Microgrids: Impact on Development of Sustainable Electric Energy Systems

Pertti Järventausta, Faculty of Information Technology and Communication Sciences/Electrical Engineering, Tampere University, pertti.jarventausta@tuni.fi

Lasse Peltonen, Faculty of Information Technology and Communication Sciences/Electrical Engineering, Tampere University, lasse.peltonen@tuni.fi

Jussi Valta, Faculty of Management and Business/Industrial Engineering and Management, Tampere University, jussi.valta@tuni.fi

Sanna Uski, VTT Technical Research Centre of Finland, Ltd; Ampner Ltd, sanna.uski@ampner.com

Pami Aalto, Faculty of Management and Business/Politics, Tampere University pami.aalto@tuni.fi

1. Definition

The concept of microgrid is evolving by leaps and bounds and assumes various forms depending on location and local requirements (Wouters 2015, 23). At the same time, the definition of microgrid is not based on a minimum or maximum size of a microgrid system but rather on function (Soshinskaya et al. 2014, 661).

A generic definition treats microgrid as a cluster of locally available or distributed generation (DG) resources, other renewable energy resources and local loads connected to the utility grid (Fu et al. 2013). More precisely, microgrids are "electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, co-ordinated way either while connected to the main power network or while islanded", as suggested by the work of the CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap (Marnay et al. 2015).

The draft version of International Electrotechnical Commission (IEC) standard (IEC TS 62898-2) for its part relates microgrids to alternating current (AC) electrical systems with loads and distributed energy resources (DER) at low or medium voltage level. However, in addition to AC microgrids, low voltage direct current (LVDC) microgrids also exist (Nuutinen et al. 2017). Some definitions moreover include not only electric but also thermal loads, that is, heat (Mohn 2012, 17). The draft IEC standard divides microgrids into isolated microgrids with no electrical connection to a centralized electric power system, operating in island mode only and non-isolated microgrids, which may be controllable units of the centralized electric power system and operate in grid-connected or islanded mode. Together, these different definitions indicate the versatility of the concept of microgrid. In practice, the realization of microgrids varies depending, for example, on available resources, market area, regulations and technology.

Microgrids have attracted more attention owing to the ongoing transition of energy systems. Electricity is becoming more crucial than before while electric energy systems are witnessing increasing penetration of variable, weather-dependent renewable energy production such as solar or wind power, or as it is conventionally termed, intermittent production. This increases the need for flexibility within the electric energy system. Microgrids can help to provide such flexibility. Simultaneously, modern societies are increasingly dependent on the security of supply which microgrids can also enhance. The “smart” electric energy systems envisioned in most Member States of the Organisation for Economic Cooperation and Development (OECD) should simultaneously serve interests such as energy-efficiency, environmental protection and reliability that can be promoted by means of microgrid solutions. In the context of developing countries, microgrids can support energy access and electrification, considering that a quarter of the world’s population lack access to electricity while 2.4 billion people use traditional biomass for cooking and heating (Mohn 2012, 17).

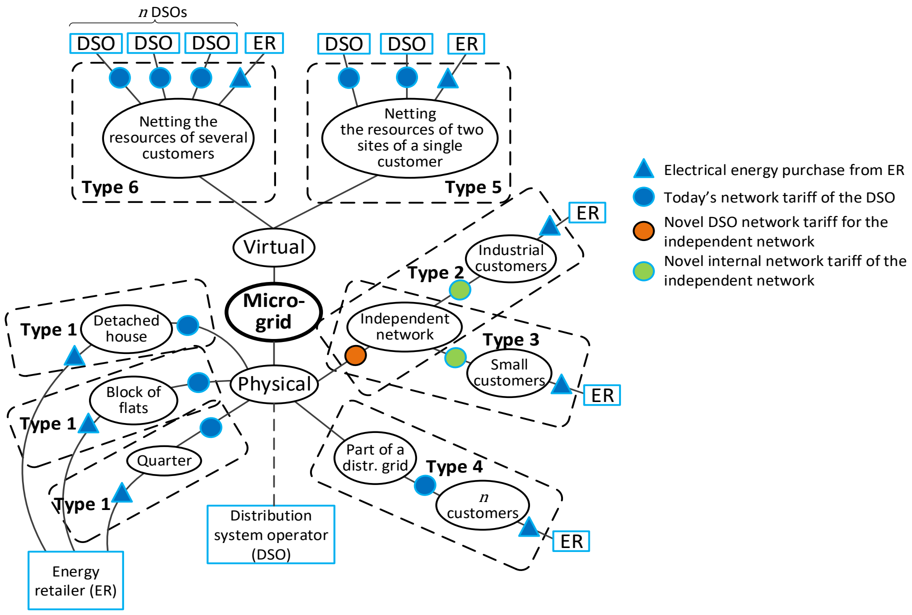
Given the availability of multiple types of microgrid solutions (see section 1.1) applicable to both developed and developing countries, they can support the sustainable development goals of the United Nations (UN), thereby ensuring access to affordable, reliable, sustainable and modern energy for everyone by 2030 (Wu and Wu 2015). Microgrids can also improve the resource fficiency of the energy system as a whole and offer several technical benefits for its operation (Vine and Morsch 2017; see section 2 below).

1.1 Types of microgrids

Various types of microgrids can be identified with region, country and market-specific differences. Microgrids vary from small systems based on the resources of an individual actor to larger ones consisting of several actors pooling their energy resources within a joint low-voltage network supplied by one secondary transformer. Microgrids may extend over a large area with multiple energy resources formed around a medium voltage network. At the other extreme, virtual microgrid comprises energy resources situated at different network locations. As a commercial entity, microgrid can also be considered a prosumer (customer both consuming and producing energy). Such a prosumer may be an individual customer (for example, the owner-occupier of a detached house) or a community consisting, for example, of the residents of an apartment block or the units of an industrial facility.

Various types of physical and virtual microgrids with different commercial connections to the Distribution System Operator (DSO) and energy retailer can be discerned (see Fig. 1). The Nordic electricity market can conveniently serve as a proxy illustrating these options owing to its advanced, open character with several independent actors trading energy and managing the grid, and hence enabling different types of microgrids.

Fig. 1. Types of microgrids and their commercial connections to the DSO and the energy market. The blue circles in the figure represent the existing grid tariffs of the DSO available to the customer. The blue triangles represent the products of the energy retailers. The total electricity bill before tax is deducted is the sum of these. The orange circle represents a new type of grid tariff structure that may yet be needed for large-scale microgrids. The green circle illustrates a new type of tariff structure



Type 1 microgrid may comprise a detached house and the resources available to it including, for example a solar PV plant, controllable loads such as electric space heating or a water boiler, electrical energy storage or an electric vehicle (EV). A block of flats can likewise form a microgrid in an energy community format utilizing similar resources, optimizing the use of common loads such as lifts and the loads of individual flats. This type of microgrid may also include buildings sited in the same quarter. The ongoing energy transitions, when combined with appropriate market design and regulation, support the emergence of type 1 microgrids in the Nordic context and further in the OECD countries (see also section 3 below).

Type 2 microgrid consists of a larger area with various energy resources and a medium voltage network. The microgrid in this case is considered a separate network with a dedicated network licence from the regulator. This may involve a large industrial customer, such as a pulp and paper mill or a shopping centre with its own electricity network and generation units.

Type 3 microgrid consists of small consumers, such as detached houses. However, not all regulatory frameworks recognize or enable this type of microgrid, as is the case in Finland in the Nordic context. From the point of view of network pricing, type 2 and 3 microgrids may require novel distribution network tariffs and separate tariffs for internal use.

Type 4 microgrid is part of the network of the DSO, built to enable island operated mode. The DSO can offer uninterrupted electricity supply to the customers within the microgrid area if the microgrid has production unit(s) and/or electrical energy storage, or access to a mobile reserve power unit.

Finally, virtual microgrids “cover DER at multiple sites but are coordinated such that they can be presented to the grid as a single controlled entity” (Marnay et al. 2015). In other words, the energy resources are located at different sites owned by an individual customer (type 5) or by several different customers (type 6). For example, in type 5 microgrid, the production of solar PV panels at a customer’s property can also be aggregated with the load of this customer on a separate property at a different geographical location. Alternatively, this type may be applicable if a block of flats rents land not in its immediate neighbourhood to develop a small-scale solar PV park. At both points of network connection the customer pays grid charges to the DSO(s). This means that the properties may be located in the areas of two different DSOs.

Type 6 is an energy community or virtual microgrid. It consists of several customers whose energy resources are aggregated by the energy retailer. Each customer pays distribution fees to the DSOs based on the measurements at the network connection point. Such virtual communities can be formed in the present electricity market environments of many OECD countries with the retailer operating as an aggregator.

2. Microgrids enabling sustainability

As microgrid types 1-4 (see above) feature mostly small-scale generation units close to the point of consumption, they enable the exploitation of abundant distributed renewable energy resources, e.g. solar or wind power, or local bio-based fuels (Murthy 2012). In some cases, micro-hydropower can also be used (Soshinskaya et al. 2014, 662). The use of local resources serves the UN sustainable development goals vis-à-vis the energy sector in several ways (see above), while also supporting wider social objectives.

Local generation close to the loads reduces the transmission losses typical of centralized power systems and decreases the loading and transmission capacity needs of the transmission system (Lasseter and Piagi 2007). With the assets of the system in effective use, the need to expand transmission capacity decreases. Possible indirect effects include enhanced local employment and economy (Mergner and Rutz 2014). Local power generation also decreases dependence on large utilities and other energy business actors that frequently operate within the confines of the fossil fuels economy (Jones 2017, 271-278), and dependence on foreign electricity imports whose environmental sustainability is difficult to ascertain. Finally, local generation can augment energy poverty by means of co-operative models allowing low-cost, wide-ranging participation. This can raise awareness of energy issues, inducing a transformation from passive consumers to active prosumers, and by extension, prompting people to make more environmentally sustainable energy choices. This can shape their energy consumption habits, thus helping to decrease greenhouse gas emissions (Koirala et al. 2016).

Microgrids can have wide-ranging sustainability effects in developed OECD countries, where the electrical power lines reach almost all consumers. In developing countries, where electricity connections may be poor or non-existent, microgrids can be deployed for purposes of electrification notably in remote areas (Basnet et al. 2015) or for increasing the reliability of power supply (Buque and Chowdhury 2016). Microgrids can also increase resilience in different environmental conditions, e.g. locations hit by hurricanes (Kwasinski 2010) or in cold climates or Arctic conditions (Whitney 2017).

Although microgrids potentially serve a wide range of sustainable development interests and can support the ongoing energy transitions, they may not always be profitable. Hence microgrids range from commercially operated for-profit solutions to partly and fully subsidized ones (Schnitzer et al. 2014, 1-2). Moreover, in commercially operated microgrids, natural gas based solutions may – depending on the context – turn out to be the most profitable. Hence, without a proper policy and regulatory framework prioritizing locally available renewable sources, the multiple sustainability benefits of microgrids may not be fully exploited (Hanna et al. 2017). Yet, even with adequate sustainability policies and regulation in place (see section 3 below), commercially driven developers have access to multiple revenue streams: e.g., participation in demand response programmes, export of on-site generation to the electricity grid, reduced cost due to added resiliency against outages and lost loads and participation in local microgrid electricity markets (Stadler et al. 2016).

Microgrids can also serve the interests of the centralized power system, considering how energy and electricity – today and in the future – are crucial to the functioning of developed societies in particular. Microgrids can provide services and support, for example in the frequency reserve market (Yuen et al. 2011), thus improving the long-term synergy between the interconnected transmission system, distributed generation and local microgrids. Distributed microgrids within a centralized power system also increase the resilience of the whole system against major black-outs. Furthermore, power supply is needed to maintain the vital information and communication technology systems operational during transmission system black-outs (Tsumura 2008). Operational, electrified islanded mode microgrids within a blacked-out centralized power system can help to restore electricity supply to customers (Wang et al. 2016), and support the power restoration of the system (Peças Lopes et al. 2005).

Finally, multiple small-scale microgrids using distributed resources within larger power systems are invaluable against cyber-attacks. Microgrids enable local power supply even in the event of the centralized power system being paralyzed by cyber-attacks. However, there are cyber security issues to be managed in all individual power systems, including microgrids (Zhiyi et al. 2017). Nevertheless, the effects of cyber-attacks on individual microgrids and the whole transmission system are of different orders of magnitude.

3. How can regulation promote sustainable microgrids?

3.1 Affordability

The affordability of microgrid solutions in comparison to the main grid is improving due to decreasing DER prices. This helps urban microgrids to increase the amount of self-produced energy, in particular solar PV. They can also offer grid services through new energy storage and management technologies. Nevertheless, unambiguous regulation is important for affordability. It decreases capital costs and establishes the framework for different business models such as energy service agreements. Governments can further reduce the capital costs with soft loans and grants. Regulated energy prices protect customers but impact financing options (IRENA et al. 2018). Whether the microgrid has the status of an electricity company likewise affects its affordability, since in such a case it has to follow the same ratemaking procedures as other utilities. For grid-connected microgrids it matters whether they can participate in demand-response markets (Burr et al. 2013). Dynamic pricing and services to reserve markets increase the opportunities to earn revenue, although they also require more advanced energy management systems.

Decreasing DER prices makes rural islanded microgrids, typical in developing countries, less dependent on expensive, volatile diesel prices. In terms of regulation and policy, rural microgrids are often part of rural electrification plans that include the development of the centralized power grid. Microgrid operators can be guaranteed exclusive rights for operating in a certain area so that they can amortise all its assets (Vinci et al. 2016). Some countries set tariff-caps for private microgrids, while some governments cross-subsidize them at the expense of the customers of the centralized power grid. In some cases, microgrids are self-regulatory (Vinci et al. 2016). The cost difference between microgrids and the centralized power grid can also be subsidized by reducing the import tariffs of the required technologies, including solar PV plants and energy management systems.

3.2 Environmental, economic and social objectives

Regarding the environmental objectives, microgrids entail emission evaluations and regulation since they typically include energy production close to population centres (Strachan and Farrell 2006). Economical regulation is moving towards more system-friendly policies aiming to reduce peak loads, so far typically handled by fossil fuel generators, and towards policies appreciating the integration of DER to the centralized power grid. For instance, feed-in tariffs are being replaced by self-consumption policies where electricity consumption takes place at the same property or is adjacent to the generation site (King 2006). Fixed feed-in tariffs have been efficient in incentivizing renewable energy investments but they may dis-incentivize local energy management or microgrid solutions. The purpose of feed-in tariffs is to maximize production from renewables but they do not take account of demand and supply peaks, and the prospects of grid services or islanding (Tao et al. 2011), as more dynamic pricing models would do (Zhou et al. 2016; Yuan et al. 2017). In most cases the current taxation rules suit conventional power systems by forming a fixed amount of the energy bill without incentivizing demand-response or self-consumption. For example, feeding any excess electricity from the microgrid into the centralized power grid should yield a fair compensation, especially if sustainably produced.

Where demand response rules exist, they are often designed for fossil fuel generation rather than distributed renewable energy resources. For instance, rules for reserve markets and capacity mechanisms have technical characteristics reminiscent of conventional generators, such as long availability and large bid sizes (Pérez-Arriaga and Knitte 2016). Connecting aggregators of small-scale distributed generation to these markets entails altering the rules and responsibilities among all actors within the scope of the grid (Eid et al. 2016). The internal market mechanisms of microgrids can increase consumer engagement and system efficiency but remain undeveloped (Mengelkamp et al. 2018). Furthermore, internal market mechanisms require smart metering of consumption, which adds costs but helps to optimize the use of resources within the system.

Self-consumption policies have economic and social drawbacks when implemented within current regulatory regimes. Self-consumption with volumetric tariffs for grid supply creates cross-subsidization from non-microgrid customers to microgrids customers (Pica et al. 2015; Burr et al. 2013). To become more cost-reflective, network tariffs are moving towards power demand charges (Villarreal et al. 2014). Maintaining the internal consumption within the microgrid tax-free has the same effect. In developing countries the customers of the centralized power grid may understandably subsidize more expensive rural off-grid solutions. Different prices between main grid and microgrid consumers, or between neighbouring villages, form political barriers in putting businesses and households in unequal situations (IRENA et al. 2018). Overall, self-consumption policies incentivize microgrids in the short term and can support energy transitions. Therefore a balanced approach is necessary (Faure et al. 2017), although equality among consumers must be the long-term aim.

3.3 Modernization objectives

The structure of the energy market significantly influences the diffusion of modern distributed energy technologies. Microgrids serve only certain customers whereas utilities have to offer the same level of service to everyone. Regulation often merely sets the minimum service level. Furthermore, utilities tend to look backwards in their planning processes because of cost-of-service remuneration, being mindful of established practices and dis-incentivised for proactive decisions. These approaches are currently challenged by regional differences in future DER adoption. Reductions in technology prices are also difficult to predict (Pérez-Arriaga and Knitte 2016). Investing in large capital-intensive infrastructure projects like transmission lines can create lock-ins where potentially more sustainable local solutions cannot emerge.

Within the EU unbundling the generation and network businesses is intended to enhance competition, presumably leading to affordable prices for customers. However, microgrids are not entirely suitable for such a competitive modernization paradigm. Microgrids are not necessarily fully competitive as they emphasize the allocation and sharing of local energy. Separating production from distribution can also increase transaction costs in small systems. That DSOs are forbidden to own storage within the EU may have grave consequences for microgrids. However, the Clean Energy Package of the EU includes the definition of Local Energy Community and exceptions for closed distribution network operators for installing extra generation capacity in order to cover energy losses and provide non-frequent ancillary services to the grid (European Commission 2017).

3.4 Reliability objectives

Microgrids can offer reliable power with the right configurations taking account of local circumstances and resources. Too excessive regulatory requirements may inhibit microgrid diffusion whereas inadequate regulation may not guarantee reliable and safe long-term power to consumers. Classifying microgrids as "distribution companies" raises the question of whether they have obligations to offer service, or are bound by consumer protection laws and need emission permits (Hirsch et al. 2018). In developed countries the liabilities inherent in DSO status and the associated permitting process, can be burdensome and a barrier to the diffusion of private microgrids. At the same time, DSOs can use a microgrid concept to improve reliability in remote communities and thereby reach their reliability standards. In developing countries local private microgrids can improve the quality of service and reliability. In such cases the private operator can work locally and may pay a small rent to the network operator for grid usage (Vinci et al. 2016, 64). In the USA utilities have franchise rights setting the service territories which, in essence, prohibit communities from undertaking infrastructure improvements on their own (Kumar et al. 2015).

The interconnection to the centralized power grid is a major regulatory issue vis-à-vis microgrids. In most cases the original guidelines for connecting distributed generation were issued when microgrids were not recognized as constituting distributed energy sources. Therefore the capability of some microgrid types for islanded operation, to continue feeding power during black-outs, is often not recognized in regulations but instead treated as disturbance to the centralized power grid (Tao et al. 2011). The capability for islanded operation increases reliability and offers added value, especially in critical loads such as hospitals. In stand-alone systems the situation is different; franchise rights or interconnections are not issued, at least until the centralized power grid extends to the area. In such projects quality issues and technical standards are important for customer protection. Licensing and permitting can ensure some level of reliability and service. Availability of information on different requirements is important while such licensing processes should also be streamlined. Small projects below one megawatt are sometimes exempted from licensing requirements in order to facilitate their implementation (IRENA et al. 2018).

4. Technical aspects in microgrid development

4.1 General features

Because several types of microgrids can be developed (see section 1 above), different combinations of grid architectures, production units and control methods are applicable. The tools and procedures for evaluating and quantifying the overall technical design of microgrids are equally numerous. The location of the grid and availability of local energy resources naturally restrict some of these combinations. Yet each combination has its own case-specific features, in particular regarding frequency, voltage stability and control, as well as power sharing methods between generation units and safety issues.

The normal operation and fault response of microgrids varies greatly depending on whether generation units are directly grid-connected (e.g. diesel-generation set) or connected to the grid via a power electronics (e.g. PV plant). In the latter case, the ability of an inverter to feed fault current is substantially lower compared to a directly grid-connected, synchronous generation unit. The dynamic response of the microgrid can be greatly enhanced in both of these cases if an energy storage system is integrated into the system. An energy storage system is often a crucial component if an uninterrupted transition from a grid-connected to islanded mode is needed.

4.2 Microgrids as part of the electricity system

Recent dynamic analyses of power systems, including islanding studies, have mostly addressed either the transmission or distribution system level. As a result, only few studies have concentrated on both system levels, their interactions, traits and challenges (Suh et al. 2017). Separate dynamic analyses have found no accuracy problems in power systems because of the still small amount of DER and low penetration of microgrids on the distribution system level. In the future microgrids may constitute a notable share of the electric power system. Therefore the transmission system operator (TSO) cannot ignore the role of microgrids while evaluating the stability of the transmission network. In the future dynamic analyses of both system levels must also be conducted in parallel.

Most islanding analyses on the transmission system level emphasize the survival of the whole or part of the transmission system. The studies conducted on the distribution network level for their part focus on proper and safe operation within a usually fairly small islanded area. Here major issues include how the islanded grid can supply uninterrupted power to critical loads, and how the safety and control issues are handled (Ma et al. 2014). Furthermore, given the existence of several different topology alternatives, a review of the fundamental distribution network architectures is needed. These include radial, ring and mesh architectures, considering their types of operation, control and management, growth model and advantages and disadvantages (Islam et al. 2017). A microgrid concept wider than the traditional one is Multi-MicroGrid (MMG), which provides connectivity to several microgrids. The concept entails rethinking the operational and planning methodologies of distribution systems to exploit the opportunities of such a novel arrangement (Celli et al. 2016).

4.3 Control of microgrids

Most of the basic control requirements between stand-alone microgrids and centralized power systems, such as load balance and stability issues related to voltage and frequency, are in principle similar (Cady et al. 2015). However, there are often two main differences: system size, i.e. the total kinetic energy of rotating masses and the total amount of apparent power of the production units and the way the production units are connected to the grid. Microgrids are typically much smaller while frequently some, or all of the production units, are connected to the grid via an inverter. In inverter-connected units, the primary source may be AC or DC.

Several types of stability studies, including various types of generating units and control methods, have been conducted. They prove that microgrids can withstand severe grid conditions in stand-alone mode if the numbers and types of generating units are properly dimensioned and appropriate control methods are selected. For example, two combinations of generating units: i) generation with static electronic converter and synchronous generator and ii) static converter connected generation, survived a severe load imbalance following two very different control strategies (Negri et al. 2017). Further, the successful control and operation of a microgrid in islanded mode consisting of several different generating units is feasible. For example, uninterrupted power supply to local loads can be provided with the combination of a diesel unit, PV plant and battery energy storage (Koohi-Kamali and Abd Rahim 2016).

Centralized power systems typically apply centralized control methods. In microgrids centralized control methods can also be used but because of the small size of the system decentralized methods can be exploited equally well. In general two types of power sharing methods between generating units are frequent. In a droop-control method, each production unit adjusts its output power based on the measured quantities of the microgrid, such as voltage and frequency. In a master and slave control method, one master unit dictates the voltage and frequency in the microgrid and other units operate on the basis of commands received from the master unit (Caldognetto and Tenti 2014).

For technical reasons a microgrid may require more than one storage technology (Sreelekshmi et al. 2016). In case of severe power imbalance within the microgrid, a further option is load shedding. Novel load shedding schemes have been proposed (Zhang et al. 2014). Uninterrupted power supply to the local loads is a major benefit in the microgrid concept. Therefore the load shedding method is usually the last countermeasure preventing the collapse of the microgrid.

5. Summary

Microgrids are relatively small-scale electricity distribution systems utilizing local resources. They may include energy storage as well as heat and cool distribution units. Microgrid solutions are deployable in developed and developing countries alike. They may comprise apartment blocks and critical infrastructures such as hospitals; or serve remote villages, larger industrial areas or communities of citizens. Types of microgrids range from those connected to the main grid to off-grid systems in remote areas, and further to energy community type virtual microgrids linking resources and consumption that are geographically separated from each other. Microgrids can support sustainable development by means of enhancing the use of locally available renewable resources, avoiding transmission losses typical of centralized electric power systems as well as excess infrastructure. Further, they may offer local socio-economic benefits, increase local awareness of energy and sustainability issues, enhance participation and improve security of supply as well as the resilience and security of the system. Suitable regulation is crucial in realizing these benefits given that until now microgrids in most localities have not been central to energy policy and law. At the same time, the microgrid concept offers flexible solutions suitable for different environments. Several combinations of grid architecture, generation units and control methods are possible depending on where the microgrid is to be deployed and what resources are to be used.

Cross-references

Alternative energy
Community engagement
Electricity
Energy prosumerism
Future energy
Local and global environmental sustainability
Policy experimentation
Sharing economy and the future of energy
Universal access to energy

References

Basnet S, Aburub H, Jewell W, Poudel A (2015) Case study of microgrid for electrification and its benefits in rural Nepal. Paper presented at the Global Humanitarian Technology Conference (GHTC), IEEE, Seattle, USA, 8-11 October 2015 https://doi.org/10.1109/GHTC.2015.7343951

Buque C, Chowdhury S (2016) Distributed generation and microgrids for improving electrical grid resilience: Review of the Mozambican scenario. Paper presented at the Power and Energy Society General Meeting (PESGM), IEEE, Boston, USA, 17-21 July 2016 https://doi.org/10.1109/PESGM.2016.7741488

Burr MT, Zimmer MJ, Meloy B, Bertrand J, Levesque W, Warner G, McDonald JD (2013) Minnesota Microgrids : Barriers, Opportunities, and Pathways Toward Energy Assurance. Available via Microgrid Institute for the Minnesota Department of Commerce. http://mn.gov/commerce-stat/pdfs/microgrid.pdf. Accessed 12 May 2018

Cady ST, Dominguez-Garcia AD, Hadjicostis CN (2015) A Distributed Generation Control Architecture for Islanded AC Microgrids. IEEE Transactions on Control Systems Technology 23(5):1717-1735 https://doi.org/10.1109/TCST.2014.2381601

Caldognetto T, Tenti P (2014) Microgrids Operation Based on Master-Slave Cooperative Control. IEEE Journal of Emerging and Selected Topics in Power Electronics 2(4):1081-1088 https://doi.org/10.1109/JESTPE.2014.2345052

Celli G, Mocci S, Pilo F, Soma GG (2016) Multi-microgrids for innovative distribution networks in rural areas, Paper presented at Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2016), IET, Belgrade, Serbia, 6-9 November 2016

Eid C, Bollinger LA, Koirala B, Scholten D, Facchinetti E, Lilliestam J, Hakvoort R (2016) Market integration of local energy systems: Is local energy management compatible with European regulation for retail competition? Energy 114:913–922 https://doi.org/ 10.1016/j.energy.2016.08.072

European Commission (2017) Proposal for a Directive on common rules for internal market in electricity. COM 864 (final 2), February 23. Available via EC. https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf. Accessed 8 May 2018

Faure M, Salmon M, Fadili S El, Payen L (2017) Urban microgrids - Overview, challenges and opportunities. Available via ENEA. . Accessed 12 May 2018

Fu Q, Hamidi A, Nasiri A, Bhavaraju V, Krstic SB, Theisen P (2013) The Role of Energy Storage in a Microgrid Concept: Examining the opportunities and promise of microgrids. IEEE Electrification Magazine 1(2):21-29 https://doi.org/10.1109/MELE.2013.2294736

Hanna R, Ghonima M, Kleissl J, Tynan G, Victor DG (2017) Evaluating business models for microgrids: Interactions of technology and policy. Energy Policy 103:47-61 https://doi.org/10.1016/j.enpol.2017.01.010

Hirsch A, Parag Y, Guerrero J (2018) Microgrids: A review of technologies, key drivers, and outstanding issues. Renewable and Sustainable Energy Reviews 90:402-411 https://doi.org/10.1016/j.rser.2018.03.040

IEC TS 62898-2 ED1 (2018) Microgrids - Guidelines for Microgrid Operation (and Control) http://www.iec.ch/dyn/www/f?p=103:38:0::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1240,23,21246. Accessed 11 May 2018

IRENA, IEA, REN21 (2018) Renewable Energy Policies in a Time of Transition. Available via IRENA. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_IEA_REN21_Policies_2018.pdf. Accessed 09 May 2018

Islam FR, Prakash K, Mamun KA, Lallu A, Pota HR (2017) Aromatic Network: A Novel Structure for Power Distribution System. IEEE Access 5:25236-25257 https://doi.org/10.1109/ACCESS.2017.2767037

Jones L (2017) Renewable Energy Integration - Practical Management of Variability, Uncertainty, and Flexibility in Power Grids. 2nd edition. London, Elsevier

King DE (2006) Electric Power Micro-grids: Opportunities and Challenges for an Emerging Distributed Energy Architecture. Dissertation, Carnegie Mellon University https://ceic.tepper.cmu.edu/-/media/files/tepper/centers/ceic/publications/phd%20dissertations/2006/doug_king_phd_thesis_2006%20pdf.pdf?la=en. Accessed 5 May 2018

Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM (2016) Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renewable and Sustainable Energy Reviews 56:722–744 https://doi.org/10.1016/j.rser.2015.11.080

Koohi-Kamali S, Abd Rahim N (2016) Coordinated control of smart microgrid during and after islanding operation to prevent under frequency load shedding using energy storage system. Energy Conversion and Management 127:623-646 https://doi.org/10.1016/j.enconman.2016.09.052

Kumar A, Azad ML, Noida G, Noida G (2015) Challenges in recent microgrid systems: A review. International Journal of Advances in Engineering & Technology 8(2):203–210 http://www.e-ijaet.org/media/22I26-IJAET0826401-v8-iss2-pp203-210.pdf. Accessed 6 May 2018

Kwasinski A (2010) Technology Planning for Electric Power Supply in Critical Events Considering a Bulk Grid, Backup Power Plants, and Micro-Grids. IEEE System Journal 4(2):167-178 https://doi.org/10.1109/JSYST.2010.2047034

Lasseter RH, Piagi P (2007) Extended Microgrid Using (DER) Distributed Energy Resources. Paper presented at the Power Engineering Society General Meeting, IEEE, Tampa, USA, 24-28 June 2007 https://doi.org/10.1109/PES.2007.385682

Ma T, Serrano B, Mohammed O (2014) Distributed control of hybrid AC-DC microgrid with solar energy, energy storage and critical load. Paper presented at the Clemson University Power Systems Conference, IEEE, Clemson, USA, 11-14 March 2014 https://doi.org/10.1109/PSC.2014.6808103

Marnay C, Chatzivasileiadis S, Abbey C, Iravani R, Joos G, Lombardi P, Mancarella P, von Appen J (2015) Microgrid Evolution Roadmap. Paper presented at the International Symposium on Smart Electric Distribution Systems and Technologies (EDST), IEEE, Vienna, Austria, 8-11 September 2015 https://doi.org/10.1109/SEDST.2015.7315197

Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C (2018) Designing microgrid energy markets. A case study: The Brooklyn Microgrid. Applied Energy 210:870-880 https://doi.org/10.1016/j.apenergy.2017.06.054

Mergner R, Rutz D (2014) Community energy in Germany: existing models, public-private funding and good practice examples. IEE/12/991. Available via Community Power http://www.communitypower.eu/images/GemanyD32.pdf. Accessed 05 May 2018

Mohn T (2012) In the Wider World, Microgrids will Flourish. The Electricity Journal 25(8):16-20 https://doi.org/10.1016/j.tej.2012.09.019

Murthy SS (2012) Micro-Grid integration with renewable energy in Indian perspective. Available via Academia.edu. https://www.academia.edu/5876047/Micro-_Grid_Integration_with_Renewable_Energy_in_Indian_Perspective

Negri S, Tironi E, Danna DS (2017) Integrated control strategy for islanded operation in smart grids: Virtual inertia and ancillary services. Paper presented at the IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), IEEE, Milan, Italy, 6-9 June 2017 https://doi.org/10.1109/EEEIC.2017.7977725

Nuutinen P, Kaipia T, Karppanen J, Mattsson A, Lana A, Pinomaa A, Peltoniemi P, Partanen J, Luukkanen M, Hakala T (2017) LVDC rules – technical specifications for public LVDC distribution network. CIRED - Open Access Proceedings Journal 2017(1):293-296 https://doi.org/10.1049/oap-cired.2017.0519

Peças Lopes, JA, Moreira CL, Resende FO (2005) Control Strategies for Microgrids Black Start and Islanded Operation. Paper presented at the 15th PSCC, Liege, Belgium, 22-26 August 2005 http://www.montefiore.ulg.ac.be/services/stochastic/pscc05/papers/fp69.pdf. Accessed 13 May 2018

Pérez-Arriaga I, Knitte C (2016) Utility of the Future - An MIT Energy Initiative response to an industry in transition. Available via MIT Energy Initiative. https://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf. Accessed 9 May 2018

Pica CQ, Martins MAI, Leites TN, Rodrigues N (2015) Proposition of alternatives for microgrid insertion in Brazilian's regulatory context. Paper presented at the Innovative Smart Grid Technologies Latin America (ISGT LATAM), IEEE, Montevideo, Uruguay, 5-7 October 2015 https://doi.org/10.1109/ISGT-LA.2015.7381243

Schnitzer D, Lounsbury DS, Carvallo JJ, Deshmukh R, Apt J, Kammen DM (2014) Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. Available via United Nations Foundation. http://energyaccess.org/wp-content/uploads/2015/07/MicrogridsReportFINAL_high.pdf. Accessed 2 May 2018

Soshinskaya M, Crijns-Graus WHJ, Guerrero JM, Vasquez JC (2014) Microgrids: Experiences, barriers and success factors. Renewable and Sustainable Energy Reviews 40:659-672 https://doi.org/10.1016/j.rser.2014.07.198

Sreelekshmi RS, Prasad A, Manjula GN (2016) Control and operation of microgrid connected Hybrid Energy Storage System. Paper presented at the 2016 International Conference on Energy Efficient Technologies for Sustainability, IEEE, Nagercoil, India, 7-8 April 2016 https://doi.org/10.1109/ICEETS.2016.7582889

Stadler M, Cardoso G, Mashayekh S, Forget T, DeForest N, Agarwal A, Schönbein A (2016) Value streams in microgrids: A literature review. Applied Energy 162:980-989 https://doi.org/10.1016/j.apenergy.2015.10.081

Strachan N, Farrell A (2006) Emissions from distributed vs. centralized generation: The importance of system performance. Energy Policy 34:2677–2689. doi: 10.1016/j.enpol.2005.03.015

Suh J, Sungchul H, Gilsoo J (2017) Development of a Transmission and Distribution Integrated Monitoring and Analysis System for High Distributed Generation Penetration. Energies 10(9):1282 https://doi.org/10.3390/en10091282

Tao L, Schwaegerl C, Narayanan S, Zhang JH (2011) From laboratory Microgrid to real markets-Challenges and opportunities. Paper presented at the 2011 IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE & ECCE), IEEE, Jeju, South Korea, 30 May-3 June 2011 https://doi.org/10.1109/ICPE.2011.5944600

Tsumura T, Takeda T, Hirose K (2008) A tool for calculating reliability of power supply for information and communication technology systems. Paper presented at the 30th International Telecommunications Energy Conference (INTELEC), IEEE, San Diego, USA, 14-18 September 2008 https://doi.org/10.1109/INTLEC.2008.4664080

Villarreal C, Erickson D, Zafar M (2014) Microgrids: A Regulatory Perspective. California Public Utilities Commission, Policy & Planning Division. www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5118. Accessed 7 May 2018

Vinci S, Nagpal D, Parajuli B, Peterschmidt N, Rohrer M, Greacen C (2016) Policies and Regulations for Private Sector Renewable Energy Mini-grids. Available via IRENA. https://www.res4africa.org/wp-content/uploads/2016/10/IRENA_Policies_Regulations_minigrids_2016.pdf. Accessed 5 May 2018

Vine D, Morsch A (2017) Microgrids: What every city should know. Available via Centre for Climate and Energy Solutions (C2ES). https://www.c2es.org/site/assets/uploads/2017/06/microgrids-what-every-city-should-know.pdf. Accessed 1 May 2018

Wang Y, Chen C, Wang J, Baldick R (2016) Research on Resilience of Power Systems Under Natural Disasters - A Review. IEEE Transactions on Power Systems 31(2): 1604-1613 https://doi.org/ 10.1109/TPWRS.2015.2429656

Whitney E (2017) Preface: Technology and cost reviews for renewable energy in Alaska: Sharing our experience and know-how. Journal of Renewable and Sustainable Energy 9:061501 https://doi.org/10.1063/1.5017516

Wouters C (2015) Towards a regulatory framework for microgrids—The Singapore experience. Sustainable Cities and Society 15:22-32 https://doi.org/10.1016/j.scs.2014.10.007

Wu J, Wu T (2015) Goal 7-Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All. Available via UN. https://unchronicle.un.org/article/goal-7-ensure-access-affordable-reliable-sustainable-and-modern-energy-all. Accessed May 1 2018

Yuan C, Illindala MS, Khalsa AS (2017) Co-Optimization Scheme for Distributed Energy Resource Planning in Community Microgrids. IEEE Transactions on Sustainable Energy 8(4):1351-1360 https://doi.org/10.1109/TSTE.2017.2681111

Yuen C, Oudalov A, Timbus A (2011) The Provision of Frequency Control Reserves from Multiple Microgrids. IEEE Transactions on Industrial Electronics 58(1):173-183 https://doi.org/10.1109/TIE.2010.2041139

Zhang H, Lai CS, Lai LL (2014) A novel load shedding strategy for distribution systems with distributed generations. Paper presented at the Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) IEEE, Istanbul, Turkey, 12-15 October 2014 https://doi.org/10.1109/ISGTEurope.2014.7028953

Zhiyi L, Shahidehpour M, Aminifar F (2017) Cybersecurity in Distributed Power Systems. Proceedings of the IEEE 105(7):1367-1388 https://doi.org/10.1109/JPROC.2017.2687865

Zhou N, Liu N, Zhang J (2016) Multi-scenarios PV-based microgrids investment decision considering feed-in-tariff regulation. Paper presented at the 11th Conference on Industrial Electronics and Applications (ICIEA), IEEE, Hefei, China, 5-7 June 2016 https://doi.org/10.1109/ICIEA.2016.7603977