Electricity for All: Issues, Challenges, and Solutions for Energy-Disadvantaged Communities

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Millions of people have limited or no access to electrical energy. A diverse group of scholars and activists, from individual researchers to nongovernmental organizations (NGOs), civil society organizations, UN, and increasingly to engineering and financial private sector firms, have been working on initiatives to address this issue, which is considered by many a human rights problem. Energy access is not only a challenge for developing economies but is also equally important for service to remote areas such as the Arctic, islands, and communities distant from the grid. Several governments and private institutions, as well as nongovernment organizations around the world, are now funding projects and a variety of initiatives to help impoverished communities, especially across Africa and remote regions, develop clean and sustainable energy systems. The IEEE is actively involved in addressing energy access issues through several initiatives, such as the Smart Village program, focusing on "integrating sustainable electricity, education, and entrepreneurial solutions to empower off-grid communities" (http://ieee-smart-village.org/). In this special issue, we concentrate on highlighting the current state of knowledge associated with strategies for bringing clean, affordable, and sustainable electricity service reliably to energy-limited communities, based on local renewable energy (RE) sources and storage systems. Sociopolitical and economic forces as well as inclusionary and exclusionary culture or practices that often define the technical approaches and solutions offer opportunities for progress on this important problem.

> The articles in this special issue cover a wide range of inter-related challenges associated with energy access in remote and often impoverished areas of the world.

I. ELECTRICITY FOR ALL

Affordable energy is fundamentally connected to achieving development goals. Access to affordable energy is essential because of its direct role in water, food, and health security, as well as to social justice and equity. Increasing affordable energy access is also a transformative resource for those who live in extreme poverty (less than $1.25/day) and for the

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"proverbially" poor who survive on less than $2/day. Thus, we believe that it is not only a moral obligation but also a matter of global conscience that we expose the IEEE community, through this issue, to technical, economic, policy, and social work and initiatives focused on addressing the plight of some 2.5 billion people in the world without reliable access to electricity or basic thermal energy services for cooking.

The vicious cycle of poverty begins with a lack of access to affordable energy. Once trapped in this vortex of deprivation, lack of modern energy services translates into low economic productivity, time consumed by drudgery, and limited opportunities for income generation. This is a major failing of the existing global energy system, vast in scope but persistent in its indifference to the needs of a third of humanity. Through an interconnected system of pipes and pipelines, power plants, and processing plants, the global energy system extracts a massive amount of primary energy annually (upward of 550 EJ) and yet leaves millions to scour slums, agricultural fields, and forests for twigs and branches for basic needs. If the energy poor are to be drawn into the mainstream of global economic well-being, then access to reliable, cheap, and sustainable energy is a fundamental requirement. Energy poverty remains a barrier to economic well-being for such a large proportion of humanity that the rationale for action now is compelling.

It is clear that universal energy access cannot be achieved without a major scientific and technical push to lower costs by a very large margin, to improve reliability also by large margins, and find robust solutions that are scalable at the global level. Our primary focus in this special issue is to describe some of the state-of-the-art technologies and policies that will yield large economic and sustainable improvements in the overall performance of existing energy systems for poor and remote communities. Therefore, in this issue, we have brought together a wide range of leading experts from North America, Europe, Asia, and South America, working on key domains that support a multilayered approach to the development of a comprehensive set of solutions to energy poverty. We draw on insights from several disciplines from basic sciences to engineering and research in political and social sciences that will be integral to the development of innovative solutions to this important problem. We believe this issue will inform the IEEE members of and help broadening the efforts to address the important challenge of universal energy access that is in full harmony with the goals of a low-carbon future.

II. ARTICLES IN THE SPECIAL ISSUE

The articles in this issue focus on various relevant technical, policy, economic, and social aspects of supplying clean, sustainable, and affordable electricity to energy-impoverished communities around the globe. All articles are authored by recognized experts in the field of energy access, and the topics discussed are of significant interest to the IEEE, covering new areas of interest for the Institute that are gaining attention and relevance among its membership, like the aforementioned Smart Village initiative or the IEEE Transactions on Sustainable Energy. This special issue will be of particular interest to IEEE members as it brings to the forefront current and relevant technical, economic, political, and social issues that frame the solutions to the energy-access problem.

The scope of the presented articles covers a wide range of interrelated challenges associated with energy access in remote and often impoverished areas of the world. We have loosely grouped the articles to reflect regional clusters, starting with articles discussing topics and approaches that are relevant and applicable to all regions, followed by articles discussing issues and methodologies that are globally relevant but applied to specific energy-poor areas of the Americas, Africa, and Asia. Thus, the first three articles describe policy and data issues and approaches relevant and applicable to all regions. The next three articles focus on topics and methodologies for remote communities in North and South America. Finally, the bulk of articles in this issue discuss various energy-access concerns and solution approaches demonstrated with specific cases and interventions in Sub-Saharan Africa and Southern Asia, where energy access issues are most critical and affect large areas and populations.

A. Global

"Affordable energy for humanity: A global movement to support universal clean energy access" first highlights the issues and challenges associated with delivering universal energy access and related improvements in quality of life to citizens from vastly diverse regions and local contexts, which are lofty goals that have eluded policy makers and governments for over seven decades. The authors discuss and recommend a global network of Energy Access Innovation Centers (EAICs) dedicated to providing services to bolster the entire supply chain of talent and expertise, design and operational requirements of system deployment, and capacity to develop and deploy low-cost, high-performance technical solutions for energy impoverished communities.

"Data standardization for smart infrastructure in first-access electricity systems" focuses on data standardization for electricity-access and RE-based microgrids, since standardization could play a significant role in the context of electricity access, as there is very limited or no grid generation and consumption data in underdeveloped communities. Different data sources and how the data could be used, technological and capacity constraints for storage of data, political and governance implications, as well as data security and privacy issues are examined. The work presented is relevant to different stakeholders such as investors, public utilities, NGOs, and communities.

Based on the proposed data standardization approach, it would be possible to create a much-needed first-access electricity system database to provide important information for project developers and energy companies to assess the potential of grid sites, estimating its demand growth and establishing universal control systems.

"Review and perspectives on data-sharing and privacy in expanding electricity access" describes existing efforts regarding the gathering and use of grid and end-user data, characterizes current data management practices, and examines how expanding access to data and data-sharing are likely to provide value and pose risks to key energy-access stakeholders. Relevant opportunities and issues are identified with recommendations for the design and implementation of new data-sharing practices and platforms. It is argued that although a common and open platform for sharing technical data may mitigate risks and enable efficiencies, benefits from financial data are more limited, recommending as well codesigning practices with each stakeholder group, increasing legal protections for end users, and using deep qualitative data besides quantitative metrics.

B. The Americas

"Renewable energy integration in Alaska's remote islanded microgrids: Economic drivers, technical strategies, technological niche development, and policy implications" explores technical challenges and mitigation strategies for RE integration, including lessons learned from the implementation of over 70 renewable-diesel hybrid microgrids in Alaska utilizing a wide range of resource and technology solutions. It is a comprehensive review of the underlying sociopolitical and economic landscape that has allowed Alaska to emerge as an early adopter of microgrid-enabling technologies and includes a discussion of Alaska's energy programs and policies and how they impact project development. It shows that the primary technical hurdles for RE integration include the management of distributed energy resources (DERs) and design for reliable and resilient operation with intermittent high-penetration renewable generation. The economic drivers include extremely high energy costs, a highly deregulated utility market with dozens of utilities, state investment in infrastructure, and modest subsidies that create a technological niche where RE projects at remote communities are cost-competitive at current market prices.

"Renewable energy integration in diesel-based microgrids at the Canadian Arctic" presents specific studies including new variable-speed generation (VSG) technologies that demonstrate the feasibility, impact, and benefits of introducing RE together with VSGs in remote microgrids in the Canadian Arctic. A two-step procedure is described to select remote communities for detailed feasibility studies of deployment of RE sources, including a generation expansion planning framework and optimization model for RE and new VSG integration applied to the selected communities, to minimize diesel dependency of isolated microgrids and maximize the penetration of environmentally friendly generation technologies. The proposed approach is applied to communities in Nunavut and the North West Territories in the Canadian Arctic, based on actual data, to study the technoeconomic feasibility of RE integration and develop business cases for diesel generation replacement with RE and VSG generation in these communities. The presented optimal plans contain diesel–RE hybrid combinations that would yield substantial economic savings and reductions on green house gases emissions, which are being used as the base for actual deployments in some of the studied communities.

"Lowering electricity access barriers by means of participative processes applied to microgrid solutions: The Chilean case" discusses a coconstruction methodology for the development of sustainable energy supply solutions. The approach exploits local RE sources in energy-limited communities, which considers a flexible and participatory design with continuous communication between the technical team of the project and the community to ensure informed decision-making around the project design. The proposed methodology allows the identification of local requirements, less often considered for design procedures based on a traditional approach, in conjunction with the communities so that the technological solution is tailored for it. Different technical solutions have been proposed and developed under this framework, such as energy management systems, demand response strategies, microgrid applications for Mapuche communities, microformers, a monitoring system that includes social aspects, and vehicle-to-grid for microgrids. The article summarizes the experience of several microgrid projects in Chile, identifies risks, impacts, control actions, and discusses their replicability in the Latin American and Caribbean region.

C. Africa and Asia

"Optimal electrification planning incorporating on- and off-grid technologies: The reference electrification model (REM)" describes a novel optimization model and program for automatic electrification planning, identifying the lowest cost system designs to most effectively provide desired levels of electricity access to populations of any given size. REM determines the most suitable modes of electrification for each individual consumer by specifying whether customers should be electrified via grid extension, off-grid minigrids, or standalone systems. For each system, the program supplies detailed technical designs at the individual customer level. The application of the proposed mathematical model for energy-access planning in Sub-Saharan Africa and South Asia is discussed, describing REM's capabilities with case examples. REM electrification planning models have high granularity and can provide concrete plans for a wide range of geographical scales, having the potential to help rationalize electrification planning and expedite progress toward universal electricity access worldwide.

"Distributed resources shift paradigms on power system design, planning, and operation: An application of the GAP model" describes the grid and access planning (GAP) capacity expansion model, which is a novel approach to assess the sequencing and pacing of centralized, distributed, and off-grid electrification strategies, jointly assessing operation and investment in utility-scale generation, transmission, distribution, and demand-side resources. It is shown that, contrary to the current practice, hybrid systems that pair grid connections with DER are the preferred mode of electricity supply for greenfield expansion under conservative reductions in photo voltaic (PV) and energy storage prices, resulting in savings of 15%–20% mostly in capital deferment and reduced diesel use. The article argues that enhanced financing mechanisms for DER PV and storage could enable 50%–60% of additional deployment and save 15 $/MWh in system costs, which have important implications to reform current utility business models in developed power systems and to guide the development of electrification strategies in underdeveloped grids.

"Least-cost electrification modeling and planning—A case study for five Nigerian Federal States" presents a modeling process to derive a least-cost electrification plan for five states in Nigeria, combining energy system simulations with geospatial information system tools. It is shown that investments of approximately $1600 million for medium- and low-voltage distribution infrastructure, minigrids, and small-scale systems would be required to achieve a 100% electrification rate. The simulated electricity system of the five states is characterized by an overall load of 1804 MW. It is shown that 1772 MW of the load requirement should be supplied by central power generation through 11 579 km of new grid lines, whereas the rest should be served by minigrids comprised of a total of 225-MW PV, 504-MWh batteries, and 198-MW diesel generators, of which only three are isolated microgrids adding up to 3 MW, plus a total of 29-MW solar homes.

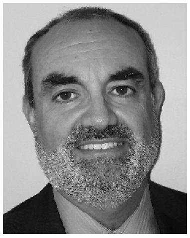
"The service value method for design of energy access systems in the Global South" introduces a novel method to gather and interpret end-user needs, aspirations, and contextual factors to improve engineering design practices for energy access in impoverished communities, based on a service-oriented approach and field exercises to gather qualitative and quantitative data from end users in focus groups. The data are interpreted as service maps that capture end-user preferences to inform tradeoffs of different design criteria, guiding the preliminary design of the energy system and ensuring that end-user needs and contexts are integrated into the design process early on. The proposed method and results of its application for the design of solar nanogrids in Kenya and Bangladesh are presented.

"Electrical minigrids for development: Lessons from the field" describes four identical capacity rural minigrid interventions undertaken in communities in Kenya and Uganda with differing socioeconomic characteristics and demographics. The article discusses the preparation stages of the interventions including community surveys that informed the technical design, deployment phases, and setup of the community cooperatives to manage the minigrid projects. The main focus is on lessons learned, including system design and minigrid performance under various load profiles. It is shown that there is clear and increasing uptake of power by the communities depending on the electricity tariff used, with the proposed approach of community-centered cooperatives running the delivered minigrids being now embedded within the rural electrification authorities/agencies in both countries, with additional similar projects being planned in 2019/2020. The application, ramifications, and replication of the presented minigrid concept as compared to other approaches are also discussed.

"Electrification processes in developing countries: Grid expansion, microgrids, and regulatory framework" presents a comprehensive review of the approaches commonly adopted for microgrid electrification, in the context of more economic and improved telecommunications and renewable generation technologies that have paved the way for new electric infrastructures, especially for emerging economies. Microgrids are considered since they are an affordable option for a rapid response to the electrification challenge, as well as allowing sharing resources with the bulk grid, which is technically and economically advantageous. A "real-life" study case is presented to highlight the operational challenges of a standalone microgrid versus a grid-connected system. Based on this experience, the need for an improved regulatory framework for effective integration of microgrids in the national grid is argued.

"Microhybrid electricity system for energy access, livelihoods, and empowerment" reports a technoeconomic feasibility and sustainability analysis for a hybrid microgrid in India, based on solar PV and biomass generation, which are widely available resources in impoverished, underserviced rural communities in the country. Energy demand and resource availability are estimated with inputs from extensive stakeholder discussions and field surveys, accounting for daily and seasonal variations in both supply and demand that consider household, community, irrigation, and commercial needs. Opportunities for the development of productive uses and their expansion through a sustainable business model are also explored. ■

ABOUT THE GUEST EDITORS



Claudio Cañizares (Fellow, IEEE) received the Electrical Engineer Degree from Escuela Politécnica Nacional (EPN), Quito, Ecuador, in 1984, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Wisconsin–Madison, Madison, WI, USA, in 1988 and 1991, respectively.

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Dr. Cañizares is a Fellow of the Royal Society of Canada, where he is currently the Director of the Applied Science and Engineering Division of the Academy of Science, and a Fellow of the Canadian Academy of Engineering. He was a recipient of the 2017 IEEE Power and Energy Society (PES) Outstanding Power Engineering Educator Award, the 2016 IEEE Canada Electric Power Medal, and various IEEE PES Technical Council and Committee awards and recognitions, holding leadership positions in several IEEE-PES Technical Committees, Working Groups, and Task Forces.

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He was involved in a leadership capacity in the Canadian energy sector over a 30-year period. He brings a unique combination of academic perspectives with extensive experience in the business sector that includes corporate planning and strategy, energy sector policy reform, power system planning, environmental and regulatory affairs, and research program management. In 2007, he joined the University of Waterloo (UW), Waterloo, ON, Canada, where he is currently the Founding Executive Director of the Waterloo Institute for Sustainable Energy (WISE), holding the prestigious Ontario Research Chair in Public Policy for Sustainable Energy. As a Leader of WISE, he focuses on bringing together the expertise of UW faculty members to develop and implement large-scale multidisciplinary research projects in collaboration with business, industry, governments, and civil society groups, to meet the Institute's vision of clean energy, accessible, and affordable for all. He is also the Co-Director, with Prof. J. Knebel at the Karlsruhe Institute of Technology, Karlsruhe, Germany, of the consortium Affordable Energy for Humanity (AE4H): A Global Change Initiative, which comprises more than 150 leading energy access researchers and practitioners from 50 institutions and 25 countries, focusing on the eradication of energy poverty. He serves on several boards at the provincial and national levels and has appeared frequently in the media (print, TV, and radio), having more than 100 publications related to energy and risk management, including seven books. He is a Registered Professional Engineer in the Province of Ontario.

Daniel Kammen (Member, IEEE) served as the first Chief Technical Specialist for Renewable Energy and Energy Efficiency, World Bank, Washington, D.C., USA, from 2010 to 2011 and was an Energy and Climate Partnership for the Americas (ECPA) Fellow with the U.S. State Department from 2010 to 2016. From 2016 to 2017, he served as the Science Envoy for the U.S. State Department, Washington, D.C. He is currently a Professor of energy with appointments in the Energy and Resources Group (ERG), the Goldman School of Public Policy, and the Department of Nuclear Engineering at the University of California at Berkeley, Berkeley, CA, USA, where he is the Chair of ERG and directs the Renewable and Appropriate Energy Laboratory (RAEL). He is a Coordinating Lead Author for the Intergovernmental Panel on Climate Change (IPCC), for which he received the Nobel Peace Prize in 2007. He is a Co-Developer of the Property Assessed Clean Energy (PACE) Financing Model, an energy efficiency and solar energy financing plan that permits installation of clean energy systems on residences with no upfront costs. PACE was named by Scientific American as the No. 1 World Changing Idea of 2009 (co-developed with Cisco DeVries). Recently, his work on urban minigrids and the EcoBlock concept was rated as a World-Changing Idea of 2017 by Scientific American. He has authored more than 400 publications and 12 books and has testified over 40 times at state and U.S. congressional hearings.