A Grid of Microgrids: Is It the Right Answer?

By NELSON MARTINS, *Life Fellow IEEE*
ANDRE LUIZ DINIZ, *Senior Member IEEE*
JOÃO G. C. BARROS
Brazilian Electrical Energy Research Center, Cepel, Cidade Universitária UFRJ, Rio de Janeiro - RJ, 21941-911, Brazil

The rapid and worldwide rise in distributed generation capacity, especially photovoltaic, has raised the issue on whether the development and operation of large interconnected systems on a national or continental level will vanish. The usual question is: will the large electric energy systems of today, planned and operated in either a centralized or decentralized way, be replaced by various independent smart-city systems, all with self-healing and other eye-catching characteristics, forming "a grid of microgrids?"

The ever-increasing participation of the distributed generation brings several benefits and challenges to the planning and operation of power systems: 1) despite the currently high relative investment cost of most renewable sources, especially while their technological maturity level is low, such sources directly extract free, clean, and renewable energy from the forces of nature, contributing to meeting the stringent targets of the nations committed to the reduction in greenhouse gases (GHG) emissions; 2) despite their intermittent power generation in a very short term when disregarding climate change issues, such sources are not subjected to severe mid-/long-term uncertainties, as for example high fuel prices or long spells of low water inflows to the reservoirs; and 3) since these distributed generations may frequently be placed very close to the loads, they reduce the need to build large capacity and long transmission lines to deliver energy from distant sources. However, in our opinion, a grid of microgrids will not be the dominant configuration for most systems due to several reasons as detailed in the sequel.

I. PREDOMINANTLY HYDROELECTRIC ENERGY SYSTEM OF BRAZIL

A grid of microgrids is not cost-effective in large predominantly hydro systems, which is—and should continue to be at least for the next few decades—the case of some countries such as Brazil. Today, the total generation capacity in Brazil is 160 GW, 67% coming from hydroelectricity, produced by more than 160 large hydropower plants with seasonal and multiyear regulation reservoirs [1]. Such plants are located in 12 major

Digital Object Identifier 10.1109/JPROC.2019.2963604

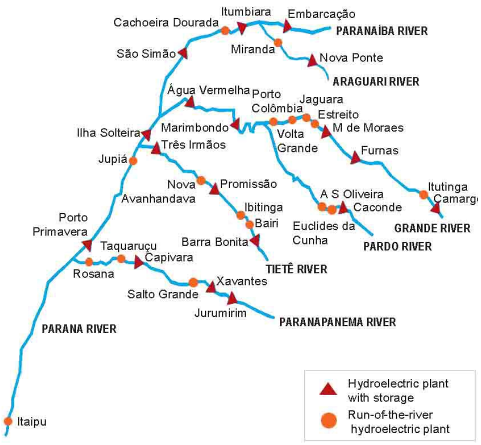

Fig. 1. ***Schematic of the hydropower plants of the Parana River Basin: circles stand for run-of-river and triangles for accumulation reservoirs.***

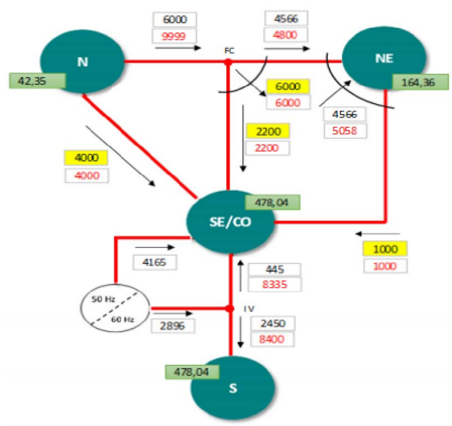

Fig. 2. ***BIPS, with intertie MW flows—operation data from February 16 to February 22, 2019 (source: www.ons.org.br).***

river basins located in different regions—some of these being quite distant from each other. The diagram of the entire hydroelectric system as well as its geo-electrical map would cover an entire page of this article and can be seen in the Operator's website (www.ons.org.br). Fig. 1 shows only the Parana River basin and its various hydroelectric projects [2] for fitting better into the confines of this paper. This large set of plants are connected to a transmission grid of continental dimensions, which was designed to harvest energy gains from the country's pluriannual hydrological diversity by transferring energy, on a seasonal level, from regions with surplus hydro energy (basins having plentiful inflows) to areas whose hydro basins have low inflows and water-depleted storage reservoirs. In this way, the water spill is minimized and the total generated energy is maximized.

The Brazilian Interconnected Power System (BIPS) is divided into four major system areas (submarkets) interconnected by long-distance, high capacity transmission corridors, whose sketch is presented in Fig. 2, which depicts power interchanges (shown in black) and maximum transmission line capacities (shown in red), for the third week of February 2019.

The Itaipu Binational hydroelectric plant is shown injecting 4165 and 2896 MW from its 50-Hz [through high voltage direct current (HVDC) transmission links] and 60-Hz generators, respectively. The power injected into the Southeastern (SE) region from the point-to-point Amazonian 6.6-GW Madeira River project, through a 2300-km-long dc transmission system, is not explicitly shown in Fig. 2.

II. LONG-TERM ENERGY GAINS BY EXPLOITING HYDROLOGICAL DIVERSITY AT CONTINENTAL LEVEL

The major source of uncertainty for the BIPS energy planning and operation is the water inflow to the reservoirs. Fig. 3 shows the historical record of the monthly inflows to the reservoirs of the major river basin in the SE region, for each year from 1931 to 2017. A marking seasonal pattern—with a dry period from May to October and a wet period having a much higher inflow variability— stands out from these recordings.

Fig. 4 shows the average monthly inflows in the 12 major hydrological areas of the BIPS. It can be seen that there exists clear seasonal complementarity among some of the equivalent reservoirs.

The strategy of building an interconnected electrical grid was mainly forged to cope with this uneven distribution of hydro inflows, allowing system planners and operators to safely exploit the multiyear regularization capability of the reservoirs and maximize the total hydro energy generation. The multiyear cycle of the water inflows to the SE and Northeastern (NE) equivalent reservoirs is evident from the recordings of the five-year period from 2014 to 2018, as shown in Fig. 5.

III. HYDROELECTRICITY WITH STORAGE: A SHIELD TO THE INTERMITTENCE OF THE SURGING RENEWABLES

The participation of wind generation is still small in Brazil (8.9% by the end of 2018) and also, highly concentrated in the NE coast of Brazil. Total wind potential as assessed by the Brazilian Wind Power Atlas is about 143 GW [3], considering a 7.0-m/s

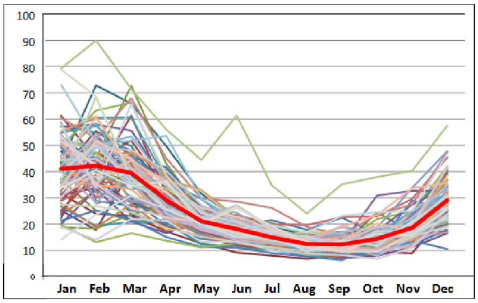

Fig. 3. ***Yearly time series of energy inflows (103 MW month) to the Parana River basin over the 1931–2017 period. The variation coefficient is seen to be as high as seven in the wet period.***

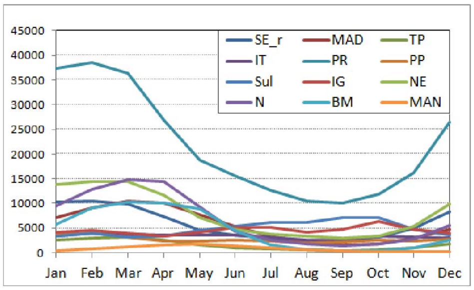

Fig. 4. ***Average inflows (MW month) along a typical year for the 12 equivalent reservoirs of the Brazilian system.***

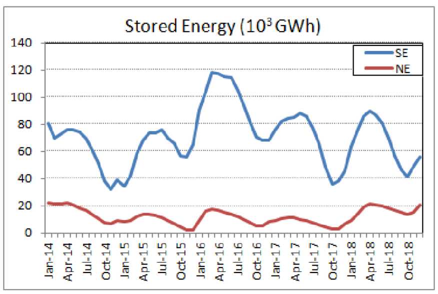

Fig. 5. ***Evolution of the stored hydroelectric energy in the SE and NE regions from 2014 to 2018 (source: www.ons.org.br).***

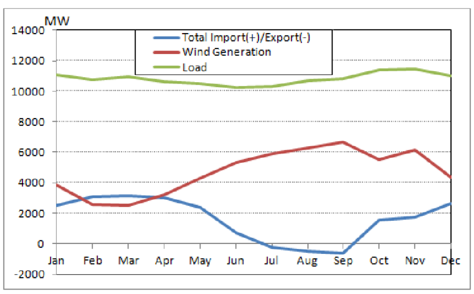

Fig. 6. ***Wind generation, total NE load and power export (−) import (+) for the NE region along 2018 (source: www.ons.org.br).***

speed and towers' height up to 50 m. There are 10 000 MW of installed wind generation in the NE region with an average capacity factor of 45%, which is considerably higher than world standards. Since the average NE load is about 10 800 MW, long transmission corridors are also important to export the instantaneous surplus of wind power to other regions of the continental size grid. Fig. 6 compares the monthly wind generation forecast in the NE area along 2018 with the total NE load, showing the average energy transfer from the NE area to the rest of the BIPS.

A more recent concern in the BIPS operation is that its transmission corridors should not be loaded at near full capacity, so as to allow the system to accommodate for the fluctuations of the NE wind power generation and the associated security threat of excessive reduction in the NE equivalent inertia.

In addition to its low carbon footprint, the high participation of wind generation in the NE region is also welcome for its remarkable complementarity with the Brazilian hydrological regime. This is shown in Fig. 7, which compares the NE average monthly energy inflows with the NE wind generation over the triennium 2016–2018.

The large energy-carrying capacity of environmentally safe, very long-distance, point-to-point HVDC (600 and 800 kV) transmission lines allowed the recent development of large, low-head hydroelectric projects in the Amazon region, e.g., Belo Monte (11 GW), Santo Antonio (3.3 GW), and Jirau (3.3 GW). Having large inflows concentrated in the wet period (from December to May), there would be large firm energy gains by building single-year accumulation reservoirs, but environmental constraints from sustainable energy development policies correctly made these projects to be built with run-of-the-river reservoirs. Since the Amazon region has scarce population and very low associated energy demand, long HVDC transmission lines were built to deliver the Amazonian electrical energy surplus in the wet period to the ever-growing load centers in the Southeast and South regions. Fig. 8 compares the total MW generation of the hydro plants in the Amazon region with the regional load along the year 2018. There are

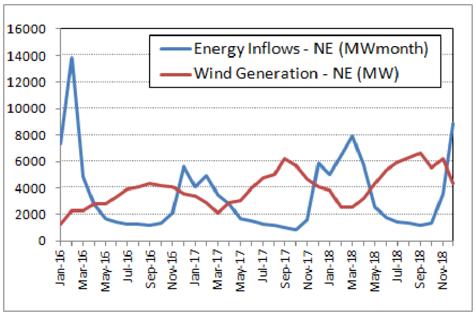

Fig. 7. ***Hydro and wind generation in the Brazilian NE area over a three-year period (source: www.ons.org.br).***

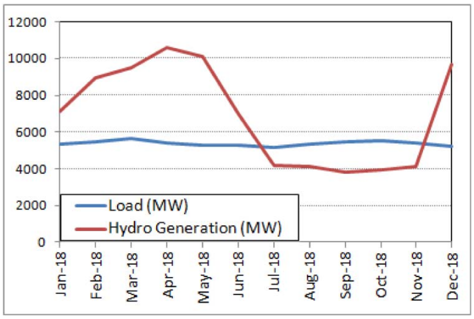

Fig. 8. ***Total hydro generation and load in the North area of Brazil in 2018 (source: www.ons.org.br).***

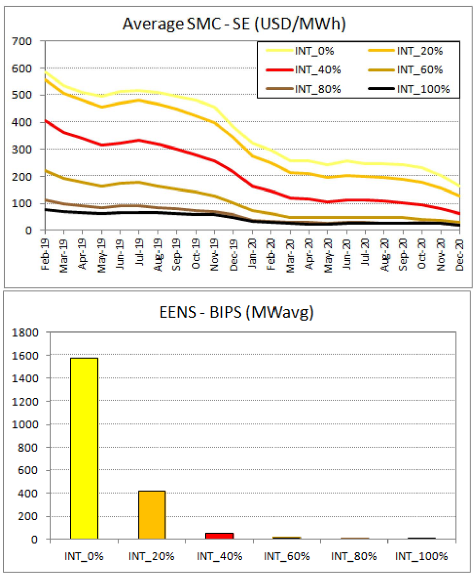

Fig. 9. ***Sensitivity analysis of the BIPS operation planning regarding the interconnection capacity among the system areas: average system marginal cost (above, in USD/MWh) and energy not supplied (below, in average MW).***

ongoing studies for building a complex of natural gas thermal power plants near the Belo Monte hydro project to export energy to the SE using the seasonal surplus capacity of the two existing 800-kV HVDC bipoles during the dry annual period of the Xingu River.

IV. BIPS ENERGY GAINS FROM GRID USAGE

The BIPS energy gains achieved with the energy-price optimization of the grid usage were estimated by performing a sensitivity analysis on the results from multiple simulations of NEWAVE, the Brazilian Operator's official energy planning and operation model [4], [5]. This software package is highly custom-fit and contains all constraints reflecting the BIPS energy planning, relative costs of its energy sources, major operating rules and perfected over two decades, with weekly updates by the Operator. The simulations presented in this section were performed by varying the BIPS inter-regional transmission limits from 0% to 100% of their nominal values, in line with the Brazilian ISO simulations for the Monthly Operation Program (PMO), for February 2019. The operation study horizon is typically ten years, but only the results of the first two years are presented. The upper part of Fig. 9 shows the average system marginal cost, which is a proxy of the weekly prices for the short-term energy simulation model [5]. The lower part in this figure shows the expected monthly volume of energy not supplied to the whole BIPS in these two years, when considering stochastic inflow scenarios. The continuously decreasing marginal prices along the two-year period are caused by a combination of two facts: first, Brazil has been facing severe droughts since 2014, therefore the current reservoir levels, especially in the Northeast region, are well below the long-term average. Second, new and cheaper energy sources are being connected to the grid over the next several years, especially wind generation, which contribute to bringing energy prices down in the near future. The very high energy prices in the short term are due to the fact that the set of running hydro plus wind power (and other renewable sources) fall short of meeting the load, and way more expensive burning fossil fuel plants have to then be run to meet demand.

Fig. 10. ***SE regional grid multi-infeed configuration formed by the inverter stations from the seven large-capacity HVDC transmission lines [8].***

V. PREDOMINANTLY THERMAL SYSTEMS—THE UNITED STATES AND CHINA EXAMPLES

Predominantly thermal systems having multiple electrical regions that encompass various time zones have their peak demands occurring at different times of the day. In the United States system, for example, if an interconnection existed, its Western system would, therefore, export energy for the Eastern system to meet the daily peak demand of the latter and, three to four hours later, the transmitted power would be reversed so that the Western system could then meet its peak demand. Extra-high-voltage (EHV) and ultra-high-voltage (UHV) HVDC transmission corridors would, through this HVDC overlay, obviate the need for building extra power plants in both Western and Eastern systems, bringing overall energy supply costs down [6]. Societal opposition to the building of these high capacity transmission links is, however, a big issue in developed as well as in developing countries.

Regarding the surging developments of UHV HVDC transmission lines in China, to carry energy from distant, clean, and renewable sources, and even from remote mine-mouth coal-based generation, to keep air-pollution away from the megacities, the authors recommend reading [7] and [8]. All the large capacity HVDC links continue to be built with the conventional line commutated converter technology but incorporating increasingly advanced protection and controls.

VI. CHALLENGING BRAZILIAN HVDC MULTI-INFEED CONFIGURATION

Long-distance HVDC bipoles at ±600 kV and, more recently, ±800 kV and even ±1100 kV, have become a reality in large grids. These HVDC corridors are environmentally safe and cost-effective for transferring power over extremely long distances with minimal energy losses (3.5% of resistive losses for every 1000 km at ±800 kV). However, given the now rising numbers of such HVDC links converging into a relatively weak regional grid, "multi-infeed" proximity effects, which can lead to harmful interactions, have arisen and have become a cause of concern to ISOs. These interactions depend on the total amount of dc power injected into a given electrical region of the system as compared to the available ac short-circuit power capacity of that region. AC/DC interaction problem mitigation is usually tackled by the combined use of synchronous condenser with special controls in the converter bridges and supplemented by carefully designed system protection schemes. As no two cases are fully alike, detailed electromagnetic transients, electromechanical stability, and voltage stability studies are required to ensure reliable operation in each particular situation. In addition, as power systems rapidly evolve, permanent monitoring and fine adjustments are regularly required. Fig. 10 illustrates the various HVDC links converging to the SE region of the Brazilian grid: four corridors with six bipoles (four operating at 600 kV and two at 800 kV). A seventh link, operating at 800 kV, has also been planned to carry the surplus wind power from the NE to the SE high energy-consuming region [9]. "Multi-infeed" related problems have been foreseen for this configuration and are under consideration by the Brazilian Grid ISO. The six HVDC bipoles will inject nearly 20 GW to the southeast regional grid, for a BIPS total load of 110 GW by the year 2020, and the temporary loss of a part of such a large amount of power injection could lead to a severe system stress and instability. By 2024, there will be a 24-GW injection from seven HVDC lines to the southeast region for a total BIPS load of 120 GW. Detailed EMT and stability studies have been conducted by the Brazilian ISO, for the cost-effective design of the hybrid ac/dc system, its control and protection functions being compounded with safe operation strategies. Cepel was commissioned by the Brazilian Operator to develop a combined EMT-electromechanical digital simulator, based on phasor dynamics technology, to more effectively study the HVDC multi-infeed dynamic performance [10].

The construction of the third Brazilian nuclear power plant has been resumed, after an over two decade interruption marred with political controversies. Despite being a zero-emission source, the nuclear power expansion alternative is considerably more costly than the wind and solar sources, whose potential is still abundant in Brazil.

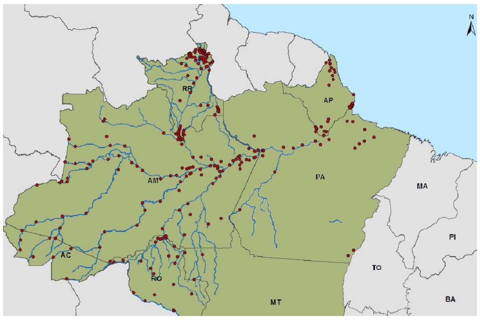

Fig. 11. *Isolated power systems in the Amazon region (http://www.epe.gov.br/en/publications/publications).*

VII. PREVAILING TREND TOWARD TRANSMISSION OVERLAYS AND SUPERGRIDS

The fairly distant, high-capacity offshore wind power developments in the Baltic Sea called for voltage sourced converters (VSC)-HVDC to tap renewable energy through a number of submarine cables that converge into a higher voltage ac/dc aerial transmission system to deliver a larger share of sustainable energy to the German market [10]. Other plans such as the Mediterranean Ring or the world supergrid, including the China–Europe electricity connection [11], [12], which appeared futuristic until recently, may become a reality in the next decade. Another important advantage of maintaining a dc or ac transmission overlay even in a "grid of microgrids" configuration is their capability to more rapidly restore the network, and all priority loads following widespread blackouts, by using a "top-down" strategy as opposed to a "bottom-up" one [13]. It is worth noting that the Virtual Power Plants [14], a cyber-based energy market operation aggregator, which has turned the distributed renewable sources economically independent of subsidies, has not yet been proven to be as effective to system restoration following blackouts as maintaining the classical initial sources of power [15]. Also, the inexorable trend toward electric vehicles for private and public transport to meet the Paris agreement on GHG emissions will be ever boosting electricity generation [16] from clean sources, however remotely located, and foster its delivery to the highly energy dependable megacities through low environmental impact, well-designed dc or ac transmission corridors.

VIII. FINAL COMMENTS

Hydro-thermal–wind energy planning and operation coordination through the strong BIPS interconnections has brought average energy gains of more than 2 GWavg to BIPS (about 2.5% of the Brazilian peak load in 2018) when compared to the individual coordination of the four major BIPS submarkets. As this coordination relies fundamentally on the availability of a strong ac/dc grid, Brazilians refer to the latter as a virtual stochastic power plant whose capacity would be in the order of 5 GW, considering the average capacity factors and the seasonal production of the various sources. With the fast expansion of the wind and solar sources in the NE Brazilian region, ensuring minimum system inertia has been a part of the Operator daily concerns. The strong Brazilian transmission grid has, however, been providing the needed stability control support, system inertia included, mostly from the geographically dispersed hydro and thermal power plants. New regulatory rules, hourly energy pricing included, will soon be implemented to remunerate the conventional generation for the vital ancillary services they are providing to the secure operation of the BIPS whose NE region incorporates a high penetration of renewables. There are good prospects in the next decade for the commercial exploration of the abundant natural gas reserves in the presalt offshore oil fields, distant 350 km from the major Southeast Brazilian load centers. There already appeared project proposals both ways: either building undersea pipelines directly from the presalt gas fields to the coastal load centers or generating electrical energy on offshore gas-powered plants and transmitting it to the continental sized electrical grid by bulk submarine HVDC cables. The constant reports on new electrical energy expansion and system reinforcements the world over constitute overwhelming evidence in favor of long-distance bulk power transmission. The risks of strong transmission systems promoting cascading blackouts of continental proportions are kept very low by advanced protection, control systems, and restoration practices [15], [17]. These risks are very much outweighed by the benefits of the interconnected grids to sustainability. Therefore, both ac and dc transmission systems will continue to be an integral part of all sustainable interconnected power systems, at least for several decades to come. Many moderetely sized power systems with good load-generation balancing and abundant renewable sources may dispense being linked to strong interconnections by deploying advanced energy storage and self-healing infrastructure. Also, over 260 small capacity and dispersed isolated power systems [18] exist in the Amazon region, where it is not economical or technically feasible to extend grid services. They are shown as red dots in Fig. 11, mainly along the rivers' gutters, being mostly (97%) run on highly expensive diesel fuel and half of them with capacities below 1 MW. When overcoming several socio-technical challenges and adopting a culture of innovation, they could have more affordable and reliable energy from the development of local renewable sources (biomass, small hydro, solar, and storage systems) to become renewable-diesel hybrid microgrids, similar to the Alaskan experience detailed in [19]. ■

REFERENCES

[1] *Brazilian National System Operator Website (in Portuguese)*. Accessed: Dec. 2019. [Online]. Available: http://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros

[2] P. T. Leite, A. A. F. M. Carneiro, and A. C. P. L. F. Carvalho, "Energetic operation planning using genetic algorithms," *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 173–179, Feb. 2002.

[3] *Atlas of the Brazilian Wind Energy Potential* (in Portuguese), Cepel, Rio de Janeiro, Brazil, 2001.

[4] M. E. P. Maceira *et al.*, "Twenty years of application of stochastic dual dynamic programming in official and agent studies in Brazil-main features and improvements on the NEWAVE model," in *Proc. 20th PSCC Power Syst. Comput. Conf.*, Dublin, Ireland, Jun. 2018.

[5] Andre L. Diniz, Fernanda S. Costai, "Short/mid-term hydrothermal dispatch and spot pricing for large-scale systems—The case of Brazil," in *Proc. 20th Power Syst. Comput. Conf.*, Dublin, Ireland, Jun. 2018.

[6] L. O. Barthold and D. A. Woodford, *Electric Power and DC's Renaissance*. Washington, DC, USA: National Academy of Engineering, 2016, pp. 53–60.

[7] P. Fairley, "China's ambitious plan to build the world's biggest supergrid," *IEEE Spectr.*, Feb. 2019. [Online]. Available: https://spectrum.ieee.org/energy/the-smarter-grid/chinas-ambitious-plan-to-build-the-worlds-biggest-supergrid

[8] (Jun. 2013). *Jeremy Bolden China Takes HVDC to a New Level, Online Article in Power Engineering International*. [Online]. Available: https://www.powerengineeringint.com/articles/print/volume-21/issue-6/special-focus-hvdc/china-takes-hvdc-to-new-level.html

[9] D. S. Carvalho and J. M. Bressane, "An 800 kV HVDC bipole to reinforce a regional interconnection and integrate a large amount of variable renewable generation," in *Proc. CIGRE Gen. Meeting*, Paris, France, 2018, Paper B4-101.

[10] S. Gomes, Jr., and L. P. Almeidaii, "The computational program AnaHVDC for the simulation of multiple HVDC links considering electromechanical and electromagnetic transients," in *Proc. 25th SNPTEE*, Belo Horizonte, Brazil, Nov. 2019.

[11] C. W. Gellings, "A globe spanning super grid," *IEEE Spectr.*, vol. 52, no. 8, pp. 48–54, Aug. 2015.

[12] Engerati.com. (Apr. 2018). *World Supergrid Part 1—Europe's Electricity Connection East to China*. [Online]. Available: https://www.engerati.com/transmission-and-distribution/article/dc-networks/world-supergrid-part-1—europes-electricity

[13] M. Henderson, E. Rappold, J. Feltes, C. Grande-Moran, D. Durbak, and O. Bileya, "Addressing restoration issues for the ISO New England system," in *Proc. PES Gen. Meeting*, San Diego, CA, USA, Jul. 2012.

[14] *What is a Virtual Power Plant?* Accessed: Jan. 2019. [Online]. Available: https://www.next-kraftwerke.com/knowledge/what-is-a-virtual-power-plant

[15] M. M. Adibi, *Power System Restoration Dynamics* (Issues, Techniques, Planning, Training & Special Considerations). Technical Paper Compendium, PES-TPC1, IEEE PES Resource Center, Jul. 2014.

[16] (Feb. 2019). *Adair Turner Should You Buy an Electric Car? Project Sindicate Magazine*. [Online]. Available: https://www.project-syndicate.org/commentary/electric-car-efficiency-climate-change-by-adair-turner-2019-02?barrier=accesspaylog

[17] *A Proposed Framework for Coordinated Power System Stability Control*, document ELT_301_1, ELECTRA, Yong Jie Fang and Others From the CIGRE Joint Working Group C2/C4.37, Dec. 2018, pp. 25–34.

[18] Energy Planning Office (EPE), Rio de Janeiro, Brazil. (Jan. 2019). *Planning the Supply for the Isolated Systems - Horizon 2023 - Cycle 2018*. [Online]. Available: http://www.epe.gov.br/en/publications/publications

[19] G. P. Holdmann, R. W. Wies, and J. B. Vandermeer, "Energy integration in Alaska's remote islanded microgrids: Economic drivers, technical strategies, technological niche developments, and policy implications," *Proc. IEEE*, vol. 107, no. 9, pp. 1820–1837, Sep. 2019.