Electrification Processes in Developing Countries: Grid Expansion, Microgrids and Regulatory Framework

A. Berizzi, *Member, IEEE*, M. Delfanti, *Member, IEEE,* D. Falabretti, S. Mandelli, M. Merlo

***Abstract*—Shortages and poor diversification of generating capacity, high environmental impacts and low qualities of supply and affordability are common characteristics of the electricity sector in most developing countries (DevCs).**

Recent cost reductions in the telecommunication sector and some generation technologies, especially renewable-based, with improved economic feasibility have paved the way for new electric infrastructures. This is especially true for emerging economies, as locally dispatched hybrid microgrids introduce flexibility and show the promise of technical and economic advantages. The design and integration of microgrids require detailed assessments to ensure the effective deployment of capital to minimize the risk of stranded assets and capital waste.

Microgrids can be considered an affordable option for a rapid response to the electrification challenge, recognizing that, in the longer horizon, a sharing of resources with the bulk electrical power system will remain, technically and economically, advantageous.

This paper presents a comprehensive review of the approaches commonly adopted for microgrid electrification. A "real-life" study case is reported to highlight the operational challenges of a stand-alone micro grid versus a grid-connected system. The need for an improved regulatory framework is presented as the cornerstone problem to be solved to allow an effective integration of microgrids in the national grid.

***Index Terms*—microgrids, developing countries, regulatory framework, electrification process**

I. INTRODUCTION

IN the last decade, dispersed generation (DG) has become a new actor driving a paradigm change in the power systems of industrialized countries. The revolution has impacted the planning, operation and maintenance of both the transmission and distribution grids [1][2][3]. At present, the concepts and practical implementation carried out in the framework of smart systems in industrialized countries (ICs), mainly based on renewable energy sources (RESs) or hybrid solutions, are of limited application in providing access to energy in developing countries (DevCs). One of the main reasons is that back-up options and stand-alone microgrid systems are commonly proposed as independent projects, which cannot be easily integrated into the bulk power system [4]. Barriers are both on the commercial side (e.g., to have common energy tariffs) and on the technical side (e.g., to have a clear definition of the grid code in order to regulate ancillary services and guarantee grid stability).

In the market of back-up solutions, the lack of the integration of distributed systems into the national grid has hindered the penetration of RES and driven final customers to opt for diesel generators or storage solutions with inverters/chargers, which often pose additional problems to grids and energy efficiency policies [5].

The development of microgrids is limited by both the uncertainty of their present economics (related to tariffs on electricity) and the risk of becoming uncompliant in the future with technical connection standards when grid connection becomes possible in the area. As a result, economic efforts are often duplicated, projects overlap and investments might be oriented to obsolete and sometimes nonefficient technologies [4][6].

In this paper, the electrification problem is discussed with respect to two macro approaches, namely, top-down and bottom-up:

- The top-down (or centralized) approach to electrification is the one followed historically in developed countries. It stays at a high level (i.e., top), managing an electrification process (e.g., performing the required planning operations) targeted to a large population of users (e.g., cities or agglomerations of villages) and using statistical estimations (e.g., population growth rate) based on macroscopic data to forecast the consumption. The building of large power plants is then planned according to the country resources and fossil fuel supplies, while the service is brought to the end users through the transmission and distribution systems.
- The bottom-up (or decentralized) approach to electrification looks at the specific features (i.e., resources and loads) of the targeted context to satisfy the electrical needs of single users or small communities. It starts from microscopic data (i.e., single electric appliances) to effectively determine

Stefano Mandelli works at CESI S.p.a., viale Rubattino, Milano, Italy (stefano.mandelli@cesi.it); all the other authors are with Politecnico di Milano, Dipartimento di Energia, Via La Masa 34, 20156, Milano, Italy (A. Berizzi: alberto.berizzi@polimi.it; M. Delfanti: maurizio.delfanti@polimi.it; D. Falabretti: davide.falabretti@polimi.it; M. Merlo: marco.merlo@polimi.it).

the customer needs (i.e., bottom) and to match them with the available energy sources in the area of consumption. Usually, the potential applications are limited to small-size off-grid power systems, tailored to the specific needs of the customer(s). In bottom-up approaches, one of the main problems is usually to ensure a microgrid design adequate for the medium-long term to meet the evolving needs of users (year after year growth of the local energy consumption), given the binding restrictions on costs that are often in place (CAPEX for the microgrid deployment) [6][7].

The focus of this paper is to investigate opportunities and issues related to the emerging economy electrification process, evaluating when a bottom-up or a top-down approach is suitable, focusing on the microgrid design problem and on the relevant regulatory framework evolution required for this transition. The paper will be based on the following structure:

- Chapter II describes the present scenario in DevCs, demonstrating the strong need for effective electrification approaches; in particular, top-down and bottom-up approaches are compared.
- Chapter III provides a review of the approaches so far adopted for microgrid design and describes a real-life study case of a microgrid, the Ngarenanyuki secondary school, which has been electrified thanks to a local microgrid equipped with an advanced monitoring infrastructure collecting data to validate the approach proposed.
- Chapter IV presents the regulatory framework as the cornerstone of the DevC power system development and provides some useful remarks on the priorities to be set for DevCs, also considering the current regulatory European framework.

II. ACCESS TO ENERGY AND RURAL ELECTRIFICATION

The number of people without access to electricity fell to 1.1 billion in 2016 from 1.7 billion in 2000, and it is expected to further decrease to 674 million by 2030. Some countries in sub-Saharan Africa (e.g., Ethiopia, Gabon, Ghana, and Kenya), are going to reach universal electricity access by 2030; however, progress across the region as a whole is uneven and not in line with population growth. By 2030, approximately 600 million out of the 674 million people still without access are expected to be in sub-Saharan Africa, mostly in rural areas [4].

Evaluating the electrification problem, a regulatory issue exists: in order to make access to the grid fair and transparent to every energy player and to provide the best directions for market and business development, a proper regulatory framework is necessary. The IEA formulated and studied some scenarios in order to state the problem and to propose to decisionmakers sensible solutions. Such scenarios present trends for the access to energy under *New policies* and further elaborate upon an *Energy for all* case that particularly impacts rural and remote areas. In particular, some general directions for decisionmakers have been identified:

- Implement policies supporting a wide range of solutions and business models; avoid barriers to new entrants and involve local communities.
- Facilitate rural electricity access by encouraging off-grid investment, making provisions for the subsequent connection of decentralized solutions to the main grid. Encourage investment in both and in their future integration.
- Make energy efficiency an integral part of energy access policies, considering that it also facilitates the uptake of new business models and increases the affordability of off-grid solutions.
- Include productive uses in energy access policies and targets.

Focusing on the development of the network infrastructure, it could be instructive to study the history of electrification in ICs in order to shape plans for the best path (optimal quality of service at least cost) to electrification in today's DevCs. To this purpose, it is necessary to evaluate the similarities and differences on the technical, social and political sides in order to evaluate if and when ICs could be a model for DevCs. A peculiarity of power systems in ICs is the high number of interconnections.

The benefits of interconnections between different grids at the local and country levels are well described in [8]:

- improving reliability and pooling reserves;
- reducing investments in generation capacity by sharing power production resources;
- improving the load factor and increasing the load diversity, taking advantage of different daily or seasonal patterns;
- scale economies in new infrastructures;
- diversity of generation mix and security of supply;
- economic exchange by the dispatch of the least expensive generation units or environmental dispatch;
- better coordination of maintenance schedules.

Moving to DevCs, of course, the abovementioned benefits of large interconnections still hold, but the initial conditions are very different. The conclusions of [9] are that the "*significant reinforcement of long-distance transmission capacity within and between systems in DevCs will be necessary to achieve the climate, security and affordability objectives of delivering electricity in the 21st century*". Therefore, in the very long-term perspective, the optimal and final goal might be to build and operate an interconnected electric system as large as possible, because the advantages are more than the drawbacks. The way to attain that goal, though, is not unanimously agreed upon: when large investments are possible, the *top-down* approach is the typical approach adopted. Nevertheless, this sometimes leads to solutions that do not reach many people, especially in the case of rural communities [4]. In rural and scattered communities, as well as when little money is available for investment, off-grid solutions (i.e., *bottom-up* electrification processes) are typically selected. The latter, though, appear quite often like emergency solutions, not integrated into a system view of the *Energy for all* framework. In the following subsections, the two just-mentioned approaches, together with a new integrated approach, will be presented.

A. Supply from bulk transmission systems

The top-down approach, with the primary objective of providing electricity by the strengthening of the transmission system, is based on the emulation of scenarios of IC: large investments and infrastructures and mainly large power plants (not necessarily RES-based) to produce power and to distribute it to everybody by means of a large high-voltage (HV) grid. From 2000 to 2016, nearly all of those who gained access to electricity worldwide did so through new grid connections, mainly in large urban centers, mostly with power generation from fossil fuels, thus preventing the exploitation of RES and the attainment of decarbonization goals [4].

The advantages of this approach are:

- generally, it offers the lowest-cost pathway to households for electricity access once the connection is available;
- it is the best for covering large distances between centralized power plants and load centers at high voltage with low losses;
- it creates the ground for a large-scale, and thus potentially more efficient, electricity market and the relevant businesses;
- it makes it possible to build large factories and/or large and cheap power plants that would otherwise be hindered by the lack of transmission infrastructure (e.g., in some countries, there is an excess of power plant capacity that cannot be exploited due to the lack of transmission facilities [10]).

Conversely, for the reasons explained in the following, the approach might not fully fit DevCs, for instance, in terms of the complexity of planning in advance the grid infrastructure and the sustainability of the costs required to deploy and maintain it.

- It requires large investments for grid extension and maintenance, as well as for large power plants: important players are needed, such as large private companies and/or state-owned companies and utilities.
- The planning and operation of large power systems require skilled and well-trained people. Long distances, typical of rural electrification, add complexity from the technical point of view. Coordinated planning and operation are mandatory, involving operators of different countries (e.g., the Southern Africa Power Pool initiative [11]).
- The return on investment might not be guaranteed in the case of a low electricity load density (in particular, in the case of a scattered community, i.e., far from the already electrified areas, a top-down approach could be ineffective due to the large investment required with respect to the energy needs).
- If the main grid is not characterized by a suitable standard of quality and reliability, customers' satisfaction level is low; in that case, industrial customers may prefer to invest in reliable backup systems or, in particularly critical cases, to generate electricity locally on their own, off-grid, thus making the grid reinforcement a stranded cost.

Many projects and studies have been carried out and are currently being developed in order to plan the best power system for the future in many DevCs, according to a top-down approach. With reference to Africa, which is among the target areas of this paper, for instance, [13] presents a study relevant to Eastern Africa, including 12 countries. Moreover, the European Commission, through its Joint Research Centre, set up a complete GIS-based database that can be used to assess input data and the best conditions to identify a roadmap to electrification ([11][14][15][16]).

B. Electrification based on microgrids and off-grid systems

In the case of rural or remote areas, the cost of connecting to a main grid might be very expensive. In that case, a different and apparently opposite bottom-up approach is often adopted.

In rural low-income communities, i.e., when the energy need is very limited (just tens of watts), Solar Home Systems (SHS) are typically adopted in order to provide people with telecommunication and lighting services [17]; otherwise, microgrids are the most common solution.

The large-scale deployment of microgrids and off-grid systems offers today a less expensive solution for the quick electrification of remote areas.

Among the advantages of this approach are [18]:

- lower electrification upfront costs in the short-term (i.e., until the energy needs of the area could be satisfied by a microgrid) and
- the quality of the supply could be better than that of unreliable main grids, thus enabling commercial and productive uses, which in turn are likely to foster electrification.

Conversely, some drawbacks can be listed:

- usually limited generated power and energy capabilities;
- restrictions due to the intermittency of the primary sources and fluctuations of loads that can result in a need for either large storage systems or diesel generators;
- during peak periods, blackouts, voltage dips and frequency variations might cause the malfunctioning of equipment;
- the need to ensure that electricity is fairly shared among all users (Demand Side Management could be useful from this point of view);
- the design of a microgrid is complex, and the management of the growth of users' energy needs is

critical.

Actually, it is not possible to identify a single solution that fits all scenarios; case-by-case pros and cons have to be evaluated in order to select the most suitable solution.

As far as the primary sources are concerned, over the last five years, renewables have started to show up, as off-grid and microgrid systems, and this shift is expected to accelerate. By 2030, renewable energy sources are supposed to power over 60% of new access [4], and off-grid and microgrid systems are going to provide 50% of new access, underpinned by new business models using digital and mobile technologies.

C. *Smart microgrids and their integration into a grid*

To have an effective electrification process, in most the situations, in authors' opinion the optimal solution could be an integrated approach, where *top-down* and *bottom-up* strategies are merged in a comprehensive procedure. Actually, microgrids (i.e., according to the motivations presented in the previous sections, the most effective solution to provide energy in a short-term scenario) should be designed considering the future possibility to connect them to a main grid so that the future grid connection will not make them a stranded investment but rather an additional resource for the grid [19][20].

In the past, off-grid microgrids were usually equipped with devices not compatible with on-grid operations; they are bound to be dismissed once a connection to the grid has become available. That is, a significant barrier for investors who would not be able to compete with the price of electricity provided by the utility, thus increasing the risk of such investments and making them less interesting.

Such a paradigm could be completely changed today [21]: Smart Grid technologies, which are, in most cases, well-established from the technological point of view, allow the design of microgrids that are perfectly interoperable with a distribution grid. Furthermore, once connected to the main grid, they can eventually become *ancillary service providers* and allow the start of a new business model. An example in this sense is smart inverters, able to adapt their function according to the off-grid or grid-connected status of the microgrid to guarantee a reliable connection to the grid (i.e., low-voltage fault ride through) and eventually to contribute to the ancillary service provision (Chapter IV presents a detailed analysis of the issue). The consideration of such new technologies can significantly speed up the race to the access to *Energy for all*, as investments are going to become more attractive.

Smart grid technology-based microgrids (SGMs), initially off-grid and then grid-connected, in the authors' opinion, can create new opportunities for business once they are included in a suitable regulatory and market framework. This is usually the best practice to be adopted today in the electrification of DevCs because it allows enough flexibility from the technical point of view while providing a significant risk reduction for investors:

- SGMs can be easily scaled up in line with rising demand, being initially not connected to a main grid and eventually connected to a main grid when available.
- SGMs are usually associated with dispersed, low-scale generators, which, in turn, are today RES-based: they can thus significantly contribute to decarbonization goals.
- Losses are usually low given the proximity of generation and loads.
- In the case of connection to the grid, SGMs are designed to meet Grid Code requirements, if any. Otherwise, the SGMs would become stranded assets.

From the technical point of view, the improvements in the Smart Grid field have led to the possibility to implement this approach easily. SGMs, equipped with advanced devices and controls, are ready for the approach proposed in the present paper. Additionally, standards and guidelines are already in place, both in Europe and North America [12][22].

From the regulatory and economic points of view, some additional points are worth noting:

- A clear and fair regulatory framework and a Grid Code must exist. Earnings from the microgrid might change completely in case of connection to the main grid, often resulting in a significant loss for the investors: the stability in time of both the regulatory framework and the Grid Code are thus mandatory [23].
- To provide a suitable rate of return on the investment in areas with a currently low density of electricity, not-connected microgrids are probably the most commercially viable solution. However, it is necessary at the political level to provide a clear national or regional grid extension plan with a well-fixed time schedule, as better explained in Chapter IV; this will allow private investors to evaluate the economic feasibility of electrification projects.

In the next section, a practical example of an application of the just-mentioned electrification strategy is discussed, with the purpose of highlighting the advantages and opportunities of that solution but also to present the practical issues that can arise in real-life implementations.

III. SMART MICROGRID ELECTRIFICATION: A REAL-LIFE EXPERIMENTAL TEST BED IN TANZANIA

Currently, in developing countries, a common approach is to consider small-scale decentralized systems as a sustainable alternative to a more traditional development of energy systems based on a centralized approach. Nevertheless, the distributed approach has evident limits (as detailed in the previous chapter) because such a scenario asks for a sensible approach in the microgrid design.

The design process of RES off-grid systems is not straightforward, since it means matching energy sources with unknown or uncertain load demands and, in the end, providing the most favorable conditions in terms of robustness (i.e., adequacy with respect to the energy needs) and costs. In the literature, many papers have investigated this subject, and several open access/commercial tools are available: they are typically based on steady-state simulations, heuristic or analytical optimization, and simple component modeling. Sinha and Chandel [24] and Khatib et al [25] reviewed software tools to size off-grid power systems. HOMER [26] is the most used software for the simulation and optimization of off-grid hybrid power systems. It determines the configuration that minimizes life-cycle costs for a particular site application. RETScreen by CANMET [27] is a renewable energy decision support and capacity building tool. iHOGA by the University of Zaragoza [28] is a C++-based software tool that exploits genetic algorithms for the multiobjective optimization of hybrid power systems. SAM by NREL [29] estimates the performance and cost of energy for grid-connected systems. PVsyst [30] is a software for the study of stand-alone and grid-connected solar systems. Poli.NRG is a tool consisting of four blocks based on a stochastic generation of load curves and scenarios; PV and batteries are scheduled in order to meet the load [31][32]. Finally, working on a regional level, OSeMOSYS by KTH is an open source modeling system for long-run integrated assessment and energy planning [33].

To properly study and relate the electrification processes for rural areas in DevCs and to test microgrid design criteria, the research team of Politecnico di Milano started a real-life experimental test bed at the Ngarenanyuki School, Tanzania. Actually, the goals were in the data gathering of technical issues and not the technical issues themselves: a willingness to change energy habits, the approach to energy, the approach to the equipment, the viability of the Man-Machine interaction proposed, etc. While the regulatory framework in Tanzania is lacking and does not allow testing the approach proposed in the paper, i.e., microgrids are not allowed to interact (provide ancillary services) with the main grid, they could just behave as aggregated loads.

Nevertheless, in the Ngarenanyuki School project, the microgrid has been designed considering the future possibility of connection to the main grid. The project proposed provides useful hints regarding the need for a proper regulatory framework to support the electrification process, an aspect that will be discussed in depth in the following Chapter IV.

A. Ngarenanyuki School - a brief history

The Ngarenanyuki School is located in Tanzania in the Arusha region, a quite rural area. In 2003, from dilapidated wood and soil buildings (Figure 1), a restructuring process started, and in 2016, the school hosted approximately 500 students (Figure 2).

The electric grid was not available in the area, and consequently, in 2013, a first rough electric infrastructure was deployed. The power source of the school was a run-of-river micro hydropower plant (MHP) based on a 3.2 kW Banki turbine coupled with a 1-phase brushless synchronous generator (230 V, 50 Hz). The water flow to the turbine is diverted from a stream that is managed by local farmers. The high variability of the water availability during the day and according to the season caused many blackouts. The frequency regulation was based on a 4 kW dump load, which dissipates the excess power in the air; similarly, voltage regulation was based on a very simple self-exciter in the synchronous machine.

Figure 1 - Ngarenanyuki School in 2003 (dilapidated wood and soil building).

Figure 2 - Ngarenanyuki School in 2016 (approximately 500 students).

In 2014, the research team of Politecnico di Milano started a collaboration with the school; the first task was related to a quantitative monitoring of the energy needs and power profiles (generation and consumption).

A box plot (Figure 3) summarizes the load consumption pattern of the school measured from June to September 2014. The line in the middle of each box is the median of the load for the respective time of the day, and the whiskers of each box show the observed minimum and maximum load values of the measured data samples. The load curve was greatly variable from day to day. Actually, the hydro energy availability fluctuates a great deal, and moreover the energy-needing tasks in the school were very irregular. Consequently, there is no clear, consistent behavior, and each day shows a quite different power profile.

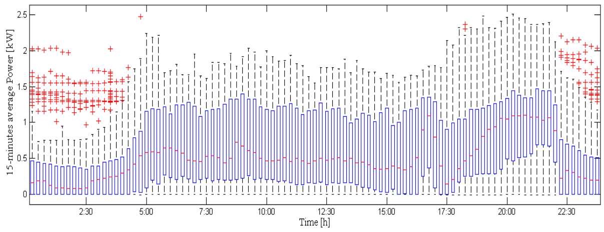

Figure 3 - Box plot of daily power consumption of Ngarenanyuki School (data from September 2014).

The data gathered are a confirmation of the common scenario of the electrification process in DevCs, characterized by huge power fluctuations and an irregular energy behavior. Consequently, it is not realistic to identify a reference daily power profile; similarly, performing a microgrid design based on the average behavior could cause criticalities (loss of load) on those days when the energy trend results are far from the average. These figures motivate the need for stochastic or robust procedures.

B. Ngarenanyuki School microgrid design

In 2015, thanks to the research project Energy4Growing (E4G), promoted and funded by Politecnico di Milano in collaboration with EKOENERGY, a new microgrid architecture has been designed and deployed in Ngarenanyuki. An advanced interface converter and a control switchboard have been designed in a hybrid microgrid architecture including a 3.2 kW micro-hydro system, a 5 kW diesel genset, a 3 kW PV-inverter and a 70 kWh battery bank (30 x 202 Ah/12 V lead-acid batteries).

Moreover, an advanced monitoring architecture coupled with a satellite data connection has been activated, i.e., data about the microgrid system function has been regularly collected. Such data are crucial for both scientific research and to monitor the behavior of the system. For instance, actual microgrid variables (voltage, current, frequency, etc.) are sampled every second and managed via a PLC data-logger. They are then processed by the E4G group and shared in order to promote scientific studies based on “real life” data (they can be freely accessed on [34]; moreover, a detailed description of the project is available in [35]). Figure 4 depicts the microgrid scheme: the new architecture relies on a double bus bar, inspired by a configuration usually adopted for large power plants, to increase the flexibility in the energy management of the school. This was motivated by the desire to be able to manage, in the future, a significant increase in the energy needs, i.e., for modular connections of new loads and generators.

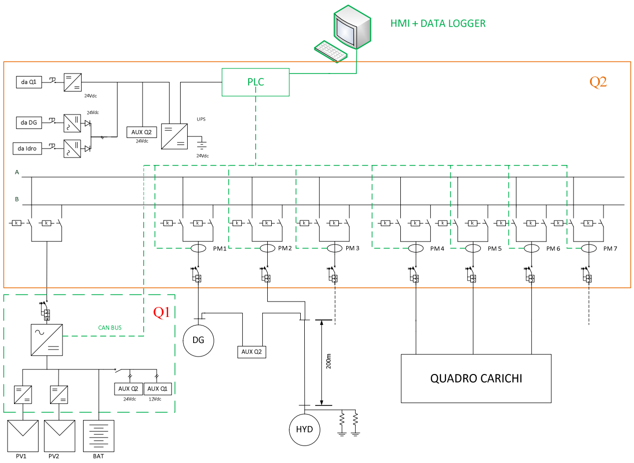

Figure 4 - Microgrid architecture deployed in the school.

According to the bottom-up/top-down integrated approach proposed in the previous chapter, the architecture has been developed based on two switchboards: Q1 and Q2. The latter is devoted to connect AC equipment: the loads, the hydro generator (the generator is already installed, working in a grid-forming configuration) and, if necessary, the diesel generator. Q1 is devoted to managing the DevC resources: the PV, batteries, etc. The interface converter can operate both in a grid-forming and in a grid-following configuration (e.g., in case the hydro generator is not working, it will act as a master).

To foster the effective use of the energy, i.e., in order to improve the approach to energy of the school staff, a MATLAB© Energy Management System (Figure 5) has been developed. It runs on an on-site computer, with an emphasis on visualization: energy consumptions and generation forecasts are exploited in order to optimize (i.e., minimize) load shedding and shifting control actions. These are calculated by an artificial neural network and fuzzy logic techniques. Every day, the EMS automatically sends reports by email on the grid status (including detected faults and alarms, if any).

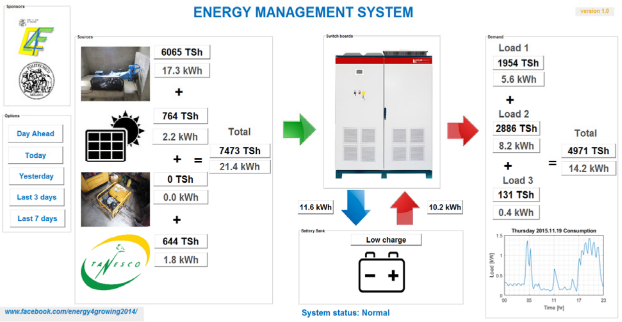

Figure 5 - EMS software Graphical User Interface to assist the school manager.

The EMS was expected to reshape energy usage habits for the better and to help increase energy efficiency. Unfortunately, based on a survey regularly filled in by the school staff, so far people have focused on the practical use of the microgrid (switching on and off generators and loads and restarting the system after a black-out), while very marginal attention has been paid to the optimal resource planning. This was motivated by the consideration that energy is a means to a goal, not a goal itself: in the school, the priority is the proper (with respect to the local habits) exploitation of processes (exams, cooking, stay-together events, etc.). Most likely, only automatic controls (to drive more efficient energy use) might be successful in such a scenario.

Thanks to the microgrid operation, the school headmaster reports increases in the enrolment, student performances, and well-being of students together with an increased access to energy. Inevitably, the improvement in energy penetration has naturally led to an increase in energy-intensive activities. In September 2017, a slightly more regular energy behavior (Figure 6) was detected, and, on top of that, the load peaks and average load were double those in 2014.

Moreover, the 2017 political elections fostered the electrification process in the area, and, in 2017, Ngarenanyuki was connected to the public distribution grid. Such a scenario was not able to be predicted a couple of years ago.

Currently, in Ngarenanyuki, most generators are not compliant with grid-connected operation. Nevertheless, thanks to the double busbar architecture, it is possible to split the grid into two zones, one supplied by the local resources and the other by the public grid, validating the motivation for such an unusual (and somewhat expensive) architecture in a small LV plant.

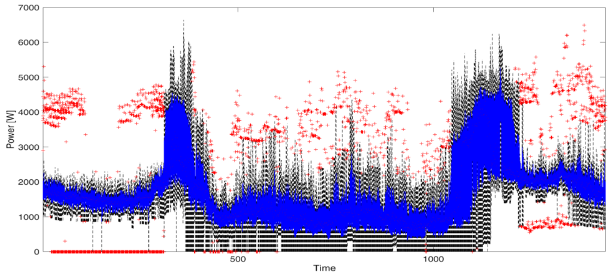

Figure 6 - Box plot of daily power consumption in September 2017 (after the microgrid deployment) – data related to the Ngarenanyuki School.

C. Ngarenanyuki energy growth over time

From the energetic point of view, new opportunities are driving a solid growth and consequently new needs. A new dormitory is now under construction, requiring the use of energy-intensive machines (pumps, a brick machine, etc.) that are incompatible (due to the power peak required) with the microgrid in place: they have to be directly connected to the public distribution grid. Such a case points out the limit of a microgrid scattered electrification process: it is not possible to design a microgrid that can properly supply an area over a medium-long-term scenario. In the Ngarenanyuki study case, before the microgrid deployment (i.e., before 2015), the load had a peak of approximately 2 kW. The microgrid architecture was thus designed in order to be as modular and flexible as possible (up to 20 kW could be managed by the double busbar architecture). Unfortunately, the new brick machine requires a peak starting power of approximately 25 kW. Figure 7 depicts the new power profile.

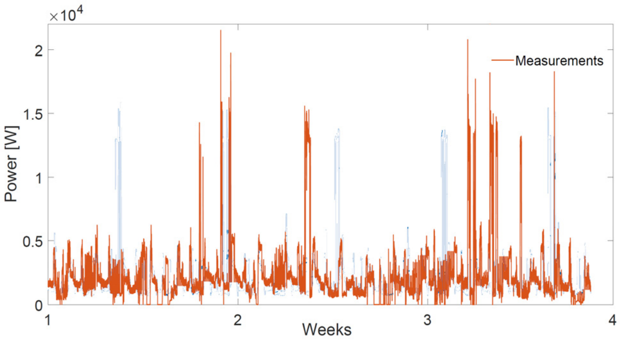

Figure 7- Load power profile samples in September 2017 – data related to the Ngarenanyuki School and to the new pumps and brick machine.

The study case demonstrates the pros and cons of bottom-up electrification approaches: they could be effective in the very short-term but, if effective social growth takes place, they are very soon going to be inadequate. The need to design microgrids in the perspective of a future - sooner or later - connection to the main grid is thus proven, and in the authors' opinion it is the most effective way to prevent wasting economic resources.

D. Monitoring of the distribution grid

Given the Ngarenanyuki microgrid connection to the Tanzanian public distribution grid, new equipment has been deployed in order to gather information on the quality and reliability of the supply. Such data are not commonly available in DevCs, resulting in only a qualitative investigation of the power quality problem. The new meters sampled each second the voltage, current and frequency over the grid. The data collected show the power quality level provided.

The frequency, sampled for 60 days, depicts huge fluctuations, up to ±0.6 Hz. Figure 8 reports the PDF of the frequency fluctuations sampled compared to data relevant to the Italian and the UK systems [36]. The data collected demonstrate the inadequate quality of the supply in Tanzania and motivate a proper evolution of the regulatory framework, that must, at any rate, fit with the local context (e.g., if generator electric protections in Tanzania were set according to EU settings, a huge number of unwanted trips would result). Similarly, black-out events have been monitored; the results (Figure 9) show an average loss of supply approximatively equal to 10% of the time in a day; such data highlight the role that microgrids could have in DevCs, even in areas already supplied by the national grid. To improve the reliability of supply, a positive interaction between local microgrids and the national infrastructure seems to be the most sensible approach.

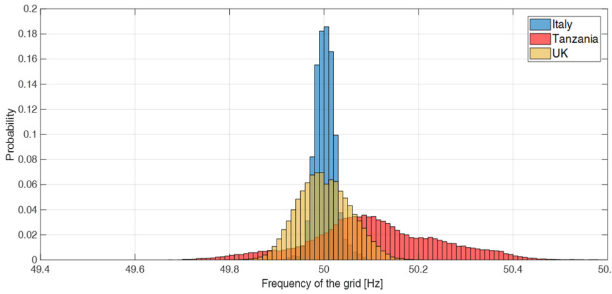

Figure 8 - Probability density function of the frequency sampled (over 60 days – Winter 2017) in a distribution grid in Tanzania – red bars. Comparison with samples relevant to the Italian grid (blue bars) and to the grid in the UK (yellow bars).

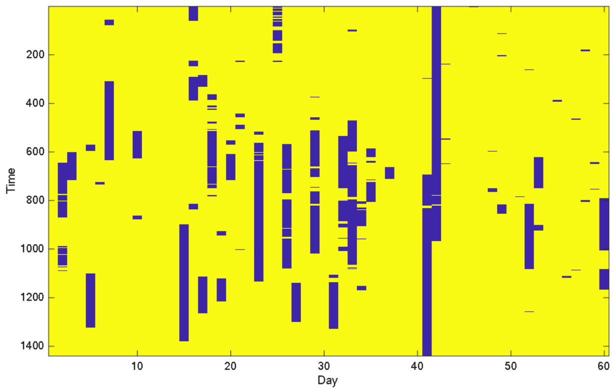

Figure 9 - Black-out events (blue bars) in a distribution grid in Tanzania (over 60 days – autumn 2017).

Finally, the quality of supply is also a major concern. In the pilot test under investigation, the voltage phasors have a high level of asymmetry between the three phases (Figure 10).

E. General conclusions gained from the experimental test

A general conclusion on the experimental project performed in Tanzania could be summarized as follows. The project had been designed as a smart microgrid for testing a bottom-up electrification process, but with the possibility of future connection to the main grid. The pilot site had been properly selected in a scattered area, i.e., an area motivating an off-grid solution. Unforeseeable evolution correlated to the political election campaign drove a fast deployment of the public distribution grid in the area, and consequently, just a few months after the deployment, the microgrid had to be rearranged to fit a top-down electrification paradigm.

Experimental evidence gathered in Ngarenanyuki showed a quite poor quality and reliability of supply; moreover, several unexpected problems had to be addressed (electrical schemes of the generators already in place, peculiar energy needs of the school, a social approach to the energy, etc.) demonstrating the need for a resilient architecture that is capable of being suitably adapted case by case.

With respect to the electrification problem, implementing a smart microgrid (see section II.C), in the authors' opinion, is the main choice to supporting the electrification and economic growth in DevCs. Unfortunately, this has not been possible in Ngarenanyuki due to the quite strict regulatory framework in place: the microgrid could behave only as an aggregated load, with no active or reactive power injections into the main grid allowed, and consequently the deployed microgrid was exploited in order to gather data related to the load and generator behavior, to test the interaction with the final users and finally to monitor the quality of the supply of the main grid (all the gathered data were publicly shared [34] in order to promote scientific research using real-life figures).

Looking at the future, in DevCs, regulating resources could be inadequate: traditional power plants could hardly support the growing energy needs. A paradigm change in the regulatory framework is required in order to promote and properly exploit microgrids, e.g., enabling ancillary services provision by these new resources. Unfortunately, the regulatory framework is quite underdeveloped: a fast and effective evolution would provide a cornerstone to support the economic growth of those countries. An in-depth analysis of the problem is provided in the next chapter.

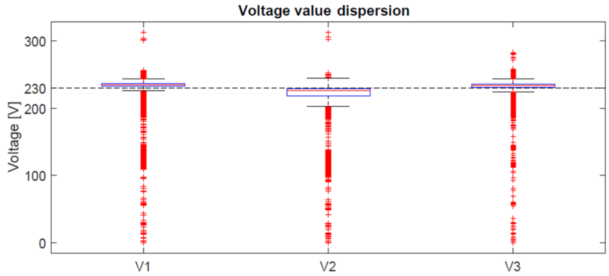

Figure 10 – Voltage fluctuation, in each phase, sampled in the public grid feeding the Ngarenanyuki area (over 60 days – autumn 2017).

IV. A SENSIBLE REGULATORY FRAMEWORK FOR EFFECTIVE ELECTRIFICATION

The previous paragraphs addressed possible strategies for rural electrification in DevCs from the point of view of the technical options. However, as presented in the following of this chapter, the regulatory framework also has a pivotal role in driving this process. In fact, this element strongly contributes to defining the most proper technical solutions for the development and operation of the power system according to national and international targets. These targets, for the specific contexts of DevCs, are not only at the energy sector level but eventually aim (even more than in high-income economies) at supporting their fast-growing economies. Accordingly, this section provides an overview of the current situation of regulatory frameworks across DevCs. Moreover, it aims at presenting some remarks to highlight the priorities for DevCs in light of international best practices. In particular, in the next paragraphs, three aspects are considered due to their relevancy and actuality within the DevC power sector.

- Technical regulatory framework (e.g., Grid Codes and technical standards): DevCs have different levels of advancement in their power system unbundling, but it is quite common that there is no clear, consolidated and enforced regulatory framework available.
- Guidelines for interconnected power system development and operations: The coordinated development and operation of interconnections are important targets for many DevCs that are part of already established power pools; this requires the adoption of a common set of rules and the harmonization of existing ones.
- Policies and incentive schemes for RES integration both at the transmission and distribution levels: The actual momentum of RES has reached DevCs as well; the proper support of RES to DevC power system

development passes through the definition of a clear framework for the integration of these technologies both at the transmission level (bulk generation) and distribution level (rural electrification and isolated systems).

A. Overview of DevC regulatory framework and current trends

In a similar way to in ICs, power system unbundling has attracted interest in DevCs at the end of the 20th century, aiming at increasing the sector efficiency and reducing system costs through the separation of activities (generation, distribution, transmission, regulation) and the introduction of competition while also improving the quality of the service. An additional motivation is the urgent need for large amounts of private and/or foreign capital to promote the expansion of the generation fleet and the development of transmission and distribution infrastructures [37][38].

In effect, the conditions of the DevC power sectors that approached the liberalization process are quite different from those that characterized the unbundling process in ICs and are summarized as follows [39][40]:

- national economies experiencing strong growth that need proper support from the energy sector;
- limited possibilities of large governmental investments;
- a steady pace in the electrification process that is not sustained by an adequate generation fleet and a resilient transmission grid;
- a very low per capita consumption (i.e., low electrification rate and low consumption), with concentrated demand in urban areas;
- a not meshed transmission grid that transfers power from a few bulk power generation nodes to urban demand nodes;
- a generation fleet based on run-of-river hydropower plants and (emergency) fossil fuel-based generators (large diesel, fuel oil);
- a state-owned vertically integrated structure of the power sector that quite often works with a deficit of economic resources due to tariffs not based on operating costs but on Unified National Tariffs that aim at accessible costs for the population;
- a transmission system that is quite obsolete and subject to frequent faults;
- system operations (operational planning and real-time operations) based on unstructured and unstandardized practices;
- few interconnection lines between neighboring countries that only aim at mutual aid during emergency conditions.

When moving to the current situation of DevCs that have already started the power systems unbundling process, different conditions of progress are present.

The majority of DevCs have established a National Regulating Authority that interacts with a national company that is derived from the former vertically integrated company. This firm typically works as the transmission system operator (TSO) and single buyer as well as the largest power producer [41][42][43]. This organization of the power sector is clear, for instance, among most of the WAPP countries [44].

In effect, in some cases, the generation sector is liberalized, while in others, it is still under the full control of the government. Nevertheless, even in a liberalized sector, a national company owns and operates the largest share of the installed power, while a number of Independent Power Producers (IPPs) own and operate new power plants (typically fossil-fueled based, namely, gas turbines, CHP, and diesel or fuel oil generators). Moreover, IPPs typically launch actions for the design, financing, implementation and operation of RES projects [45]. Both traditional and RES-based IPPs operate through Power Purchase Agreements (PPAs) that define all the aspects related to the technical and economical operations of the system. In a highly uncertain environment, PPAs are the most common tool employed to limit the risk associated with private investments [46]. Nevertheless, this often is detrimental for the real improvement of the power sector since, for instance, IPPs typically do not take part in the provision of Ancillary Services.

In a way similar to the generator sector, the DSO is integrated within the national company that is derived from the former vertically integrated company.

With regard to interconnections, currently, the main goal shows a shift from mere mutual aid between neighboring countries during emergency conditions to a means for a better exploitation of resources from countries with an excess of low-cost power production to countries with a power deficit and/or high-cost power production [47]. This is resulting in several projects addressing interconnection lines between countries (see, for instance, [48]). Moreover, besides high-voltage “energy corridors”, there is also interest in HVDC interconnections as well as back-to-back facilities [49].

With regard to the progress toward the target of 100% access to electricity, an awareness of the role of the bottom-up approach based on small-scale isolated systems for the electrification of remote rural areas is now consolidated [50][51][52][53]. As a matter of fact, some countries consider the bottom-up approach as a proper solution to provide an adequate power supply service to remote areas. In contrast, others consider it as a temporary solution that is needed to promote local development while waiting for the expansion of the national grid [50][54]. No matter the reasoning, in all DevCs, Rural Energy Agencies (REAs) have been set up to promote programs and projects dealing with the implementation of microgrids and the diffusion of stand-alone systems such as solar home systems and solar torches.

In light of the current situation of DevCs, the development of national power systems, the energy market unbundling, and the process of rural electrification require a set of rules and roadmaps defining roles and coordinating the actions of the different stakeholders involved. This set of rules can be organized as follows.

- National grid codes and technical standards.
- Interconnection guidelines.
- Connection Codes and Policies for RES.

DevC *Grid Codes* are necessary as a means to define technical rules for the development and operations of the power systems as well as to interact with stakeholders. In this regard, different conditions can be recognized across countries.

- Technical rules and operational procedures are documents belonging to the state-owned firm that is derived from the former vertically integrated company. They are not publicly available, and they do not cover all the topics addressed in modern Grid Codes (for instance, compliance procedures, metering, and ancillary service requirements are typically lacking). Moreover, they may not be fully implemented, as the actual operations tend to be a mix of procedures and the experience of the staff. As a matter of fact, the knowledge of these rules is scattered across the company according to the specific tasks. The interactions with external stakeholders (IPPs) are regulated through dedicated rules (e.g., PPAs) subject to negotiations and hence changing from case to case.
- A complete draft of a Grid Code is publicly available following a development process that attempts to properly involve the stakeholders as well as the NRA [55][56]. The Grid Code development process is often triggered by donors as side activities within actions aiming at attracting private investment at the national level. The Grid Code covers the full range of topics that pertain to modern power systems but is lacking in defining specific elements (settings, procedures, approaches) that properly fit with the conditions and real perspectives of the DevC power systems. In effect, in these cases, the Grid Code is often based on the documents adopted by industrialized countries (e.g., former UCTE operation handbook, current Network Codes), which are taken as a reference without proper critical analysis and adaptation. Nevertheless, it is quite common that this document is not enforced and hence it is not implemented.
- A complete draft of a Grid Code is publicly available following a development process that attempts to properly involve the stakeholders as well as the NRA [57]. Parts of this Grid Code are adopted and implemented for system operations and stakeholder regulation. For these parts, the code has been adapted to the conditions and needs of the power systems, and all of the laws, procedures, and requirements are well defined. Nevertheless, derogations are often considered for IPPs, resulting in a not uniform application of the code.

As mentioned earlier, the shift of interest toward interconnections has brought about the need for *interconnection guidelines* that aim at harmonizing both the development and the coordinated operation of interconnected power systems. In this regard, most of the initiatives are headed by local power pools (e.g., WAPP, EAPP, PAN-ARAB region) supported by international donors [58][59][60]. These initiatives go in two main directions.

- Develop regional master plans that focus on the medium, long-term planning of the generation, transmission infrastructure, synchronization facilities and interconnection facilities [50][54]. The master plan aims at coordinating the development of interconnected power systems and at providing countries with a priority list of power system projects.
- Harmonize the national connection requirements and operational procedures. Operational guidelines have been developed following the approach and the structure of already available documents, namely, the UCTE operation handbook in the past and currently the ENTSO-E Network Codes. In a similar way to Grid Codes, the reference guidelines are often not properly adapted to the specific context, thus leading to documents that are seldom implemented and considered within national policies.

Considering RES technologies (e.g., wind and PV power parks), few experiences of the definition of technical rules (connection requirements and operational rules) can be recognized, so far, in DevCs [61]. These basically refer to actions aiming at developing Grid Codes or Interconnection guidelines, but they do not find real implementation. Indeed, despite the growing efforts in RES of foreign private investors supported by international donors, the experiences of implementing and operating RES power plants connected to the transmission grid are limited. In these cases, the connection requirements, necessary technical capabilities, and operational agreements, as well as incentives and purchase prices, are always negotiated and considered within specific PPAs. Actually, PPAs are the privileged tool for RES projects. This is true even though policy frameworks aiming at paving the way to increasing shares of RES have been developed [62][38].

The regulatory frameworks for Distributed Generation and isolated systems are even more limited than for large RES actions [63][64]. No technical standards are considered for very small isolated systems aiming at supplying power to very remote single users. The same applies for small isolated systems implemented as back-up by users that already have access to a local distribution grid. In this case, no licenses or permissions are needed by the local DSO, which does not require any specific technical features. When moving to isolated microgrids that supply power to several users in isolated areas, technical and economic aspects are considered in the licenses that, in most cases, the NRA needs for the implementation, operation and provision of the service to end-users. In contrast, when a microgrid, which was originally set up as isolated, is connected to the national grid, again PPAs are considered to define both technical and economic aspects.

B. Remarks and comments on DevC regulatory framework perspective

In light of the current situation of the regulatory frameworks in DevCs, the following remarks and comments can be provided.

- In a DevC, attention must be given to the process of the *adaptation*, *adoption* and *implementation* of new regulatory frameworks. Both when dealing with National Grid Codes and Interconnection Guidelines, (i) international best practices must be adapted to DevC situations, (ii) the resulting regulation must be adopted as law, thus binding to them all stakeholders, both state and private companies, and (iii) compliance procedures must be set up to check the actual implementation of the regulation.
- DCs shall prioritize the following topics in developing their own regulatory frameworks: (i) Requirements for generators, (ii) Operational planning procedures, and (iii) Ancillary service provision (frequency control in particular).
- The requirements for generators of DevCs can replicate most of the international best-practices rules (requirements for frequency and voltage stability, system management requirements, requirements about robustness of units) as mandatory prerequisites to be connected. Nevertheless, the actual exploitation of these capabilities may not be required now, but they are only being considered for future conditions. This is especially true for large RES power plants connected at the transmission level, as well as units that are initially designed to operate as isolated systems.
- With regard to the operational planning, it is necessary to adopt the basic procedures (off-line analyses such as load forecasting, unit commitment, dispatching, maintenance planning, N-1 static analyses, etc.) in order to enable real-time operations with a lower uncertainty and lower responsibility of control center operators.
- Concerning ancillary services, there is a strong need to implement the classical structure (with related equipment) for frequency and voltage control. This also entails the need to fill the gap in having the knowledge within the local TSO of the real capabilities and real performances of each power plant (state-owned and IPP-owned).
- Attention should be given to the development of standard procedures to implement bilateral agreements within different timeframes and between different countries as well as within the suppliers and demand facilities of a country.
- Looking at rural electrification with off-grid systems, it has to be highlighted that currently no technical standards accepted at the international level have been developed so far. Steps toward this perspective have been taken in the last few years with the publication of some technical guidelines and dedicated reports and the establishment of working groups [65][66][67]. Standards will probably be available in the medium term (up to 5 years).
- Considering the electrification process from the bottom-up approach, the perspective should be: (i) to reach a harmonization of the technical specifications in order to further reduce the cost of deployment (this is addressed mainly by the development of technical standards), (ii) to consider, for microgrids in particular, the adoption of the connection requirements that are needed for DG in order to properly address the future connection to a distribution grid.

V. CONCLUDING REMARKS

In the paper, the problem of developing country electrification needs has been introduced and discussed from both the technical and the regulatory point of views.

The electrification process can be classified into top-down and bottom-up approaches. The former is based on a classical evolution of the national transmission and distribution grid, while the latter is looking to scattered areas where stand-alone microgrids could provide a technically and economically viable solution. In the paper, a third approach (named a smart microgrid) is also discussed, which stresses the need to properly design microgrids in order to allow a future connection to the national grid and the provision of ancillary services, allowing the microgrid to support the reliability and quality of supply. This is needed to guarantee to final users (citizens) proper support for their energetic growth.

Moreover, such a solution could ensure a reliable and stable scenario to support the economic activities of private investors: the local microgrid has to not be out of date once the national grid will be deployed, but rather the two infrastructures are going to work and positively interact with each other.

In the paper, a real-life study case relevant to a microgrid in Tanzania is also presented. The experimental test reported results useful to presenting the approach proposed and to stress how many uncertainties have to be managed in such scenarios. DevCs are typically not stable scenarios, i.e., a linear design and deployment approach is typically unrealistic: the deployment of the main grid is strongly linked with the political sphere, typically unstable in these countries; the fast growth of the energy needs and the very fluctuating trends of the loads require a resilient microgrid architecture and control logic; and the interactions with the final users and the social approach to energy are major concerns that require suitable solutions and, once again, an architecture capable of being adjusted case by case.

In this context, the regulatory framework has been identified as a cornerstone for such an innovative approach. Consequently, in order to allow a fast and economically sustainable grid development, preventing future costs of adaptation, it would be desirable to introduce technical requirements to be applied already now to the individual microgrids, even in different territorial contexts. The final goal is to make them able to work both in islanded mode and in connected mode, according to the bottom-up/top-down integrated approach (smart microgrid) proposed in this paper, when the boundary conditions will allow the development of the transmission network.

VI. ACKNOWLEDGEMENTS

The authors thank Matteo Moncecchi, Silvia Corigliano, Claudio Brivio, and Benson Mbuya for their strong contribution to the Ngarenanyuki microgrid deployment and for the overall contribution to the Energy4Growing project.

VII. REFERENCES

[1] M. Delfanti, D. Falabretti, M. Merlo, "Distributed Generation impact on distribution network losses, Electric Power System Research, Vol. 97, 2013, Pages 10-18.

[2] V. Oree, S. Z. Sayed Hassen, P. J. Fleming, "Generation expansion planning optimisation with renewable energy integration: A review", Renewable and Sustainable Energy Reviews, Vol. 69, March 2017, Pages 790-803

[3] P. S. Georgilakis, N. D. Hatziargyriou, "A review of power distribution planning in the modern power systems era: Models, methods and future research," Electric Power Systems Research, vol. 121, pp. 89–100, Apr. 2015

[4] IEA, Energy Access Outlook 2017, from poverty to prosperity, World Energy outlook Special Report, 2017.

[5] A. Brew-Hammond, "Energy access in Africa: Challenges ahead," Energy policy, vol. 38, pp. 2291-2301, May 2010.

[6] D. P. Kaundinya, P. Balachandra, and N.H. Ravindranath, "Grid-connected versus stand-alone energy systems for decentralized power—A review of literature," Renewable and Sustainable Energy Reviews, vol. 13, pp. 2041-2050, Oct. 2009.

[7] S. Szabó, K. Bódis, T. Huld, and M. Moner-Girona, "Sustainable energy planning: Leapfrogging the energy poverty gap in Africa," Renewable and Sustainable Energy Reviews, vol. 28. pp. 500–509, 2013.

[8] J. Casazza, "The Development of Electric Power Transmission: The Role Played by Technology, Institutions, and People", IEEE, 1993.

[9] IEA, "Large-scale electricity interconnection - Technology and prospects for cross-regional networks", 2016.

[10] Power Africa, http://medium.com/power-africa/, 2019.

[11] S. Szabó, K. Bodis, T. Huld, I. Pinedo-Pascua, U. Tromboni and M. Moner-Girona, "Energy options in rural Africa: solar and diesel distributed systems vs grid extension". UNIDO ICS Course "Renewable energies for decentralized systems: supporting tools and best practices for green energy and sustainable development", Trieste, Italy, 4-8 June 2012.

[12] IEEE PES Technical Report PES-TR22: Contribution to bulk system control and stability by Distributed energy resources connected at distribution level, IEEE, January 2017.

[13] Eastern Africa Power Pool (EAPP): EAPP regional power system master plan, vol. 1: main report, December 2014.

[14] European Commission, Joint Research Centre, Science for the AU-EU Partnership: building knowledge for sustainable development, 2017, ISBN 978-92-79-69510-0, doi:10.2760/55224, JRC107753

[15] Dimitrios Mentis et al Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa. Environ. Res. Lett. 12 085003, 2017

[16] JRC, Renewable Energies Rural Electrification Africa, http://re.jrc.ec.europa.eu/re2naf.html

[17] Energypedia, "PicoPV Database", 2011.

[18] M. Harper, "Review of strategies and technologies for demand side management on isolated microgrids." Lawrence Berkeley National Laboratory and Schatz Energy Research Center, 2013.

[19] R. Deshmukh, J. P. Carvallo, and A. Gambhir, "Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design," LBNL-6222E, 1171612, Mar. 2013.

[20] B. Tenenbaum, C. Greacen, T. Siyambalapitiya, and J. Knuckles, From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa. The World Bank, 2014.

[21] B. Tenenbaum, C. Greacen, T. Siyambalapitiya, J. Knuckles, "From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa", The World Bank, 2014.

[22] IEEE PES Technical Report PES TR67: Impact of IEEE 1547 Standard on Smart Inverters. IEEE, May 2018.

[23] R. Deshmukh, J. P. Carvallo, A. Gambhir, "Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design", Prayas (Energy Group), March 2013. Available: http://www.prayaspune.org/peg/publications/item/246-sustainable-development-of-renewable-energy-mini-grids-for-energy-access-a-framework-for-policy-design.html

[24] S. Sinha, S. Chandel, Review of software tools for hybrid renewable energy systems, Renewable and Sustainable Energy Reviews 32 (2014) 192–205. doi:10.1016/j.rser.2014.01.035.

[25] T. Khatib, I. A. Ibrahim, A. Mohamed, "A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system", Energy Conversion and Management 120 (2016) 430–448. doi:10.1016/j.enconman.2016.05.011

[26] National Renewable Energy Laboratory (NREL), HOMER - Hybrid Renewable and Distributed Generation System Design Software (2010)

[27] CANMET, RETScreen International Home (2016)

[28] University of Zaragoza, Software iHOGA - improved Hybrid Optimization by Genetic Algorithms (2013)

[29] National Renewable Energy Laboratory (NREL), System Advisor Model Report (2014)

[30] PVSyst S.A., PVSyst photovoltaic sofware (2016)

[31] S. Mandelli, C. Brivio, E. Colombo, M. Merlo, "A sizing methodology based on Levelized Cost of Supplied and Lost Energy for off-grid rural electrification systems", Renewable Energy 89 (2016) 475–488.

[32] C. Brivio, M. Moncecchi, S. Mandelli, M. Merlo, "A novel software package for the robust design of off-grid power systems", Journal of Cleaner Production, (2017), 166 (2017) 668-679.

[33] OSeMOSYS project, http://www.osemosys.org/, 2018.

[34] Energy4Growing, www.e4g.polimi.it, 2019.

[35] Energy4Growing Facebook page, https://www.facebook.com/energy4growing2014/, 2019.

[36] D. Falabretti, M. Moncecchi, C. Brivio, M. Delfanti, M. Merlo, V. Musolino, "IoT-oriented management of distributed energy storage for the primary frequency control", 2017 17th IEEE International Conference on Environment and Electrical Engineering, June 6-9, Milano, Italy.

[37] S. Karekezi, J. Kimani, "Status of power sector reform in Africa: impact on the poor", Energy Policy, Volume 30, Issues 11–12, September 2002, Pages 923-945.

[38] S. Mandelli, J. Barbieri, L. Mattarolo, E. Colombo, "Sustainable energy in Africa: A comprehensive data and policies review", Renewable and Sustainable Energy Reviews, Vol. 37, September 2014, Pages 656-686.

[39] A. Eberhard, V. Foster, C. Briceño-Garmendia, F. Ouedraogo, D. Camos, M. Shkaratan, "Africa infrastructure country diagnostic Underpowered: The State of the Power Sector in Sub-Saharan Africa", May 2008. Available: https://openknowledge.worldbank.org/bitstream/handle/10986/7833/482140ESW0P11110Power0Sector0Review.pdf?sequence=1

[40] J. Turkson, N. Wohlgemuth, "Power sector reform and distributed generation in Sub-Saharan Africa", Energy Policy, Volume 29, Issue 2, January 2001, Pages 135-145

[41] "The Single-Buyer Model", Public policy for the private sector, The World Bank group, December 2000, Available: http://siteresources.worldbank.org/EXTFINANCIALSECTOR/Resources/282884-1303327122200/225Lovei-1211.pdf

[42] Ç. Çelik, "Electric power market models in developing countries". Available: http://www.emo.org.tr/ekler/99fe6b0b444c238_ek.pdf

[43] F. Vivien, S. Witte, S. G. Banerjee, A. Moreno, "Charting the Diffusion of Power Sector Reforms across the Developing World", 2017. Available: https://openknowledge.worldbank.org/handle/10986/28853.

[44] West African Power Pool, http://www.ecowapp.org/en/countries, 2019.

[45] A. Eberhard, K. Gratwick, E. Morella, P. Antmann, "Independent Power Projects in Sub-Saharan Africa", World Bank Group, 2016. Available: https://openknowledge.worldbank.org/bitstream/handle/10986/23970/9781464808005.pdf?sequence=2&isAllowed=y

[46] K. N. Gratwick, A. Eberhard, "An Analysis of Independent Power Projects in Africa: Understanding Development and Investment Outcomes", Volume26, Issue3, May 2008, Pages 309-338

[47] A. Medinilla, B. Byiers, K. Karaki, "African power pools: regional energy, national power", February 2019. Available: https://ecdpm.org/publications/african-power-pools-regional-energy-national-power/

[48] CLSG Intercconection project, https://www.transcoclsg.org/project-presentaton/, 2019.

[49] L. E. Jones, N. Kirby, Developing and Integrating Africa's Regional Electricity Systems and Markets Using VSC-HVDC, Cigrè Symposium 2015, May 2015, Available: https://www.researchgate.net/publication/280013150_Developing_and_Integrating_Africa%27s_Regional_Electricity_Systems_and_Markets_Using_VSC-HVDC

[50] Federal ministry of power, works and housing, Federal Republic of Nigeria, "Rural electrification strategy and implementation plan (RESIP)", July 2016, Available: http://rea.gov.ng/download/rural-electrification-strategy-implementation-plan-resip/.

[51] Energy and Extractives Global Practice, African Region, World Bank, "Program appraisal document for the Ethiopia electrification program", 2018.

[52] World Bank, "Environmental and social systems assessment for the Ethiopia Electrification Program", 2018.

[53] Ministério da Energia e Águas, Angola, "Angola Energia 2025, Angola power sector long-term vision", 2016.

[54] The World bank, "Ethiopia - Electrification Program for Results: Environmental and social systems assessment (English)", 2018. Available: http://documents.worldbank.org/curated/en/537951498119172627/Environmental-and-social-systems-assessment

[55] Kenya National Transmission Grid Code, https://www.kengen.co.ke/?q=node/186, 2019.

[56] Kenya Energy Regulatory Commission, www.erc.go.ke/services/electricity/electricity-regulations/, 2019.

[57] Ghana Energy Commission, http://www.energycom.gov.gh/regulation, 2019.

[58] West African Power Pool, http://www.ecowapp.org/en/documentation, 2019.

[59] The Eastern African Power Pool, http://eappool.org/, 2019.

[60] World Bank, "Integration of Electricity Networks in the Arab World: Regional Market Structure and Design", (2013).

[61] Kenya Grid Code, http://www.kplc.co.ke/img/full/wm9o9bvTXEvC_Kenya%20Grid%20Code.pdf, 2019.

[62] E. Gordon, "The Politics of Renewable Energy in East Africa", August 2018. Available: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/08/The-politics-of-renewable-energy-in-East-Africa-EL-29.pdf

[63] ESKOM, "Standard for the interconnection of embedded generation", Available: http://www.eskom.co.za/Whatweredoing/Pages/Technical_Specifications_And_Standards.aspx

[64] L. Odarno, E. Sawe, M. Swai, M. J.J. Katyega, A. Lee, "Accelerating Mini-Grid Deployment in Sub-Saharan Africa: Lessons from Tanzania", World Resources Institute, Available: https://www.wri.org/sites/default/files/accelerating-mini-grid-deployment-sub-saharan-africa_1.pdf

[65] International Electrotechnical Commission, "IEC TS 62257 series: Recommendations for small renewable energy and hybrid systems for rural electrification"

[66] CIGRE WG C6.38 "Rural electrification" proposal, https://cigre-usnc.org/wp-content/uploads/2018/07/TOR-WGC6.38_RuralElectrification.pdf, 2019.

[67] Alliance for Rural Electrification, https://www.ruralelec.org/, 2019.