the local energy market, such as inter-house connections through pipes with hot water, or air conditioning in households. Somewhere between the approach based on intelligent collective learning and that referring to linear prediction one can find stochastic methods based on alternative scenarios. Those scenarios include both short-term flexibility and long-term uncertainty, for a given catalogue of technologies used in a distributed energy system, which allows using weak, non-deterministic assumptions and thus insulating the resulting predictions from the impact of false assumptions.[18] Interestingly, this methodology is consistent with much earlier ones, which makes it familiar for many practitioners of the energy industry.[19]

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[15] S. Touzani, A.K. Prakash, Z. Wang *et al.*, "Controlling distributed energy resources via deep reinforcement learning for load flexibility and energy efficiency", *Applied Energy*, vol. 304, 2021, 117733; R. Haider, D. D'Achiardi, V. Venkataramanan *et al.*, "Reinventing the utility for distributed energy resources: A proposal for retail electricity markets", *Advances in Applied Energy*, vol. 2, 2021, 100026; S. Zhang, D. May, M. Gül, P. Musilek, "Reinforcement learning-driven local transactive energy market for distributed energy resources", *Energy and AI*, vol. 8, 2022, 100150.

[16] Y. Xia, Q. Xu, H. Qian, L. Cai, "Peer-to-Peer energy trading considering the output uncertainty of distributed energy resources", *Energy Reports*, vol. 8, suppl. 1, 2022, pp. 567–574.

[17] T. Sidnell, F. Clarke, B. Dorneanu *et al.*, "Optimal design and operation of distributed energy resources systems for residential neighbourhoods", *Smart Energy*, vol. 4, 2021, 100049.

[18] A. Flores-Quiroz, K. Strunz, "A distributed computing framework for multi-stage stochastic planning of renewable power systems with energy storage as flexibility option", *Applied Energy*, vol. 291, 2021, 116736.

[19] S. Jin, S.M. Ryan, J.-P. Watson, D.L. Woodruff, "Modeling and solving a large-scale generation expansion planning problem under uncertainty", *Energy Systems*, vol. 2, no. 3, 2011, pp. 209–242; Y. Feng, S.M. Ryan, "Scenario construction and reduction applied to stochastic power generation expansion planning", *Computers & Operations Research*, vol. 40, no. 1, 2013, pp. 9–23.

The actual resilience of distributed energy resources

The resilience of DER systems, such as they are designed presently, seems promising, which is substantiated by studies of DER systems in areas afflicted with frequent local blackouts.[20] Still, when resilience is considered for extreme conditions, such as war, DER systems present two major weaknesses. Firstly, they are sensitive to the working of supply chains. Dispersed structures of this type generate a steady demand for maintenance services, which includes spare parts. Disturbances in supply chains are highly impactful when emergency situations last longer than the maintenance cycle.[21] Secondly, DER systems are closely connected to digital platforms that facilitate coordination between local installations.[22] The technology of digital cloud seems to be promising in that respect, especially as regards reducing peaks and valleys in demand for energy, and the underlying logic consists in mirroring a cloud of shared energy with a digital cloud, in a local network of small installations.[23] As those digital technologies allow creating country-wide platforms for smartly trading local surpluses of energy, local power installations must become partly accessible digitally from remote locations. That creates a meta-risk of systemic failure in the digital network that underpins the national power system.[24]

When distributed energy systems are based on local installations combining renewable sources of energy (photovoltaic & wind) with battery-based energy storage, they seem to change the economic role of low-voltage networks (LV) and the way they work. Wasiak et al.[25] present a controlled experimental environment for reli-

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[20] R. Wu, G. Sansavini, "Energy trilemma in active distribution network design: Balancing affordability, sustainability and security in optimization-based decision-making", *Applied Energy*, vol. 304, 2021, 117891.

[21] D.M. López González, J. Garcia Rendon, "Opportunities and challenges of mainstreaming distributed energy resources towards the transition to more efficient and resilient energy markets", *Renewable and Sustainable Energy Reviews*, vol. 157, 2022, 112018; D.M. Maschio, B. Duarte, A.E. Lazzaretti *et al.*, "An event-driven approach for resources planning in distributed power generation systems", *International Journal of Electrical Power & Energy Systems*, vol. 137, 2022, 107768.

[22] V. Tikka, A. Mashlakov, A. Kulmala *et al.*, "Integrated business platform of distributed energy resources – Case Finland", *Energy Procedia*, vol. 158, 2019, pp. 6637–6644.

[23] T. Yan, J. Liu, Q. Niu *et al.*, "Distributed energy storage node controller and control strategy based on energy storage cloud platform architecture", *Global Energy Interconnection*, vol. 3, no. 2, 2020, pp. 166–174.

[24] S. Howell, Y. Rezgui, J.-L. Hippolyte *et al.*, "Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources", *Renewable and Sustainable Energy Reviews*, vol. 77, 2017, pp. 193–214; S. Pazouki, E. Naderi, A. Asrari, "A remedial action framework against cyberattacks targeting energy hubs integrated with distributed energy resources", *Applied Energy*, vol. 304, 2021, 117895.

[25] I. Wasiak, M. Szypowski, P. Kelm *et al.*, "Innovative energy management system for low-voltage networks with distributed generation based on prosumers' active participation", *Applied Energy*, vol. 312, 2022, 118705.

able testing of the above issues, where controllable devices located in prosumers' installations allow generating ancillary services with energy and minimizing the use of storage capacities for voltage regulation.

Conclusion

The management of DER systems, with a strong orientation on national security, needs to account for the collectively intelligent nature of networks that make DER systems. Individual local installations in a system of distributed energy resources, together with their local operators, form a collectively intelligent social structure. This, in turn, allows using the theory of complex systems (aka complexity theory) as conceptual framework for managing DER systems. Complexity theory can be traced back to the works of Herbert Simon, who argued that big sets of heterogenous phenomena spontaneously generate meta-structures of coordination, after reaching a critical size. It is possible to study social systems as hierarchies of emergent coordination structures, stacked upon one another.[26] In its more modern version, complexity theory forms the theoretical base for simulating alternative states of a given social system with the help of artificial intelligence. The essential assumption is that apparently random actions in component entities of the system produce, in the same system, both patterned behaviours, and meta-structures of coordination.[27]

From the perspective of management, and once we assume that DER systems are emergent structures, collective intelligence in DER works mostly by imitation and coordination between individual agents, with markets being important mediators in that coordination. Models such as the ants' colony seem particularly suitable for rigorous quantitative simulations of collectively intelligent adaptation in the population of participants in DER networks.[28]

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[26] H.A. Simon, "The architecture of complexity", *Proceedings of the American Philosophical Society*, vol. 106, no. 6, 1962, pp. 467–482; P.W. Anderson, "More is different: Broken symmetry and the nature of the hierarchical structure of science", *Science*, vol. 177, no. 4047, 1972, pp. 393–396.

[27] P.C. Anderson, A. Meyer, Complexity theory and process organization studies, [in:] *SAGE Handbook of Process Organization Studies*, eds. A. Langley, H. Tsoukas, Thousand Oaks, CA: SAGE Publications Ltd, 2016, pp. 127–143; J. Ladyman, K. Wiesner, *What Is a Complex System?*, New Haven, CT: Yale University Press, 2020, Kindle Edition, p. 15–17.

[28] A. Gupta, S. Srivastava, "Comparative analysis of ant colony and particle swarm optimization algorithms for distance optimization", *Procedia Computer Science*, vol. 173, 2020, pp. 245–253; D. Di Caprio, A. Ebrahimnejad, H. Alrezaamiri, F.J. Santos-Arteaga, "A novel ant colony algorithm for solving shortest path problems with fuzzy arc weights", *Alexandria Engineering Journal*, vol. 61, no. 5, 2021, pp. 3403–3415.

Using complexity theory involves an essentially non-commanding approach to the management of DER systems. It is hardly conceivable to develop a viable and resilient DER system just by the fiat of the government, communicated top-down through the social structure. The deployment of distributed energy resources can be achieved only through creating market-based communities of exchange. The most critical factor to manage in DER systems seems to be the stability and viability of supply chains. Efficient, resilient supply chains of spare parts and technical services are necessary to maintain dispersed energy resources at a state-of-the-art technological advancement, and, at the same time, crucial to their economic and environmental sustainability.

There is substantial evidence that businesses exposed to supply-chain-related risks develop very risk-specific strategies to manage those contingencies. However, the strategy of the type "Control, Share and Transfer" seems to override significantly other types of risk-management strategies.[29] This, in turn, means that proper management of supply-chain-related risk relative to distributed energy systems involves, most of all, the development of proper financial instruments and markets: insurance contracts, specific types of financial securities, and workable forms of business association (partnerships and companies). That corroborates the need for approaching the management of DER systems from the perspective of complexity theory: financial markets are hardly manageable in a top-down manner.

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The management of distributed energy resources for national security

Abstract

This article investigates the possibilities of using distributed energy resources (DER) to increase the resilience of national energy systems and national security, including the case of war. A review of literature is conducted, regarding the management of DER systems. Conclusions focus on the specificities of managing such systems for national security, namely: a) the importance of complexity theory as basic framework for strategic planning in DER systems b) the management of risks relative to disruptions in supply chains and c) the role to be played by financial instruments and markets.

Key words: energy security, distributed energy resources (DER), national security, energy resilience