Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 80 (2019) 269–274

www.elsevier.com/locate/procedia

26th CIRP Life Cycle Engineering (LCE) Conference

An ecosystem perspective for the design of sustainable power systems

Varuneswara Panyam[a], Hao Huang[b], Katherine Davis[b], Astrid Layton[a]

[a] *Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA*
[b] *Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA*

Abstract

The evolution of power systems has recently seen a strong increase in renewable energy integration. This evolution has resulted in bi-directional pathways with two-way exchanges between the grid and consumers that is beginning to resemble the cyclic organization of food webs. Ecologically-similar cycling of materials and energy in industrial networks has previously been shown to improve network efficiency and reduce costs. The cyclic organization of food webs is proposed here as a design principle to quantify the effectiveness of two-way connections between the grid and consumers. The presence of ecosystem-like cycling in traditional power grid networks is investigated using the ecological metrics cyclicity and cycling index. Two hypothetical 5-bus grids are modified to replicate the two-way exchanges of real power systems with consumer renewable energy generation. The results show a positive correlation between increased structural cycling in grids and reliability improvements measured by the North American Electric Reliability Corporation (NERC) standard N-1 contingency analysis. These results suggest that the metrics cyclicity and cycling index can play a role in quantifying and improving the sustainability of power grids.

Keywords: Food webs; power systems; cycling; sustainability; electric grid design; ecological modeling; resilience

---

1. Introduction

1.1. Power grid sustainability

Sustainability in the context of power grids is not concretely defined, even though it is a priority for grid design and maintenance. Grid sustainability is defined here as the ability of the grid to survive and sustain in the long term with changing consumer needs and generation technologies [1, 2, 3]. The following factors are identified as critical to enhancing the sustainability of power systems [1, 4]:

- Power source (renewable energy vs fossil fuel)
- Structural longevity of grid components
- Resilience of the grid to disturbances
- The efficiency of generation and transmission
- Profitability for the service providers
- Environmental impact of grid components

Grid evolution has seen the addition of components that help continuously monitor loads, balance generation and usage, and improve reliability and resilience. These changes are referred to as ”Grid Modernization” [4]. Despite these many improvements, reliability and resilience is still an active area of research for power systems [4]. The U.S. has suffered from several widespread blackouts in the past, examples include: the New York City blackout of 1977 (a cost of $1.2 billion in 2017 dollars); the Northeast blackout of 2003 (losses estimated at $ 6 billion) [5] and East coast power outages due to Hurricane Sandy in 2012 (costs estimated at $ 80 billion) [6]. Grid component failures can lead to cascading failures across the grid while natural disasters can knock down lines and components resulting in grid overloads.

The most sustainable grid scenarios include a high use of renewables and nuclear power along with high network resilience [3]. The increasing affordability of renewable power sources has resulted in strong increases in their prevalence [7]. This increase has not yet replaced traditional fossil fuel based power plants, which have a strong negative impact on the environment [8], however it’s growth is formative: annual US electricity generation from solar and wind energy increased by a factor of 11 from 2006 to 2016 [7].

---

[*] Corresponding author. Tel.: +1-979-922-4118
E-mail address: vpanyam@tamu.edu (Varuneswara Panyam).

10.1016/j.procir.2018.12.005

1.2. Power systems with distributed generation vs ecosystems

Renewable energy systems installed at consumer locations (for example, solar panels on a home or commercial roofs), allow consumers (also referred to as loads) to use their own power and sell back extra. This two-way exchange of power between the grid and the consumer is known as net-metering. Customer participation in net-metering is becoming more popular every year [9] as seen in Figure 1 and public electric utilities in the U.S. are required to offer net metering when requested [10]. These small scale power generating units are known as distributed generation (DG) systems [11] and are changing grid operation. As a result of consumer sell back, the traditionally linear grid is evolving into a complex network with circular pathways reminiscent of the cyclic organization found in ecosystems.

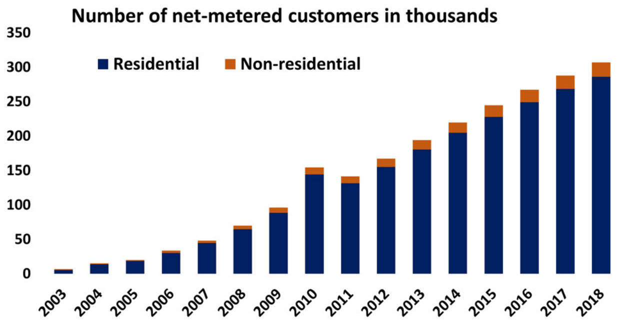


Figure 1. The number of net-metered customers in the U.S. Data until 2010 from [9] and a linear forecast suggests a further increase through 2018.

Organisms in a food web are classified as prey and predators (producers and consumers) and the complex interplay between them leads to high amount of cycling [12]. Past research indicates that food webs have evolved to have a highly cyclic organization [13, 14, 15, 16] that results in the efficient use of available resources [17, 18, 19]. Structural cycling in these natural systems exists primarily due to detritus, waste generated by actors, creating feedback from actors that are traditionally only consumers [16]. Paths that connect actors indirectly (actors that are separated by one or more actor) are another inherent feature of highly cyclical food web networks. Indirect pathways have been found to dominate direct ones, resulting in cycles that impact network stability [20, 21, 22]. Similarly complex indirect pathways exist in power systems, industrial networks, economic networks and other human resource networks. This has inspired studies to look for relationships between ecosystem-like cycling, efficiency, and robustness in industrial and economic resource networks [23, 24, 25] as well as thermodynamic cycles [26]. Improving cycling to promote the efficient re-use of waste and consequently reduce environmental impact has been extensively examined by Layton et al. [27, 28]. Their results show that the bio-inspired design of industrial networks results in economically and environmentally superior networks compared to traditional, less cyclic, design goals. Power systems may benefit from Nature's rich repertoire of sustainable organization and structure, and have not yet been analyzed from the perspective of ecosystems.

An analogy between ecosystems and power grids is made, both are networks of entities - species in food webs and components in power systems - that circulate material and energy. This analogy is the basis for a two-fold approach to sustainability, addressing grid reliability and renewable energy integration into the grid. First, ecological cycling is investigated as a measure to quantify cyclic pathways in grids and second, this cycling is related to the N-1 reliability of the grid.

2. Methods and model

2.1. Power grid test cases

Eight hypothetical grids and two realistic grids are used as test cases. The grids are simulated using the commercial software package PowerWorld Simulator [29]. Nine out of these ten grids are free models included in PowerWorld. The tenth grid is a 37-bus real power grid from [30]. As flow data for real power systems is difficult to obtain, these eight synthetic grids, which closely resemble real grids in their structure and connectivity, are used in the analysis here.

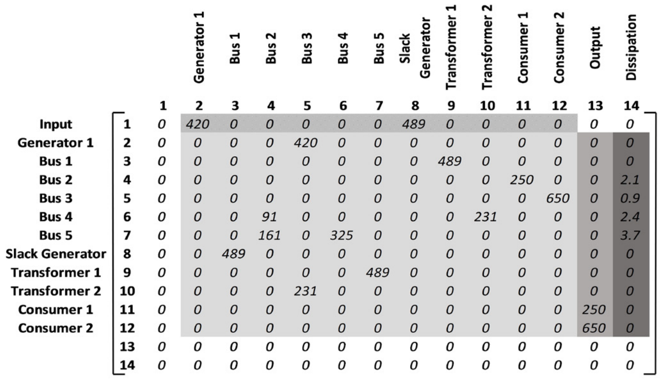
Power delivery from generators to consumers is dependent on the magnitude of transferred power, including real power P and reactive power Q. The integral of P over time gives the energy flow within the system. Q supports the system's voltage, allowing for power flows between actors. The successful operation of a power system must satisfy the real power balance between generation and load plus loss, maintain the system's voltage rated values, and keep all components functioning within their real and reactive power limits [30]. Real power is taken as primary flow between actors and reactive power is neglected. The real power flow values are obtained by solving the power flow equations. These are a set of nonlinear algebraic equations and depend on the system topology, network parameters, and the system's initial state. PowerWorld Simulator [29] is used here to ensure that the power flow equations are satisfied for each test case.

2.2. Modelling power grids as food webs

Food webs are complex networks of prey-predator type interactions and are visualized using a digraph, from which the information is quantified in matrices. The food web matrix [**F**] contains the structural information and the flow matrix [**T**] contains the flow magnitude information. Each power grid component (buses, generators, transformers, and consumers) is considered equivalent to a species in the food web. These actors are drawn inside the system boundary and the dissipation from transmission lines are considered as losses in the corresponding end buses (terminal bus of a transmission line).

The ecological flow matrix [**T**] is a $(N+3)$ x $(N+3)$ matrix, where N is the number of actors in the network, whose elements are the power flows between various components in the system. The element T_{ij} is nonzero if there is a nonzero flow from node i to node j. Figure 2 illustrates the flow matrix for the basic 5-bus power grid. The inner light grey section contains the inter-compartmental flows. The inputs, useful outputs, and dissipation that crosses the system boundaries are entered in the cross-hatched top row, the medium grey second to last column, and the dark grey last column respectively. The food web matrix

[**F**] is a N x N matrix made up of ones and zeros, where a one represents an interaction and a zero no interaction. [**F**] quantifies the presence and direction of the inter-compartmental flows in [**T**]. An element F_{ij} is equal to 1 if there is a flow from i to j and 0 otherwise. The number of non-zero elements of [**F**] is equal to the number of total links in the network (L).



			Generator 1	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Slack Generator	Transformer 1	Transformer 2	Consumer 1	Consumer 2	Output	Dissipation
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Input	1	0	420	0	0	0	0	0	489	0	0	0	0	0	0
Generator 1	2	0	0	0	0	420	0	0	0	0	0	0	0	0	0
Bus 1	3	0	0	0	0	0	0	0	0	489	0	0	0	0	0
Bus 2	4	0	0	0	0	0	0	0	0	0	0	250	0	0	2.1
Bus 3	5	0	0	0	0	0	0	0	0	0	0	0	650	0	0.9
Bus 4	6	0	0	0	91	0	0	0	0	0	231	0	0	0	2.4
Bus 5	7	0	0	0	161	0	325	0	0	0	0	0	0	0	3.7
Slack Generator	8	0	0	489	0	0	0	0	0	0	0	0	0	0	0
Transformer 1	9	0	0	0	0	0	0	489	0	0	0	0	0	0	0
Transformer 2	10	0	0	0	0	231	0	0	0	0	0	0	0	0	0
Consumer 1	11	0	0	0	0	0	0	0	0	0	0	0	0	250	0
Consumer 2	12	0	0	0	0	0	0	0	0	0	0	0	0	650	0
	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2. Flow matrix [**T**] for the 5-bus power grid (B5_2).The inner light grey section documents the inter-compartmental flows. The inputs, useful outputs, and dissipation that crosses the system boundaries are documented in the cross hatched top row, the medium grey second to last column, and the dark grey last column respectively.

2.3. Ecological cycling metrics

The metrics *cyclicity* (λ_{max}) and *cycling index* (*CI*) are used by ecologists to measure the presence and strength of cyclic pathways and cycling in an ecosystem. Cyclicity is calculated from the food web matrix and *CI* from the flow matrix.

Cyclicity quantifies the presence and strength of structural cycles in a network and is calculated as the magnitude of the largest real eigenvalue of the structural adjacency matrix [**A**], Eq. 1 [16]. The structural adjacency matrix [**A**] is the transpose of the food web matrix. The Perron-Frobenius theorem guarantees the existence of an eigenvalue with a modulus greater than all others for non-negative matrices [31]. A simple proof of how maximum eigenvalue captures cyclic pathways in graphs described using spectral properties of digraphs can be found in [31]. Cyclicity can be a value of zero (no cyclic pathways present), one (at least a single cycle with a path length greater than 1), or any value greater than one. Cyclicity also measures the rate at which the number of cycles in a network proliferate with increasing path length. Food webs are made up of many highly complex cyclic pathways and therefore are characteristic of higher cyclicity values [32].

$$|\mathbf{A} - \lambda\mathbf{I}| = 0 \tag{1}$$

Cycling index (*CI*, also known as Finn Cycling Index *FCI*) is the ratio of the cycled throughflow (TSTc) to the total internal throughflow (TSTf) in the network (Eq. 2) [33, 15]. Cyclicity and *CI* quantify the extent of cycling from different perspectives. *TSTf*, following Eq. 3, is the sum of inputs and all the inter-compartmental exchanges in [**T**] [33]. *TSTc* is computed following Eq. 4, where [**L**] is the Leontief's inverse matrix whose diagonal elements (L_{jj}) indicate the average number of times a quantum of flow passes through the same actor [12].

$$CI = \frac{TSTc}{TSTf} \tag{2}$$

$$TSTf = \sum_{i=0}^{N}\sum_{j=0}^{N} T_{ij} \tag{3}$$

$$TSTc = \sum_{j=1}^{N} T_j \left(\frac{L_{jj} - 1}{L_{jj}}\right) \tag{4}$$

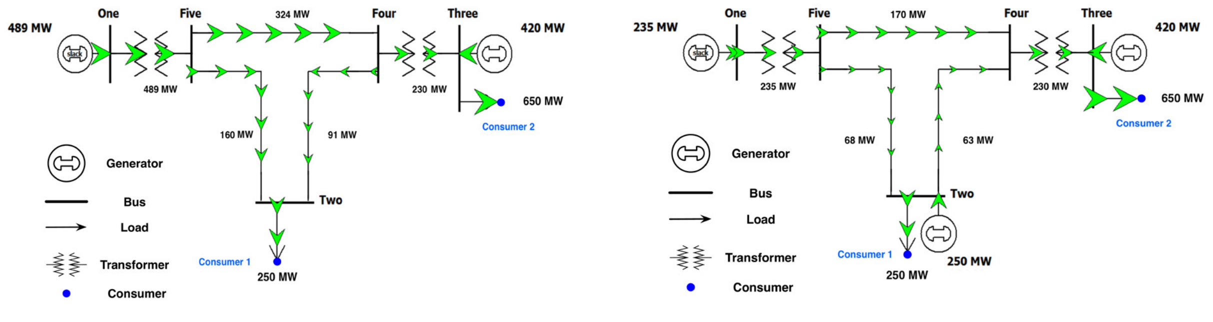
2.4. Grid modifications

Two 5-bus power grids, $B5\_1$ and $B5\_2$ (which have different loads and components), were selected for modification from the set of sample cases available. The three modifications made to each mimic distributed generation that occurs in real power grids. $B5\_1$ and $B5\_2$ are moderately complex with realistic loads and connections, making them ideal for demonstrating the newly transpiring cyclic pathways caused by distributed generation. The distributed generation is created by adding a generator with varying capacities in the place of the load, representing a consumer becoming a small source of power generation, as seen in Fig. 3(b), where a 200 MW generator replaces consumer-1 changes, thereby changing the connections from the original B5_1 grid Fig. 3(a). The addition of a generator changes the phase angles at different buses in the grid leading to change in power flow magnitudes and directions in some of the transmission lines.

Three consumer-1 modifications of increasing generation capacity (50, 150, 250 MW) are made to the $B5\_2$ grid. An assumption is made that the excess generation at consumer-1 is supplied to the grid only during half of its active time period, since renewable energy can be unpredictable. During the non-generation period consumer-1 is assumed to receive power from the grid, and the original grid configuration is active. The sum of the corresponding power flows (T_{ij}) in each period are considered as the entries in the flow matrix, representing the average network structure and function. The 4 consumer $B5\_1$ grid is modified with 40MW generating capacities at one, two, and three consumers.

2.5. N-1 contingency analysis

Contingency analyses are critical in power system operation and power market analyses to predict the behavior of the grid during various outage scenarios including a single-element outage, multiple-element outages, and sequential outages [34]. The N-1 contingency analysis is considered the primary reliability standard by North American Electric Reliability Corporation (NERC), where 'N' stands for the number of major components in the system [35]. The N-1 contingency analysis assesses whether the system can withstand the loss of any single major piece of equipment without violating voltage or equipment



(a) (b)

Figure 3. (a) The original grid $B5\_2$ as represented in PowerWorld and (b) the modification of customer-1 generating 200 MW.

loading limits while delivering required energy [30]. An N-1 contingency analysis is performed using PowerWorld on all the grid scenarios to examine whether the added cycling due to distributed generator makes the grid more or less reliable.

3. Results

The λ_{max} and CI for the eight original grids and one of the two realistic grids are all zero. The 37-bus realistic grid however has a λ_{max} value of 1.0 and a CI of 0.00089. The cyclic pathways in the modified B5_2 grid are highlighted in Fig. 4, showing that a total of three cycles exist in the system when consumer-1 is producing an excess generation of 200 MW.

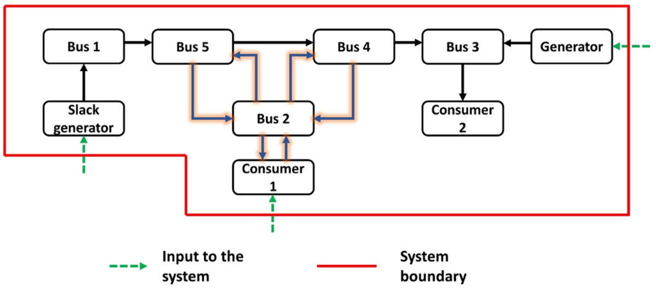


Figure 4. The modified B5_2 pathways and connections averaged over an entire day when consumer-1 has an excess generation of 200 MW. This representation is the combination of the two network scenarios shown in Fig. 3.

Analysis of 104 food web models [36], available in the package *enaR* for use in the free programming language *R*, reveals that food webs have a mean λ_{max} value of 4.35 and a mean CI of 0.39. The grid modifications are summarized in Table 1 and show that the cycling that is introduced through the consumer generation brings the grid closer to the average cyclic structure and function of food webs. The reliability of the modified networks, as measured by the N-1 contingency analysis, is also shown to increase with these modifications. The number of violations in the N-1 contingency analysis of the original and modified power grids are shown in Table 1. An exponential decrease in the number of violations is observed in the N-1 contingency analysis as the modifications increase the number of cycles in the grid. Increasing cyclicity and CI both show a smooth exponential correlation with decreases in the number of N-1 violations, as seen in Fig. 5 and 6.

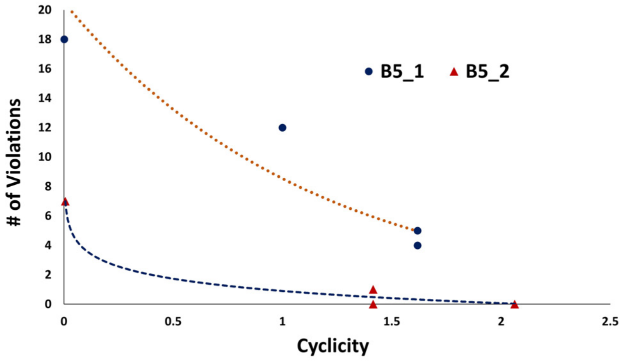


Figure 5. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cyclicity increases (x-axis).

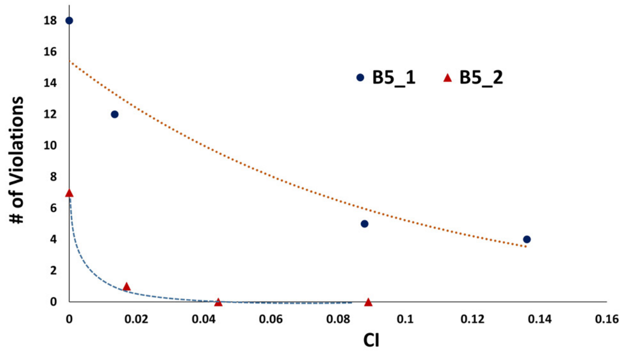


Figure 6. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cycling index (CI) increases (x-axis).

4. Discussion

The results suggest that cycles are not present in traditional power grids, all the unmodified grids except for the 37-bus system had λ_{max} and CI values of zero. The 37-bus system did demonstrate extremely weak and simple cycling with a CI of 0.00089 and a λ_{max} of one. Based on the behavior of the other nine grids this appears to be an exception rather than the rule, however more large grids need to be investigated to further support that traditional power grids have a one-way chain-like structure. The two cycling metrics are used in ecology to identify cyclic energy pathways that influence food web network characteristics such as robustness, organizational efficiency etc.

Table 1. The cycling index (*CI*), cyclicity (λ_{max}), and N-1 contingency analysis violations of the original grids (B5_1 and B5_2), grids modified with excess generation at consumer 2 (B5_1a), consumers 2 and 4 (B5_1b), and consumers 2, 3, and 4 (B5_1c), and consumer 1 (B5_2d, B5_2e, B5_2f). The grid IDs are used for identifying modifications to the original B5_1 and B5_2 grids

Grid ID	**Grid Modifications**	λ_{max}	**CI**	**# N-1 violations**
B5_1	Sample case - original	0	0	18
B5_1a	40 MW at consumer-2	1	0.0135	12
B5_1b	40 MW at consumer-2 and -4	1.618	0.0878	5
B5_1c	40 MW at consumer-2, -3, -4	1.618	0.136	4
B5_2	Sample case - original	0	0	7
B5_2d	50 MW at consumer-1	1.414	0.0158	1
B5_2e	150 MW at consumer-1	1.414	0.0347	0
B5_2f	250 MW at consumer-1	2.06	0.0637	0

The results suggest that they may be useful in the design of robust power systems as well, as the two metrics effectively quantify power cycles and correlate strongly with improved N-1 reliability ratings.

Cycles in power systems at an instant cannot exist because it requires real power to traverse over a loop and come back to its origin that is against Kirchhoff's laws and dissipates excess power. Considering power flows over longer time periods may vary the magnitudes but will not change the flow directions in the traditional grids. Directional changes do however occur in the consumer sell-back grid scenarios, as seen in Figure 4. It is important to note however that, from a resilience perspective, in the modified configurations not all links are simultaneously active and the intermittent and somewhat unpredictable nature of renewables due to their dependence on weather conditions, unlike traditional fossil-fuel based electricity generation, makes these connections difficult to depend on in critical situations.

Modifications made to the 5-bus grids show increasing improvements to the N-1 reliability measure, with the number of violations in the network exponentially decreasing as the amount of cycling increased. The largest amount of total excess generation that was sold back to the grid saw the highest *CI*, 120MW total in B5_1c had a *CI* of 0.136. The highest amount of generation at a single consumer resulted in the highest λ_{max} and the best N-1 rating, 250MW in B5_2f had a λ_{max} of 2.06 and zero N-1 violations. The violations counted by the N-1 analysis can be either overflow in transmission line, voltage exceeding its limit in a bus, or both. A lower number of N-1 violations means more consumers receive the required power without disruptions. Future work will focus on analyzing power grids with more consumers, enabling a higher number of distributed generation systems to be placed in the grid.

4.1. Renewable energy storage

The integration of renewables locally requires a reliable and affordable energy storage system for such distributed generators, especially in scenarios with higher generation values and thus higher cycling. Electricity storage devices can store electricity when production exceeds demand and use the storage during peak-demand periods to ensure a balance for demand and supply [37]. The grid with the highest λ_{max}, B5_2f, also has the highest generation of 250MW. The higher cyclicity value in B5_2f is due to the slack generator receiving power, which does not occur for B5_2d and B5_2e where the lower generations of 50 and 150 MW are not enough power to require storage. The unexpected intervals that occur with renewable source require energy storage, a field that is still relatively new. These electricity storage technologies must be robust, reliable and economically competitive [38]. Commercial electricity storage technologies, for example pumped hydro, flywheels, electrical batteries, and compressed air energy storage, are available for large scale renewable energy generation. The problem of optimal placement of storage devices with the objective of maximizing reliability is an area of further work.

4.2. Cyclicity vs cycling index for power systems

Differences in meaning between cyclicity and cycling index gives value to using both metrics, and can be explained using the grids B5_2d and B5_2e. Figure 5 shows that cyclicity for these two grids is the same, whereas the number of violations observed are different (the same is true for B5_1b and B5_1c). *CI* however varies for all the modified grids. The physical connections in B5_2d are the same as those in B5_2e resulting in λ_{max} remaining the same, however the 150MW excess generation in B5_2e leads to a higher magnitude of power being cycled (higher *CI*). A larger data set of power grids needs to be investigated to further reveal the relationship between N-1 reliability and cycling.

5. Conclusion

Distributed generation resulting from consumer installed renewable energy generators has seen a steady increase over the years, resulting in a rise in consumer sell-back to the grid. The circular power flow pathways that result from this sell back resemble the cyclic structure and organization characteristic of ecological food webs. Traditional power grids have revealed that no cyclic structure exists, however when modified to mimic basic consumer sell back the grids showed both cyclic structure and an increasing magnitude of cycled power. The ecological metrics cyclicity and cycling index are able to quantitatively measure the presence and complexity of cyclic pathways in the grid as well as the magnitude of power that is cycled. The results suggest that increasing the prevalence and magnitude of consumer power generation increases the ecosystem-type cycling as well as improves the N-1 reliability rating of the grid. The characteristically cyclic organization of ecosystems may provide a new approach to analyze these emerging sustainable two-way grids.

Acknowledgements

The authors would like to thank Bogdan Pinte for his help in the early stages of this work and the Texas A&M Energy Institute for their support of this project.

References

[1] Quadrennial energy review: Energy transmission, storage, and distribution infrastructure, Tech. rep., DOE, US (2015).

[2] M. Child, O. Koskinen, L. Linnanen, C. Breyer, Sustainability guardrails for energy scenarios of the global energy transition, Renewable and Sustainable Energy Reviews 91 (April 2017) (2018) 321–334. doi:10.1016/j.rser.2018.03.079.

[3] E. Santoyo-Castelazo, A. Azapagic, Sustainability assessment of energy systems: integrating environmental, economic and social aspects, Journal of Cleaner Production 80 (2014) 119–138.

[4] Transforming the nation's electricity system: The second installment of the quadrennial energy review, Tech. rep., DOE, US (January 2017).

[5] J. Minkel, The 2003 Northeast Blackout–Five Years Later - Scientific American (2008).

[6] D. Henry, J. E. Ramirez-Marquez, On the impacts of power outages during hurricane sandy—a resilience-based analysis, Systems Engineering 19 (1) (2016) 59–75.

[7] P. Beiter, M. Elchinger, T. Tian, 2016 renewable energy data book, Tech. rep., NREL (2017).

[8] B.-W. Yi, J.-H. Xu, Y. Fan, Inter-regional power grid planning up to 2030 in china considering renewable energy development and regional pollutant control: A multi-region bottom-up optimization model, Applied Energy 184 (2016) 641–658.

[9] U. EIA, Participation in electric net-metering programs increased sharply in recent years - Today in Energy (2012).

[10] C. Schelly, E. P. Louie, J. M. Pearce, Examining interconnection and net metering policy for distributed generation in the united states, Renewable Energy Focus 22 (2017) 10–19.

[11] J. Marsden, Distributed generation systems: A new paradigm for sustainable energy, in: Proc. 2011 Green Technologies Conference, IEEE, 2011, pp. 1–4.

[12] S. Allesina, R. E. Ulanowicz, Cycling in ecological networks: Finn's index revisited, Computational Biology and Chemistry 28 (3) (2004) 227–233.

[13] S. R. Borrett, B. C. Patten, Structure of pathways in ecological networks: Relationships between length and number, Ecological Modelling 170 (2-3) (2003) 173–184.

[14] B. C. Patten, On the quantitative dominance of indirect effects in ecosystems, in: Proc. Third Int. Conf. State-of-the-Art Ecol. Model., International Society for Ecological Modelling, 1982, pp. 27–37. doi:10.1016/B978-0-444-42179-1.50006-7.

[15] B. C. Patten, Energy cycling in the ecosystem, Ecological Modelling 28 (1-2) (1985) 1–71.

[16] B. D. Fath, G. Halnes, Cyclic energy pathways in ecological food webs, ecological Modelling 208 (1) (2007) 17–24.

[17] A. Layton, B. Bras, J. Reap, M. Weissburg, Biologically Inspired Closed Loop Manufacturing Networks, in: Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition, 2013, pp. 1–10.

[18] E. P. Odum, The strategy of Ecosystem development, Science 164 (1969) 262–270. doi:10.5822/978-1-61091-491-8_20.

[19] R. E. Ulanowicz, Identifying the structure of cycling in ecosystems, Mathematical Biosciences 65 (2) (1983) 219–237. doi:10.1016/0025-5564(83)90063-9.

[20] D. DeAngelis, P. Mulholland, A. Palumbo, A. Steinman, M. Huston, J. Elwood, Nutrient dynamics and food-web stability, Annual Review of Ecology and Systematics 20 (1) (1989) 71–95.

[21] R. Herendeen, Energy intensity, residence time, exergy, and ascendency in dynamic ecosystems, Ecological Modelling 48 (1-2) (1989) 19–44.

[22] M. Loreau, Material cycling and the stability of ecosystems, The American Naturalist 143 (3) (1994) 508–513.

[23] A. Layton, B. Bras, M. Weissburg, Improving performance of eco-industrial parks, International Journal of Sustainable Engineering 10 (4-5) (2017) 250–259.

[24] R. Bailey, B. Bras, J. K. Allen, Applying ecological input-output flow analysis to material flows in industrial systems: Part ii: Flow metrics, Journal of Industrial Ecology 8 (1-2) (2004) 69–91.

[25] G. Liu, Z. Yang, M. Su, B. Chen, The structure, evolution and sustainability of urban socio-economic system, Ecological Informatics 10 (2012) 2–9.

[26] A. Layton, J. Reap, B. Bras, M. Weissburg, Correlation between thermodynamic efficiency and ecological cyclicity for thermodynamic power cycles, PLoS One 7 (12) (2012) e51841.

[27] A. Layton, B. Bras, M. Weissburg, Ecological Principles and Metrics for Improving Material Cycling Structures in Manufacturing Networks, J. Manuf. Sci. Eng. 138 (10) (2016) 101002. doi:10.1115/1.4033689.

[28] A. Layton, B. Bras, M. Weissburg, Industrial Ecosystems and Food Webs: An Expansion and Update of Existing Data for Eco-Industrial Parks and Understanding the Ecological Food Webs They Wish to Mimic, J. Ind. Ecol. 20 (1) (2016) 85–98. doi:10.1111/jiec.12283.

[29] Powerworld simulator [online] (2018) [cited PowerWorld Simulator].

[30] J. D. Glover, M. S. Sarma, T. Overbye, Power System Analysis & Design, SI Version, Cengage Learning, 2012.

[31] S. Jain, S. Krishna, Emergence and growth of complex networks in adaptive systems, Computer Physics Communications 121 (1999) 116–121.

[32] S. R. Borrett, B. D. Fath, B. C. Patten, Functional integration of ecological networks through pathway proliferation, Journal of Theoretical biology 245 (1) (2007) 98–111.

[33] J. T. Finn, Measures of ecosystem structure and function derived from analysis of flows, Journal of Theoretical Biology 56 (2) (1976) 363–380.

[34] A. J. Wood, B. F. Wollenberg, Power generation, operation, and control, John Wiley & Sons, 2012.

[35] NERC, Transmission operations (2006).
URL http://www.nerc.com/files/TOP-004-2.pdf

[36] M. K. Lau, D. E. Hines, P. Singh, S. R. Borrett, enaR: Ecological Network Analysis with R.

[37] G. Simbolotti, R. Kempener, Electricity Storage: Technology Brief, Tech. rep. (2012).
URL www.etsap.org-www.irena.org

[38] D. Lindley, Smart grids: The energy storage problem, Nature News 463 (7277) (2010) 18–20.