The role of electrical energy storage in Sub-Saharan Africa

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Abstract

In developing countries energy is recognized to be essential for promoting equitable growth, to foster social inclusion and to preserve the environment. Nevertheless, the current state of the energy sectors of developing countries still represents a major hindrance to the fulfillment of this goal. In this frame, electrical energy storage may allow a cost-effective exploitation of renewable sources in order to cope with the improvement of the power supply service via local national grids, but mainly it may become a building block of rural electrification through integration within off-grid systems. This paper focuses on electrical energy storage in sub-Saharan Africa providing an overview of the main aspects of this theme. Indeed, the specific features of the power sector in sub-Saharan Africa are analyzed with regards to the framework of application of electrical energy storage. The typical technologies implemented in this context and the status of the market as well as of the economic models to support the diffusion of storage together with renewable energy technologies are highlighted. Moreover, an overview of technical aspects such as storage capacity sizing and interface converters for integration with renewables are described. Finally, an experimental application of a hybrid micro-grid in rural Tanzania is presented. With this paper, our aim is to provide an overall view, within the main technical and non-technical aspects, of electrical energy storage in a context – sub-Saharan Africa – which has a huge potential, both in market terms, but also with regards to the possibility to develop and implement alternative technical solutions which may be integrated in the high income countries power systems as well.

Keywords

Electrification, Energy Storage Technologies, Business models, Storage Design, Micro-grid

1. Sub-Saharan Africa energy scenario

Energy demand in sub-Saharan Africa (SSA) has grown by 45% from 2000 to 2012, but access to modern energy services, though increasing, remains limited [1]. Per capita average electricity consumption is comparable to the amount consumed by a 50W light bulb operating on a continuous base. This amount is hardly enough to cover the daily basic need of single households and it cannot meet community as well as productive energy needs. The power sector is not adequate, nor reliable in the majority of the SSA countries: frequent power shortages are threatening the development of the productive sector, while the losses in poorly maintained transmission and distribution networks are often twice the World average and they contribute to increase the overall primary energy consumption [1]. Moreover, electricity tariffs are high and due to the poor quality and quantity of the supply, the use of back-up and emergency petrol/diesel generators increases the final electricity costs and has environmental consequences.

Besides, according to the New Policy Scenarios (NPS) of IEA, the SSA grid-based generation capacity (currently 90GW) will grow four times to 2040 [2]. Renewable energy technologies (RET) are expected to play a major role in this growth: hydropower has large technical potential and additional capacity might contribute in mitigating the average electricity costs and phasing out oil-fired power, PV and wind markets are expanding while attention to geothermal source is also growing [1]. Again in the NPS, off-grid solutions (like home/community based systems or micro-grid) will provide electricity to 70% of those gaining access in rural areas. In particular two third of off-grid systems in rural areas are expected to be powered by PV, small hydropower or wind.

Many governments of SSA are becoming aware of these changes and are promoting reforms to remove regulatory and political barriers to enable RET penetration into the power sector. Nevertheless despite this positive trend, even in the most favorable scenario, a significant gap in the distribution of resources will remain across SSA with special reference to the urban-rural disparity [3]. This means that especially at rural level the strategy for scaling up access to electricity need to be redesigned, overcoming the dichotomy between centralized and off-grid electrification approaches and probably aiming at integrating small-scale RET in local micro-grids or connecting them to the national grid. In this a frame, electrical energy storage (EES) can play a relevant role.

In this regard, with this paper we provide an overview of the main aspects of application of EES in SSA with particular reference to the context of rural areas. In particular we pose attention both to technical and non-technical issues underlying the key factors that differ from SSA and high income countries. In Section 2 two typical electrification approaches (top-down and bottom-up) are introduced, an overview of the different frameworks of applications of EES within these approaches is provided and the typical EES technologies solutions are discussed. In Section 3, an overview of the market situation and economic models to properly support RET and EES in rural areas is provided. In Section 4 the focus is on technical aspects; specifically the classical approaches for EES capacity sizing are describe together with basic models for dynamic analyses as well as typical architectures of interface converters for EES integration with RET. Finally in Section 5 the Energy4Growing project and the related experimental application of a hybrid micro-grid integrating RET and EES in a rural school of Tanzania is presented.

2. Overview of EES applications in Sub-Saharan Africa

Two different approaches can be recognized as regards the process of electrification in SSA with reference to the urban-rural dichotomy: namely *top-down* and *bottom-up* approaches. Accordingly EES can play different role.

2.1. Top-down and bottom-up electrification approaches

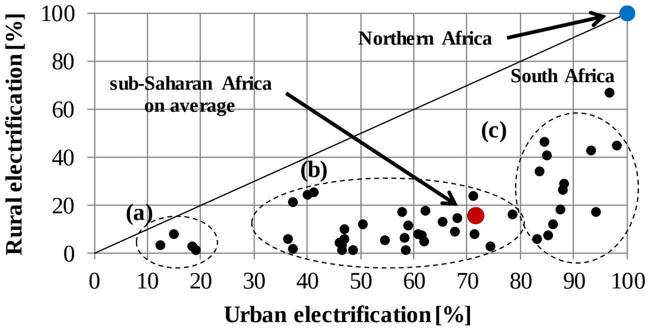

Figure 1 SSA countries representation according to rates in urban and rural electrification (2012) [2,4]

A key element to understand the situation of electric power systems in SSA lies in the different conditions of urban and rural areas. In this regards, considering the electrification rates of these two areas the situation of SSA countries is presented in Figure 1. The graph shows that on average, SSA countries have about 72% and 15% electrification rates for urban and rural areas respectively. Moreover, four groups can be recognized.

a) A number of countries report the poorest conditions – namely South Sudan, Central African Republic, Chad and Liberia – they are also tail-end in the Human Development Index ranking [5] and, despite very low values (urban and rural rates below 20% and 10% respectively), they show a urban-rural disparity.
b) The majority of SSA countries lie in the range of 35-80% urban electrification rates and below 25% in rural ones. Hence it is clear the trend in SSA to first address urban areas while secondly coping with rural electrification.
c) A number of countries report urban electrification rates above 80%: some have rural electrification below 20%, while others reaching up to 50%. In this latter case countries with medium Human Development Index such as Ghana, Gabon, Equatorial Guinea, and Cabo Verde are reported.

d) South Africa, exceptional in SSA as for income level, reports the highest electrification rates; nevertheless also in this case a disparity between urban and rural areas can be recognized.

Lastly, the conditions of Northern Africa countries that report 100% electrification both in urban and rural contexts are highlighted. It is worthwhile to notice that these figures results from data employed by international institutions and retrieved by local statistical offices and/or governmental bodies. Accuracy of these data, mainly for rural areas, may be questionable. Indeed, while for urban areas data reflects the connections to the local national grids (i.e. users are registered for bill payments), in rural areas electrification related to small isolated systems are probably not considered. Nevertheless, these data reflect the general different conditions between urban and rural areas and lead to highlight two different technical approaches to provide electric power: *top-down* and *bottom-up*.

We refer to the *top-down* approach as regards the electrification process which has been historically followed in SSA as well as in high income countries based on the paradigm of centralized electrical systems [6–8]: large hydropower or fossil fuelled plants interconnected by a transmission grid which supplies power to consumers through radial distribution grids. Nevertheless, while high income countries reached 100% electrification rates with this approach, SSA countries are still facing considerable difficulties in increasing electrification rates. In particular, rural areas are the most afflicted by this situation, since governments paid more attention to urban areas where economic activities are more significant. Moreover, rural electrification has generally the highest costs within the top-down approach being not balanced by a local market (low load factors and low affordability for local people). Therefore utilities are reluctant to extend the service to rural areas. A second main element that characterizes power systems in SSA is the low reliability: load shedding is common as well as supply interruptions (according to [9] 8.3 outages with duration of 4.3 hours occur on average in a month in SSA).

We refer to the *bottom-up* approach in relation to the electric energy supply in rural areas by means of systems which operate separately from the grid (i.e. off-grid) feeding nearby consumers. Historically small-scale petrol/diesel generators (from few kW to tens of kW) have been employed by private consumers or local services (schools, clinics, NGOs, churches, etc.) [10–12]. Off-grid small generators have been employed also as multi-functional platforms at village level to provide electric as well as mechanical power [13]. Currently, also in areas covered by the grid, small back-up generators are becoming quite common since they are employed by local enterprises to compensate grid outages. Indeed, in SSA 48% of firms own or share a generator [9]. Also larger diesel generators (from hundreds of kW to few MW) are employed in off-grid configurations to supply power through a local distribution grid in remote towns [14] or to act as emergency power source for sections of the existing distribution grids [15].

Beside petrol/diesel generators, RET are also employed in rural areas to supply power with a bottom-up approach. Traditionally these are small hydropower systems, but thanks to the decrease of costs and the increased availability of suppliers, other RET have appeared in the past two decades. Moreover there is potential also for systems coupling PV–EES–diesel generators, both with regards to new installations, but also for diesel generator retrofitting [14,16].

2.2. EES in top-down and bottom-up electrification approaches

EES can play a key role both in top-down and bottom-up electrification approaches.

Historically EES have been rarely implemented in *top-down* approach. Indeed, as well known, power systems integrate technical solutions to face congestions, security issues, events unpredictability, and power quality problems (i.e. voltage and frequency control) without the exploitation of EES. Nevertheless, nowadays these challenges are more prominent due to the increasing penetration of RET. In this frame, EES are considered a solution offering flexibility to the system and addressing most of the mentioned issues. In particular, potential applications of ESS in top-down systems are [17–21]: load levelling/peak-shaving, RET integration, spinning reserve, customer-side peak shaving, primary frequency regulation, voltage control in distribution network, investment deferral, arbitrage/energy trading.

As a matter of fact, nowadays the application of EES within the top-down electrification approach is a prerogative of high income countries where the involved actors (i.e. Transmission System Operators (TSO), regulatory authorities and producers) have the technical and economic capabilities to develop new regulations and set up pilot projects [22]. On the contrary, despite the national grids of SSA would benefit from the integration of EES (also in combination with distributed RET generation), little or no actions have been taken so far mainly because of the lack of economic capabilities. Only few pilot projects run by private companies can be found in South Africa [23].

Within the *bottom-up* approach and particularly in the context of SSA, EES (namely electrochemical batteries), apart for petrol/diesel generators and hydropower plants are mandatory to exploit the potential of RET. Indeed off-grid systems benefit from the use of EES to mitigate both short-term fluctuations (to ensure the instantaneous power balance) and intermediate-term energy deficiency which are typical consequences of unpredictability of RET. In this regard, we distinguish four typical applications of EES (Table 1).

Table 1 Typical off-grid applications for electrochemical-batteries and key features

	Application type	Storage capacity range	Power source size range	Typical power source Typical architecture
(1)	Solar Home Systems	from few Wh up to about 10kWh	from few to hundreds of W	PV Stand-alone, *dc*
(2)	Mid-size off-grid PV systems	from tens to hundreds of kWh	from few to hundreds of kW	PV Stand-alone, *ac*
(3)	Micro-grids	from tens to hundreds of kWh	from tens to hundreds of kW	Micro hydropower – Integrated PV, small wind, diesel/petrol generators Isolated grid, *ac*
(4)	Grid-tied back-up systems	from tens of kWh	from few to hundreds of kW	#

(1) The first application type is *solar home systems* (SHS). We mainly refer to SHS as systems typically employed to provide basic power service to single households and composed of PV modules, electro-chemical batteries, charger and end-use appliances. The smallest SHS are solar lantern, which are portable devices comprising a PV module up to about 10W, a single battery with capacity ranging from few to tens Wh and a charge controller. These are *dc* systems with voltage ranging from 2.4 to 12V often integrating battery, charger and a led lamp in a single case [24]. Besides, a socket for mobile charging is also often implemented. Mid-size SHS are typically 12V *dc* systems which employ a PV module of tens of W together with a battery of few kWh. Still they can be portable: the case integrating the battery and the charger can be disconnected from the PV module (portable as well) and from the wirings of electrical devices. End-use appliances are mainly lamps, but often one or more external sockets are provided to supply power to other devices. The largest SHS reach up to hundreds of W for PV module(s) and several (tens) kWh battery capacity. When these sizes are employed, systems can be either *dc* or *ac*. In the first case 12-24V systems can be adopted, while in the second one an off-grid inverter is required.

Off-grid systems ranging in the sizes of SHS are also employed for telecom systems, small schools, clinics, and small commercial activities. Moreover, SHS systems also find application as back-up system of the grid for urban areas users. In this case, consumers are willing to have a further power source coupled with EES in order to compensate the outages of the grid. Back-up SHS typically supply power to the devices connected to the grid thanks to an off-grid inverter and a manual switch which allows selecting the power source.

(2) The second application type is mid-size off-grid PV systems. These are represented by isolated plants based on PV power source which supply power to an *ac* system. In this case, PV installations range from few to hundreds of kW with some larger cases reaching up to 1MW, while EES capacity ranges from tens to hundreds of kWh. The demand for these systems comes from large households, but mainly from public institutions, schools, health centers, hospitals, small productive initiatives and site specific activities such as mines, touristic resorts, and telecommunication. The basic scheme of these systems is composed by PV modules and batteries strings which are connected on a *dc* bus via solar controller / battery charger. Then *ac* power is supplied to the loads by means of an off-grid inverter. The voltage of the *dc* bus is defined by the inverter and typically increases with the rated power.

Mid-size off-grid PV systems give rise to interest also for substituting or integrating with petrol/diesel generators. Nevertheless this proves to be a difficult task since several different aspects need to be considered. According to the share of installed PV power, different architectures can be considered with specific battery chargers, inverters, and control systems [25]. Besides, energy efficiency and energy management actions need also to be introduced. Indeed, in rural area applications, it often occurs that the generator is operated for few hours a day and all appliances are left on all the time and they are switched off by shutting down the generator. In these conditions there is a limited need of efficiency since the marginal running costs are negligible. Moreover, the generator capacity is usually much higher than the baseload and it is useful to keep the loads at least some 50% of rated capacity for a better generator performance. When substituting or integrating with PV and EES that offers 24h services, energy efficiency becomes essential, and all technologies, appliances and habits need to be changed. In the absence of these actions the batteries are easily exposed to deep discharges and long period without full charge thus reducing their lifetime. Finally, mid-size off-grid PV systems are also employed by consumers as a back-up system of the grid typically in urban areas. They can be sized in order to supply a share of the average daily requirement (i.e. the supply power to specific loads for few hours) and they are operated with off-grid inverter(s) by a manual switch which allows selecting the power source.

(3) The third application type is represented by application of RET in *ac* micro-grids which address the power supply for remote villages, large school campuses, and hospitals. Traditionally hydropower systems (from few to hundreds of kW) have been the main renewable source for micro-grids in case of proper water streams availability [26–28]. These systems are typically designed as *run-off-river* (i.e. no upstream water basin is available) and they often employ electronic load controllers based on dump resistors to provide frequency regulation. Despite this solution goes to the detriment of efficiency (i.e. dump resistors dissipate energy on air or water), it allows having free-maintenance, low-cost and reliable system control. Beside hydropower systems, other RET are appearing in rural areas of SSA thanks to the decrease of costs, the development of technological solutions (mainly for the system control aspects) and the increased policy efforts and availability of suppliers. Indeed, micro-grids integrating different energy sources (PV, small wind, petrol/diesel generators) are still rare, but feasible as for the technological state of the art [29–33]. The power size of these systems for rural electrification can range from tens to hundreds of kW while the storage ranges from tens to hundreds of kWh.

Two typical architectures are considered for integrating energy sources in a micro-grid: *series*- and *parallel-functioning*. The *series-functioning* approach (Figure 2) requires that all generators, including all the rotating machines are connected in parallel via a *dc* bus which is further connected also to the battery pack. This approach allows simple management logics, but integrating several power sources brings about complexity as regards power electronics interfaces and the *dc* bus. Indeed, the *ac* network is generated by means of a *grid-forming* inverter while rectifiers are needed to interface the power sources with the *dc* bus. This requires a data bus to integrate the rectifiers and define the active and reactive power set points of each power sources in order to control the *dc* voltage. Moreover, applying this architecture in SSA, the nominal power of the inverter sets the maximum power of the energy sources thus limiting the micro-grid expansion.

The parallel-functioning approach (Figure 3) requires that the generators can be connected in parallel by means of the *ac* bus. Obviously, in this case trade-off solutions can be implemented, e.g. the rotating machines (i.e. traditional generators and hydro turbines) can be connected to the *ac* bus, while PV, wind turbine, and batteries are connected to the *dc* bus. The *ac* grid can be generated by means of a rotating machines connected to the *ac* bus, thus leading the other power sources and the bi-directional inverter to work in *grid-following* mode. On the *ac* side, if several generators are available they can be managed according to the typical control approaches of meshed grids; this allows avoiding the data bus and results in easier integration of further power sources thus expanding the micro-grid. On the contrary, more adequate management logics (e.g. to share the power among several different power sources, to control frequency and voltage) as well as more sophisticated inverters are required.

In both architectures, according to the load profile and load types, to the features of available of renewable sources, and to the dynamic capabilities of the rotating machines and power electronics, the battery pack can be required to predominantly provide power service, thus addressing short-term power fluctuations, energy service, thus addressing intermediate-term energy deficiency (i.e. day/night cycle), or both of them. This affects the selection of the proper electro-chemical battery technology, the total capacity and the logics to manage the dispatchable resources (i.e. diesel generators and hydropower).

(4) The forth application is represented by grid-tied back-up systems for customers already connected to the grid. Similarly to back-up systems based on SHS or mid-size off-grid PV systems, grid-tied back-up systems are implemented to assure continuity and quality of the supply where interruptions and severe voltage fluctuations recur. Nevertheless in this case, a charger system is employed to charge the battery pack by taking power from the grid, then, when outages occur, an off-grid inverter supplies power to the user electrical devices. PV modules are rarely implemented to reduce the cost of purchasing power from the grid, since, in this view, the simple option in SSA, is to implement an off-grid system which does not interact with the grid. This aspect brings about the issue of lack of regulations and experiences in SSA countries (as well as in the developing world) as regards the implementations of grid-tied distributed systems capable to exchange energy in both directions with the national grid (i.e. to absorb and supply).

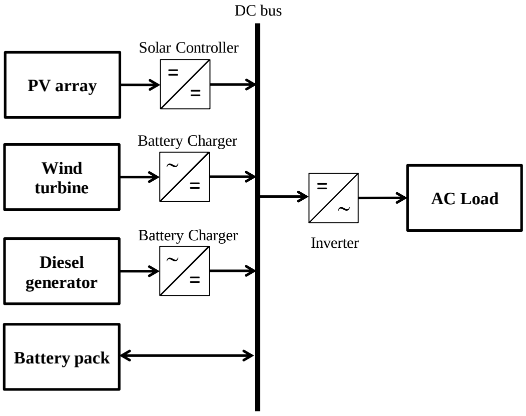

Figure 2 Micro-grid with *series-functioning* architecture

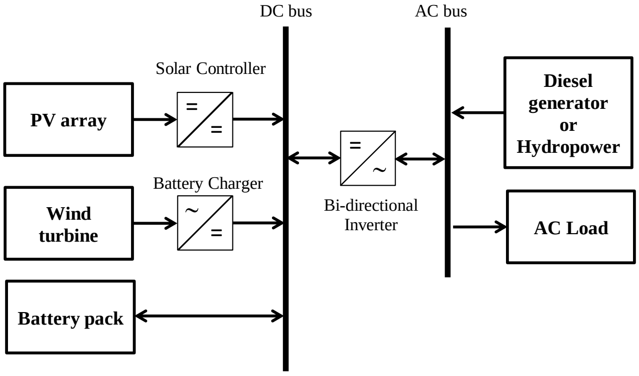

Figure 3 Micro-grid with *parallel-functioning* architecture

2.3. Considerations as regards EES technologies

With regards to the technologies for EES, we highlight that electric energy can be stored in many different forms such as direct electric, electrochemical, and mechanical [19,34]. Hence there is a wide range of EES technologies currently available with different strengths and weaknesses [17,19,20,35–42]. Nevertheless, as well known, there is no one-fits-all solution for EES, and one should choose the most suitable technology after carefully considering the specific application. This consideration is even more important in SSA, due to the limited economic availabilities of these applications.

For application of EES within the top-down electrification approach and for energy intensive applications (e.g. load levelling, renewable integration) EES with low power/capacity ratio are preferable, for instance sodium-sulphur or lead-acid batteries. Otherwise, in power intensive applications (e.g. primary frequency regulation, customer-side peak-shaving) high power/capacity is advisable, such as ZEBRA or lithium-ion batteries [22].

For application of EES within the bottom-up electrification approach in SSA, selecting the best technology in terms of performance and durability is not the top priority; bur cost and availability on site play a relevant role in the final decision. Therefore the battery technology choice is usually defined by the economic capacity of the donor or investor. Thus, lead-acid batteries, which have benefited of years of development with inevitably cost reduction and global spread, represent the most appropriate choice for all the applications (SHS, mid-size PV systems, micro-grid, and grid-ties back-up systems) leaving small chances to competing technologies [43–45]. In particular lead–acid maintenance-free batteries (AGM or gel sealed batteries) are mostly seen in those applications. In larger and well financed installations, especially in the telecommunication sector, the 2V tubular and larger-surface positive plate batteries, offering a higher number of cycles even in hot areas, are often used. In order to reduce sulphuration of the negative plates, which is typically induced by long period without full charge and reduces the life-time, gel type lead-acid batteries can be employed. Sometimes batteries employed in SHS are modified car batteries. The main modification is to make the positive plate thicker to allow more and deeper cycles [46].

As regards lithium batteries, they are rarely seen in SSA applications despite leveraged kWh costs of lithium are comparable to lead-acid batteries (when considering the potential depth of discharge and the number of cycles) [17]. Indeed, the initial investment cost is a barrier both for investors and donor agencies. Moreover inverters need to be configured to run with lithium batteries and this is not always possible with the limited technology options with local suppliers. $LiFePO_4$ are the only lithium technology that may have a share in SSA market in the next future. They are well-suited for cycle-charging application when high power/capacity ratio is required. Moreover, four cells of $LiFePO_4$ in series produce a similar voltage to six lead-acid cells in series. For this reasons, they are often used in solar lantern or to replace lead-acid batteries in portable power systems applications.

Finally in the smallest applications of SHS, nickel-cadmium stationary batteries are sometimes implemented since they allow avoiding the charge controller. Nevertheless they suffer from nonsynchronous behavior of the battery stack and have the important disadvantage of high toxicity of cadmium which is even more relevant in SSA. Indeed in most rural areas there are no recycling systems, and most of the used batteries will end up in the soil so that there is a high chance that cadmium gets into the food chain [46].

3. Overview of economic models and regulatory frameworks

Each of the above applications of EES responds to different economic models, market growth patterns, policies and regulations. Despite the lack, fragmentation and inconsistency of information and data across SSA, it is possible to depict a framework for each application thanks to recent international agencies efforts, field experiences and indirect sources.

With regards to SHS, the market is estimated with a figure of 5-10 million worldwide [16]. Leading African countries are Kenya (320,000), South Africa (150,000), Zimbabwe (113,000) and Tanzania (65,000) [16]. Data are most likely underestimated, the market is developing fast and the reduced cost of PV makes them accessible by private individuals outside incentive policies and international funds. A 2015 survey run in 5 Tanzanian regions sponsored by GDF showed that PV penetration in rural area can be estimated at some 5% of households thus bringing in 300.000-350.000 a rough estimation of SHS installations in rural Tanzania. SHS are usually paid upfront by final users, the retail cost of a reliable SHS can be estimated in some 3-4.5 €/W for an *ac* system with a PV/battery ratio of 1:1.5. The system design is usually kept as simple as possible, in order to reduce installation cost and prevent system outbreaks. The choice of the equipment is mainly done on a cost basis often at detriment of system reliability. The cost of the battery accounts for some 30% of overall cost when a lead low maintenance leisure battery is chosen, and up to 50% with a maintenance free gel AGM battery. On local markets it is possible to find a huge variety of battery brands without quality control and adequate labelling. Access to retailers is limited and so it is product choice. Often installations are done with second hand products or automotive batteries.

To overcome quality and credit access barriers, in many SSA countries, a number of providers are offering SHS services in the form of leasing. Those systems are commonly known as “pay-as-you-go” solutions [47]. Customers do not need to pay the full investment cost, but pay fixed monthly electricity bills according to their installation size. The providers own the system until it is fully paid back by the customers. Their technicians do the installation and assure long term maintenance. Remote monitoring tracks SHS functioning data to prevent outbreaks. In most cases the providers take care of wiring inside the buildings and provide led lights and other electrical appliances to final users, in order to control system loads and consumption. Pay-as-you-go companies are offering a new and effective business model for the dissemination of SHS. Nevertheless the establishment of a commercial, financial and technical network to run the business is a costly activity and dispersed village do not represent a profitable market area. In Tanzania alone pay-as-you-go companies are targeting more than 200,000 installations by the end of 2015 and this is consistent with the national target of 1 million SHS by 2017 [48]. M-kopa, a pay-as-you-go company in East Africa, alone has recently announced to have reached the 250,000 installation in Uganda, Kenya and Tanzania [49].

Mid-size off grid PV systems demand is still limited by the competition with petrol/diesel generator and aid resources are the main driver of the sector. Indeed institutional customers usually do not have the capital capacity to pay for the systems and the private sector still perceives the installation of EES as too risky. Despite a RET based-system would be paid back in a short time, in marginal areas petrol/diesel generators are still the most viable option: the technology is well known and there is no need of selecting and trust a technician, on the contrary RET-ESS need to be carefully sized and this implies to precisely know future electricity consumption, the investment may suddenly become redundant in the event of national grid extension, and the introduction of RET need to be complemented by energy efficiency measures. With petrol/diesel no matter how expensive running costs are, the investment is limited and the fuel cost will be covered if the economic activity is running well. Moreover, when the installation of PV systems is sponsored by donors, the long term economic sustainability of the project may be at risk as beneficiaries will hardly have the economic capacity to replace the battery once exhausted. On the other hand, no companies or financial institutions offer leasing services for the installation of off-grid PV systems, as it is in the SHS. The investment risk and the scattered distribution of larger customers make the activity too risky.

No specific policies or regulations are found affecting this market sector, off-grid installations for auto-consumption it is an unregulated activity. In some cases the principle is defined in primary legislation [50], in other cases a threshold is defined and under a given capacity, such as 1MW, no license is needed and no regulations apply [51].

Referring to micro-grids, estimates report some 150,000-250,000 systems operating worldwide [16], while a number of successful installations are documented [52–56]. However, not all rural settlements far from the grid represent a good potential for micro-grids. Very often households in rural villages are dispersed and even villages with a high population density may not fit with feasible micro-grid projects. Micro-grids may be owned by national electricity companies, private companies, local cooperatives or municipalities. The cost of EES makes the integration of RET a difficult option for micro-grids. When diesel micro-grids are operated by the national electricity companies, the capital cost to convert them in RET is often excessive when compared to other investment priorities in the electricity sector. In Tanzania this has pushed the regulator to introduce a different feed-in tariff with a premium for RET connecting to the nationally owned micro-grids [57]. Indeed, most RET based micro-grid experiences come from cooperation projects. Usually when micro-grids are nationally owned, customers' electricity costs are equalized within the national electricity tariff, whereas when the projects are run by independent bodies a local tariff is introduced and project sustainability is more at risk.

The recent development of hybrid micro-grid to supply a number of customers outside the framework of national electricity companies has often seen the project implementer to seek consultation with national regulatory authority to approve proposed service tariff. In Cape Verde the regulatory authority has been involved in tariff setting for 39kW PV mini-grid system [52]. In Guinea Bissau the regulatory authority is involved in tariff approval of 1MW hybrid diesel-PV mini-grid [54].

With regards to grid-ties EES for already connected customers, introduction of net-metering like options is still confined to national legislation initiative and little support is found from international cooperation efforts [58]. Some experiences may be found in Cape Verde and Gambia [59,60]. In some other African countries the introduction of net metering is under evaluation, e.g. Kenya [61].

4. Overview of technical aspects for EES off-grid applications

4.1. Elements of EES capacity sizing

One of the important steps in the design process of off-grid systems is the sizing of power sources ratings and EES capacity. In literature, a common approach to carry out this employs steady-state numerical simulation methods [62–67]. These methods can be considered as *steady-state* since they are based on the solution of the energy balance between energy sources, EES and consumer loads for a given time step (usually one hour). No dynamic interactions between the different system components are taken into account. The energy balance is solved for a whole year and key techno-economic parameters are computed for a given system life-time (i.e. loss of load probability and net present cost). These parameters are employed to identify the optimum system sizing by comparing different configurations (i.e. a number of systems having different power sources ratings and storage capacities) [68–71]. As a matter of fact, this is a simulation-based trial and error process.

Regarding EES modelling in steady-state approaches, *ideal* battery model is typically employed. Attention is given to the energy aspect of capacity sizing (i.e. kWh) and, for instance, the influence of temperature variations on performances, the variability of EES capacity according to operating current, and the electrical circuitry are not considered. Ideal battery models estimate the amount of energy that flows through the battery and the change in the battery state of charge (SOC). Specifically, for each time-step of the simulation, the difference between the power source output $E_G(t)$ and user load $E_L(t)$ net of interface-converter efficiency is calculated:

$$\Delta E = E_G(t) - \frac{E_L(t)}{\eta_{IC}} = \begin{cases} discharging\,, & \Delta E < 0 \\ charging\,, & \Delta E \geq 0 \end{cases} \tag{1}$$

Then the battery energy content (i.e. the battery SOC) is updated based on the previous energy status $E_B(t\text{-}1)$ and taking into account battery efficiencies (charge η_B^+ and discharge η_B^-):

$$E_B(t) = \begin{cases} E_B(t-1) + \Delta E\, \eta_B^+, & \Delta E > 0 \\ E_B(t-1) + \dfrac{\Delta E}{\eta_B^-}, & \Delta E < 0 \end{cases} \tag{2}$$

$$SOC(t) = \frac{E_B(t)}{E_B^*} \; with\; E_B^* = C_B^* V_B^* \tag{3}$$

where E_B^* is the rated capacity of the battery related to nominal capacity C_B^* [Ah] and rated voltage V_B^*.

During simulation, the battery is normally subjected to some constraints:

$$E_B^{min} < E_{Bat}(t) < E_B^{max} \tag{4}$$

$$E_B^{min} = E_B^* \, SOC_{\min} \tag{5}$$

where E_B^{max} is the maximum allowable energy level which is normally equal to the rated energy of the battery, and E_B^{min} is the minimum allowable energy level for lifetime preservation purpose. This is normally linked to a minimum SOC (or maximum depth of discharge).

An advanced model for steady-state analyses is the *kinetic* battery model [72,73]. This model treats the battery as a two tanks system: part of the battery's energy storage capacity is immediately available for charging or discharging, but the rest is chemically bound. At high discharge rates, the available tank empties quickly, and very little of the bound energy can be converted to available energy before the available tank is empty. At slower discharge rates, more bound energy can be converted to available energy before the available tank empties, so the apparent capacity increases. Moreover, this approach considers that the battery's ability to charge and discharge depends not only on its current state of charge, but also on its recent charge and discharge history.

Given a mathematical model of the battery and the steady-state simulation, the optimization is typically performed based on the loss of load probability (LLP) [67] which is the percentage of the user load that remains not satisfied at the end of the simulation. The LLP, over a period of *N* time-steps, is computed as follows (*LL(t)* is the lost load at time step *t*):

$$\mathrm{LLP} = \frac{\sum_{t=1}^{N} \mathrm{LL(t)}}{\mathrm{E_L(t)}} \tag{6}$$

$$\mathrm{LL}(t) = \begin{cases} \dfrac{E_L(t)}{\eta_{Inv}} - \left(E_G(t) + E_B(t-1) - E_B^{min}\right), & SOC(t) < SOC_{min} \\ 0, & SOC(t) \geq SOC_{min} \end{cases} \tag{7}$$

Beside the LLP, typical optimization parameter is the net present cost (NPC) that is computed as follows:

$$NPC = C_{Gen} + C_{Batt} + C_{Others} + \sum_{i=1}^{LC} \frac{CF_i}{(1+r)^i} \quad [€] \tag{8}$$

Where C_{Gen} and C_{Batt} are the investment cost of power sources and batteries, and CF_i is the cash flows (i.e. replacement and O&M costs) generator during the *ith* year respectively.

As expressed in Eq. 8, the NPC also depends by the number of replaced batteries during the life cycle. Therefore, estimating the lifetime of a battery becomes fundamental. Thus, it is necessary to understand how the different operational modes influence the charge capacity and hence the ageing of the batteries. In this regards, some mathematical models have been developed in order to take into account the life-time of batteries in steady-state sizing analyses. In the following the most common ageing models are reported [74]:

- *equivalent full cycles to failur*e: this method defines the end of a battery lifetime when a specified number of full charge-discharge cycles are reached. The estimation of the lifetime consists of adding the cycles I by the battery and updating the number of full cycles as follows:

$$f_{B,LT}(t) = f_{B,LT}(t-1) + \frac{I(t)\Delta t}{C_B^*} \tag{9}$$

the battery will reach the end of lifetime when the number of cycles to failure declared by the manufacturer is reached.

- *"Rainflow" cycles counting*: this method is based on Downing's algorithm [75]. It counts the charge/discharge cycles Z_i that correspond to each SOC range (split in m intervals) for a year. For each interval there is a number of Cycles to Failure (CF_i). Accordingly battery duration, in years, can be calculated as follows:

$$Life_{Bat} = \frac{1}{\sum_{i=1}^{m} \frac{Z_i}{CF_i}} \quad [years] \tag{10}$$

- *the weighted ageing model*: lifetime data by manufacturers are based on well-defined test conditions. Cycle lifetime is simply determined by discharging the battery with a constant current to a certain depth of discharge and a subsequent full charge with a given charging regime. However, in real application, the operating conditions typically deviate from these standard operating conditions and the Ah throughput of the battery may vary. The weighted Ah ageing model [76] takes these deviations into account by using specific weights and makes the assumption that the battery is at the end of its lifetime once the weighted Ah throughput has exceeded the expected one.

It is worthwhile to mention that these models are quite simple when compared with the advanced ones employed to analyse battery ageing for applications in high income countries scenario (whether in electric supply service or electric vehicles) [77–82]. Nevertheless, their basic approach fits well with the applications in rural areas of developing countries where high uncertainty and lack of input data are typical in the design process of off-grid systems, and are hardly to adapt with more advanced and sophisticated methods.

4.2. Elements of EES dynamics and interface converters

A good understanding of EES dynamics performances can aid in improving the reliability of the system. Accordingly, appropriate dynamic analyses are essential to verify the proper functioning of each single component and the interactions among them [83–86]. Such analyses are typically carried out for short intervals (from few to tens of seconds) in order to study the monitored electrical quantities (voltage and frequency) and to verify the proper system functioning under particular circumstances. They are based on circuit models of the components and on the solving of the related equations within the continuous time-domain.

For instance, in [87] a model based on the equivalent circuit is presented (Figure 4). This model can be simulated in power system analysis software (PSCAD, Matlab Simulink, etc.) to study the electromagnetic transients and dynamics of the EES. Another example of a simplified linearized battery model for small-scale dynamic studies is reported in [88] (Figure 5). Where P^{b*} and P^b are the reference power and actual output power for the battery respectively, E^b is the state of energy, P_{max} and P_{min} are the maximum and minimum charging power, and T_b is the time constant for the battery. This model can be utilized to study the small signal stability, e.g. frequency deviations in any power system.

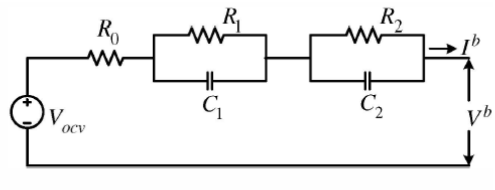

Figure 4 Second order Randle model

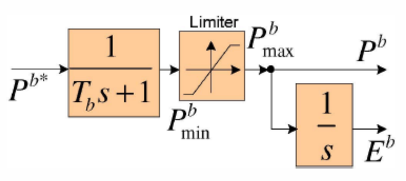

Figure 5 First order battery energy storage model

Considering the specific applications in off-grid systems, EES need additional equipment to adapt their output voltage and current to the requirements of the grid to which they are connected (voltage level and synchronization). According to system configuration, the *dc* output of batteries needs to be adapted to the *ac* or *dc* voltage level of the grid and a power converter is usually applied for this purpose. Therefore, for grid interaction studies, the complete model of battery and converter needs to be represented.

Depending on the storage technology and the application, the power converter will enable the connection between two different *dc* voltage levels (for a *dc* micro-grids), or between a *dc* voltage bus and an *ac* voltage bus (for *ac* micro-grids). For this reason, the most suitable topology used for the power converter will always depend on the particular application. In general, power converters applied to batteries must have the following features: ability to control bidirectional energy flow for regulating charging and discharging process of the battery bank; high efficiency; fast response (frequency regulation applications).

Figure 6 shows a generalized interface for coupling batteries to a single-phase *ac* micro-grid. When the voltage level of the battery system is sufficient, the connection can be directly made via the single-phase bidirectional converter module. When connecting the batteries to a *dc* micro-grid, the most popularly used topology is the bidirectional boost converter (Figure 7 a, b). These two topologies enable connections to a higher and lower voltage buses and can operate properly against voltage fluctuations coming from the batteries [89,90].

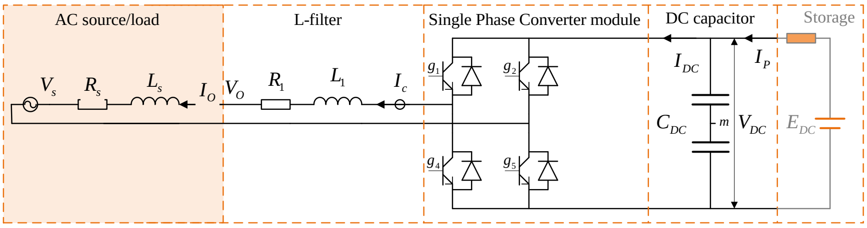

Figure 6 Generalized interface for coupling batteries to a 1-phase *ac* micro-grid

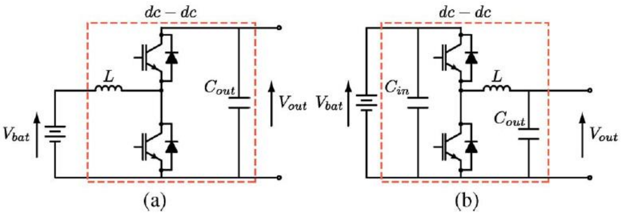

Figure 7 Buck-boost *dc-dc* converters

In case of high voltage ratio or when isolation is needed between the batteries and the rest of the system, a *dc*/high frequency *ac/dc* stage with a transformer in the intermediate high frequency *ac*-stage is used (Figure 8), resulting in significant space and weight reduction compared to a conventional line-frequency transformer. The transformer will electrically decouple the two sides and the converters will provide bidirectional control [91].

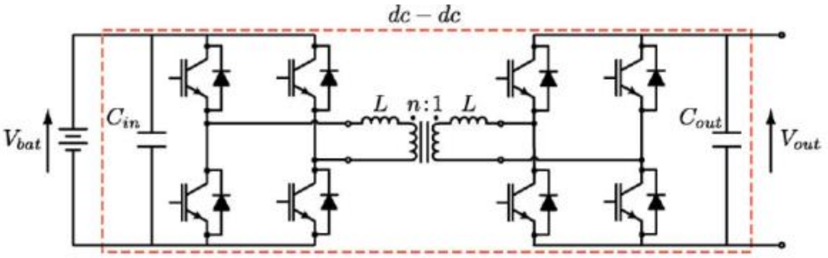

Figure 8 Isolated *dc-dc* converter with medium high frequency transformer

To connect batteries to an *ac* grid, motor or generator, an inverter (three phase two level) is usually used (Figure 9) [92,93]. Modular energy storage can be built-in by several strings, and these strings can be connected in parallel to a common *dc* bus by step-up *dc–dc* converters. Then, the *dc* bus is connected to the *ac* grid by an inverter. This topology is shown in Figure 10, where conventional *dc–dc* boost converters and conventional three-phase two-level *dc–ac* inverter are used as coupling and power conditioning system [94].

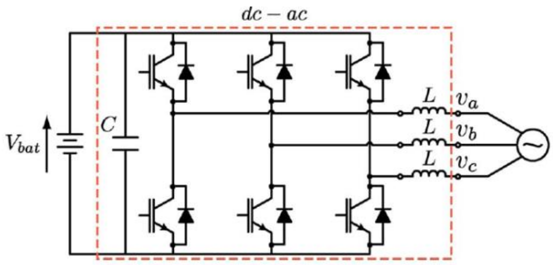

Figure 9 Conventional *ac-dc* converter (3 phases)

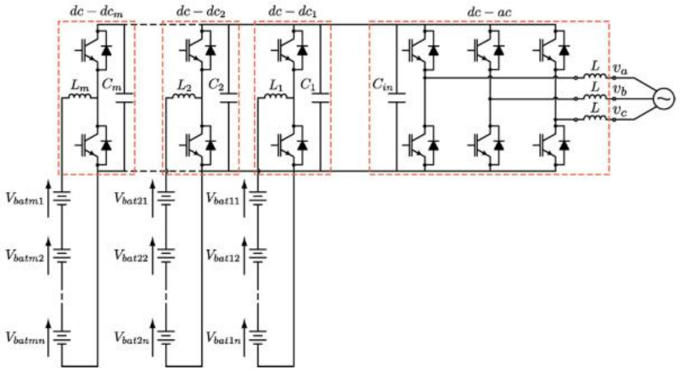

Figure 10 Modular *ac-dc* converter with built-in energy storage (1 and 3 phases)

Finally, in off-grid operation, special attention needs to be put on the synchronization aspect: the passive filter on the *ac* side, and the potential interaction between the converter operation and the passive elements of the electrical grid. A detailed electromagnetic model with switching action, modulation and control is expected to reveal potential interactions between the battery converter and any other converter or component in the system (transformer, electrical machines, etc.). Such a detailed model can be simulated in EMTDC/PSCAD and Matlab Simulink [87,95].

5. The Energy4Growing project: an experimental application in rural Tanzania

The project Energy4Growing (E4G) [33] (*www.facebook.com/energy4growing2014*) aims at studying, developing and implementing an off-grid power system to supply electricity to the school of Ngarenanyuki, a rural village in northern Tanzania. The targeted school is attended by about 460 students, 85% of them are resident in the institution facilities which include classrooms, offices, dormitories, library, kitchen, teachers' houses, etc.

The school, since 2009, has been equipped with a run-off-river hydropower system based on a 3.2 kW Banki turbine coupled with 1-phase synchronous generator. In this system, the turbine always works at full capacity according to the stream flow and the frequency regulation is based on a 4 kW dump load which dissipates the excess power on air. The turbine water flow is diverted from a stream which is managed by local farmers; therefore water availability is highly variable during the day and according to the season. Accordingly an operator manually regulates the turbine distributor in order to keep proper pressure in the penstock. Owing to the unpredictability of the available water and hence to the discontinuity of the power supply, the school also installed a 5 kW petrol generator which is manually operated according to the needs. A toggle switch permits choosing the power source to be used, while a group of breakers permits to connect/disconnect specific loads. The operator manages the system checking the proper working conditions of the hydro turbine, selecting the power source to be employed and operating the loads. Despite the school staff had a fair practical experience as regards the system functioning, the system management was far from being effective and efficient, and hence several blackouts occurred.

In such a framework, the E4G project, started in 2013, has addressed the improvement of the power supply service of the school by increasing the generating capacity and by adopting an energy management system (EMS) capable of integrating different power sources effectively and efficiently. Specifically, the project has implemented a hybrid micro-grid architecture suitable to exploit RET and EES in the most reliable way while exploiting advanced regulations and control techniques.

The initial project activities were related to the installation of an electric meter to reliably quantify the school consumptions. Six month of measures highlighted that a key element to be taken into account in the micro-grid design is the very high rate of growth in consumption. Moreover, another key element deeply affecting the micro-grid development was that just after one year the project start the Tanzanian transmission system operator (TSO) planned a grid extension involving the areas of Ngarenanyuki. To date the school is still not connected to the grid, nevertheless the E4G micro-grid design had to be updated in order to fit with this new external bound.

Besides these specific elements that influenced the system design, Ngarenanyuki pilot project can be considered as a significant case study for SSA scenario since it embraces the typical conditions of bottom-up implementations via micro-grids: (i) RET may be already in place as well as petrol/diesel generator for back-up and/or peak consumption management, (ii) high rate of growth in consumption is expected, (iii) possible future connection to the national grid can occur.

With respect to the two electrification approaches, the Ngarenanyuki application initially could have been classified as a bottom-up approach, but considering the national grid extension plan, the design has been reviewed order to comply with the TSO top-down grid control. In the end, it is a significant demonstration of micro-grid architecture able to work properly in both configurations. In accordance with this aim, the micro-grid combines the power systems already available on-site with new installations (PV panels and lead-acid batteries) by means of an interface converter (IC) with specific control units. Figure 11 shows the architecture of the micro-grid which comprises a *dc* energy sources aggregation (Q1 board) and an *ac* double bus-bar system (Q2 board). In particular, Q1 is a *dc/ac* control board connecting PV panels and the lead-acid battery pack to the IC. The loads, the hydro turbine and petrol generator are connected to the *ac* double bus-bar board (i.e. Q2). Finally, an industrial PLC measures and controls the micro-grid, acting on the switchers of each line while calculating proper power set points for the IC.

Different operation modes have been implemented: manual mode, automatic mode, and grid-connected.

In *manual mode*, the operator can manage the loads connection/disconnection and can select the power source. During this mode the PLC controls Q1 to implement grid forming operation.

In the *automatic mode* the PLC measures voltage, current, frequency, and power and manages the system by means of four configurations:

1. Q1 on-grid – following the hydropower system. In this operation mode the hydro generator manages voltage and frequency of the grid, while Q1 is controlled in *following mode*. The control board of Q1 implements the MPPT algorithm to maximize the PV power. The PLC detects the dump-loads operating status and extracts the power (otherwise dissipated) to charge the battery pack;
2. Q1 off-grid – forming mode. In this operation the PLC defines the IC voltage and frequency set-points, and it monitors battery SOC in order to properly manage its discharge limits;
3. hydropower in stand-alone mode. This operation mode is activated when the batteries SOC is too low, then the PLC manages the loads connection according to hydro production and different load priorities;
4. double bus-bar mode. This configuration allows the hydropower and Q1 to work together, each one on a single bus-bar and occurs in case of large power fluctuations (detected measuring both voltage and frequency). In this case and when the micro-grid is working in mode 1, the load lines are progressively switched to the second bus-bar which is managed by Q1 in forming mode.

Finally, in *grid-connected mode*, the national grid is connected to the *ac* double bus-bar board Q2 and the Ngarenanyuki electric system is managed as a single entity. The hydropower and petrol generator already in place are based on a grid forming synchronous machines that cannot operate connected to an external grid, consequently, in the future, the micro-grid configuration will have to be defined according to the available energy resources.

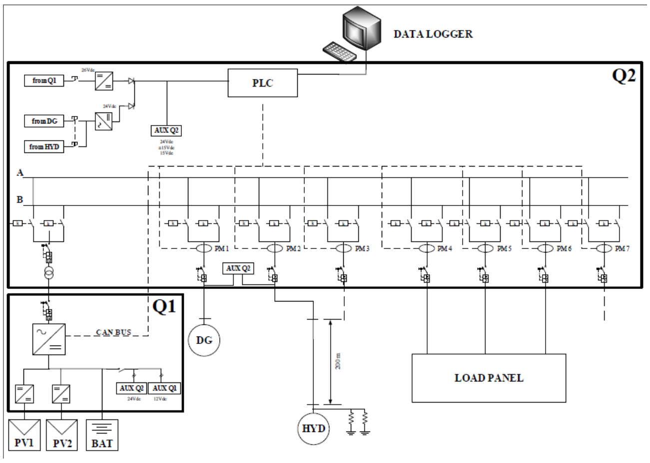

Figure 11 Micro-grid architecture for Ngarenanyuki school

Looking at the integration of the lead-acid battery pack in the micro-grid, some issues can be highlighted. In the original system (hydropower based), the dump loads kept the balance between generation and consumption while assuring stability at 50 Hz. On the other hand, the stability was preserved to the detriment of energy dissipated into the air by the dump load. Now, the new architecture can limit the dissipated energy. Indeed the PLC leaves only a small part of the hydropower to the dump load in order to carry out a fast regulation (i.e. guarantee stability control), but it takes as much energy as possible from the hydropower system to charge the battery. In other words, the battery pack is operated in order to absorb part of the power on the dump load thus minimizing the dissipated energy and increasing the system efficiency. Nevertheless, this raises issues as regards the life-time performances of the battery pack. In fact, this can increase the charge/discharge cycles of the battery pack thus decreasing its lifetime. Therefore it would be necessary to monitor and analyze the conditions of the battery pack in order to update and optimize the system control logics, with the aim of obtaining the longest life-time.

With respect to the business model, as discussed in Par. 3, the CAPEX has been founded by the E4G project while the OPEX is managed by the school. This way, the school board has been directly involved in the micro-grid management, motivating them to an effective and efficient exploitation of the system.

It is worth underlining how the micro-grid deployed in Ngarenanyuki requires several control actions (devoted to switching on/off the loads, the generators, to regulating the battery charge, etc.), consequently a synoptic control scheme has been developed (Figure 12). This scheme is very different in comparison to other commercial solutions and it is absolutely not common for local technicians. Therefore, as part of the project activities, 10 days on-site training program was carried out in April 2015 in order to interact with the local staff, to evaluate their needs and show how to manage the micro-grid via the control panel. Actually, the local technical staff has only a primary education and no electric system skills, but after training they acquired all the capabilities required to properly manage the system, and they have quite acted independently so far.

Figure 12 Synoptic control scheme

6. Conclusions

Currently, RET represent a big hope both for high income countries, in order to achieve a sustainable development, and for SSA in order to drive a social growth, with specific emphasis on rural areas. The well-known bounds of renewable sources (i.e. unpredictability, undispatchability, intermittence) could be a serious problem in high income countries, with critical effects on the power quality and on the security of supply; vice versa they could be a minor factor in SSA rural areas. Indeed, in these areas, local conditions can be largely improved even with a limited and slightly irregular increase in the available amount of energy. These considerations motivate a different approach to the electrification problem, i.e. a different approach to the EES solution design and management.

In this paper we have addressed these topics by describing the configurations capable of integrating EES in the local energy ecosystem, both for the case of on-grid and off-grid solutions. Two main electrification approaches have been introduced: top-down and bottom-up. The first is typically related to the national (politically driven) development of the transmission grid; the latter typically refers to rural areas where stand-alone or micro-grid systems deployment could be the only viable solution in the short-midterm scenario. We have also provided an overview of the market situation and economic models to properly support properly support RET and EES in rural areas. Finally, the case study of the micro-grid implemented in the E4G project has been presented. It shows the complexity of implementing a micro-grid system based on RET and integrating ESS. The proposed micro-grid architecture has been developed in order to properly manage the significant changes in a Tanzania secondary school’s energy needs, to integrate different types of generation sources already in place and, last but not least, to be compliant with respect to a future connection to the national electric grid. From the technical point of view, the project aims at demonstrating that top-down and bottom-up electrification approaches can be successfully merged and, in our opinion, such a merge is a cornerstone in order to achieve an effective electrification of SSA. Nevertheless, to this aim, the regulatory framework is a big issue, on which a lot of work is necessary.

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