Clean energy and mini-grid toolkit

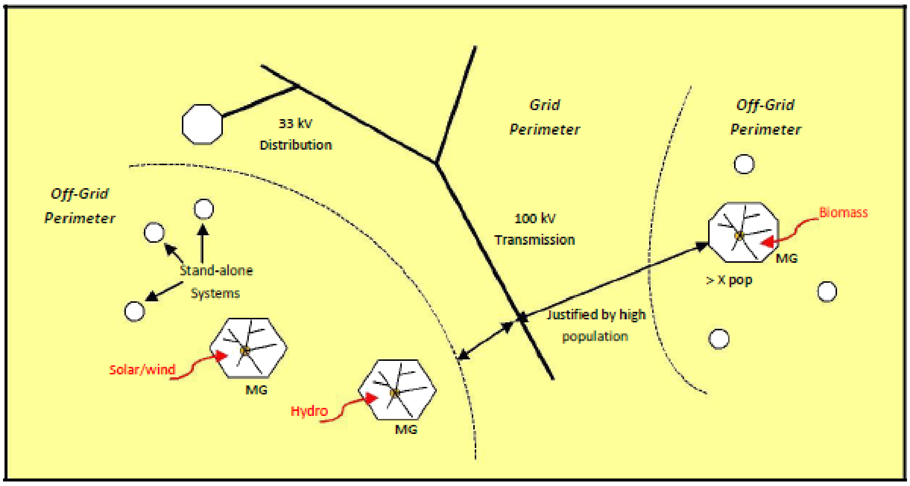
Module 2
Rural electrification and mini-grids

1. General introduction

Electrification is the process of powering by electricity and, in many contexts, the introduction of such power by changing over from an earlier power source, usually in a particular region or national economy. **Rural electrification** is the process of bringing electrical power to rural and remote areas. A "rural" area or countryside is a geographic area that is located outside towns and cities. Thus, it encompasses all population, housing, and territory not included within an urban area. Whatever is not urban is considered rural. Rural areas are characterised by their remoteness and low population density. This implies that often the demand for electricity is low and the financial profitability of electricity supply services is not ensured.

The three **alternatives for providing electricity access in rural areas** are[1]:
a) national grid extension, b) mini-grids, and c) stand-alone systems.

Figure 1 On-grid, mini-grid and off-grid electrification



Source: DFID-IED (2013)

On-grid electrification encompasses all network or sub-grid or generating systems that are connected to the grid and run by a national utility or by an independent power producer (IPP). Grid connection often is the most expected solution as it is supposed to provide more power and energy to the customers at a lower price. However, rural electricity connections are costlier to construct than urban connections because the customers are scattered over a wide area, access is more difficult and the consumption usually is much lower, often less than 1000 kilowatt-hours (kWh) per year. For large-scale grid extension to be feasible, the system needs to be functioning well enough to support the additional capacity and demand and enable recovery of costs. In many developing countries this is not the case and would require a refurbishment of the existing infrastructure (generation and grids), improvement of the performance of the utilities through local capability building, implementing best practices for operational improvements (e.g., loss reduction programmes) and resolving fuel supply issues by ensuring the appropriate fuel supply chains and logistics infrastructure are established.

Off-grid systems (isolated systems) are all distribution networks that are isolated from the main grid (typically more than 10-20 km) and is supplied by independent sources of power (fuel- or renewables-based) and operated by a national utility or any other operator. In rural areas and settlements further from the grid, mini-grid and off-grid solutions may be more attractive, for a number of reasons. They can often be deployed more rapidly than grid solutions. and there is often a significant potential local business- building and job creation opportunities from these solutions.

[1] See for example, EUEI-PDF Mini-Grid Policy Toolkit, IEA Energy Access Outlook (2017) and DFID-IED (2013) for general information

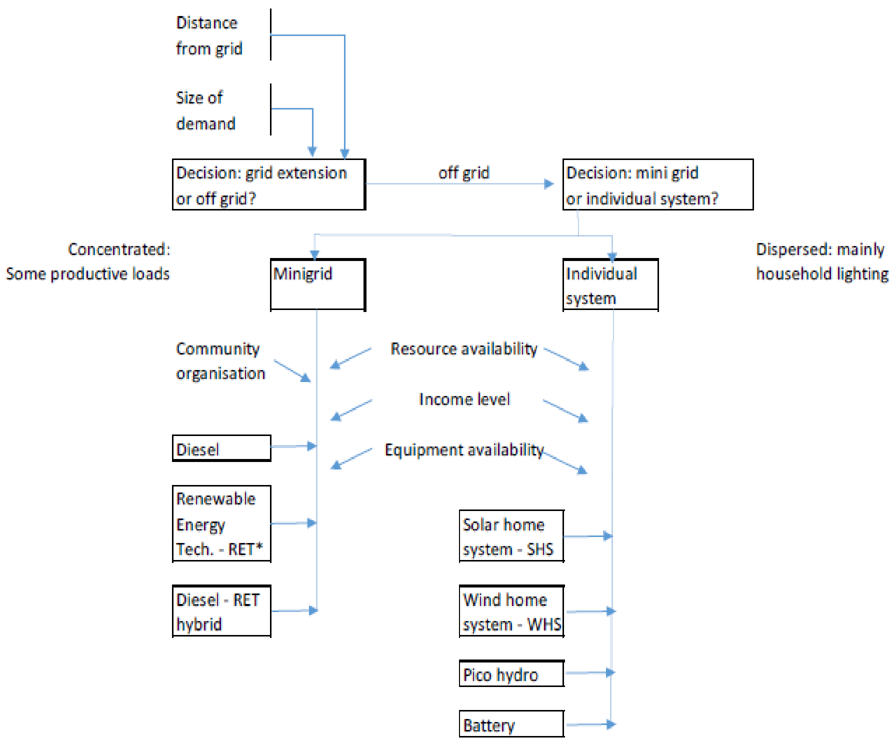
Stand-alone systems are isolated power systems that usually supply one rural customer (household, community infrastructure, battery charging station, multifunctional platform, water pumping station) without distribution and range in the size of 0 to 5 kW. According to the power dimension, they can be grouped into four categories: a) portable lights (i.e. rechargeable & solar lanterns), b) mini kits (i.e. pico-hydro, pico-solar systems), c) home systems (supplied by solar SHS or pico-hydro) and residential systems (generally supplied by hydro, wind or solar –with diesel backup or not). The systems are installed directly at the end-user's house without any distribution networks. Their advantages are affordability in terms of initial investment (compared to the two other approaches) and the immediate benefits (replacing kerosene, battery or other expensive energy sources). The main disadvantage is the limitation in terms of electrical power, which allows only low load applications to be connected.

Mini-grid systems are systems where all or a portion of the produced electricity (by any source) is fed into a small, low and medium voltage (LV/MV) distribution grid (single or three-phase) that provides several end-users with electricity. These are usually in the size of 10 kilowatts (kW) to a few megawatts (MW). Systems below the size of 10 kW are often referred to as **micro-grids** (usually low voltage and single phase) and supply a few or several end-users. **Clean (or green, or low-carbon)** mini-grids are grids that are powered by one renewable energy carrier or a **hybrid** system (with other renewables and/or fossil fuels). A mini-grid will basically include a power generator and a network to distribute the electricity to the accessible consumers, to avoid the high costs of extending the main grid to these isolated areas. Those consumers should then be distant from the main grid (e.g. over 10-20 km), fairly close to each other (e.g. < 150m or density > 50 customers/km²) and with sufficient load demand (>200kWh/year). More on mini-grid power generation and design in Information Sheet No.3.

2. Rural electrification planning

Mini-grids are mostly used where grid extension is not economically attractive but where communities live in a core village or small town with houses in close proximity. The different suitable option for a particular area, mini-grids, grid extension, and solar home systems, make **rural electrification planning** a complex and dynamic task, but one that is highly recommended to conduct. In general, electrification planning has the aim of maximising access to electricity in a given territory, within a certain time horizon. In principle, this planning should be technology- neutral and use present costs in optimising electricity supply options. Figure 2 summarises the decision-making considerations.

Figure 2 Rural electrification decision-making



Source: World Bank (2008). RET = renewable energy technology (solar, hydro, wind, biomass)

The critical question in electricity access is not which of these solutions should be adopted, but rather in what way a combination of these solutions should be adopted. The three electrification options do not necessarily exclude other. A mini-grid system can be either isolated (off-grid) or grid-connected. In the latter case, the aim of the grid connection is usually to sell extra energy or to compensate the deficit of energy. Stand-alone systems can be considered as complementary to mini-grids and can be integrated into mini-grid programmes for the remoter, scattered and out of reach households. A battery charging service integrated into the mini-grid could also provide a minimal level of service for those remote households.

The **optimal choice** for a particular country or area is driven by the availability of resources, the regulatory and policy environment, the institutional and technical capacity, and the relative costs of each of these solutions. Each comes with its own set of advantages and challenges, and the highest impact will be achieved when grid, mini-grid and off-grid solutions are appropriately traded off and then combined to resolve the challenges in each different market. The following specific issues need to be considered[2]:

- *Level of demand:* The level of energy access required is dependent on the needs of each community, such as a) size and density of the population, b) long-term demand (in kWh and terms of energy services) and peak load (in kW), c) existence of priority loads such as public institutions (schools, health centre, administrative centre, trade centre), d) existence and demand (growth) of productive end-users. This is also linked to the ability and willingness to pay (see Information Sheet No. 4);
- *Length of time for delivery:* Given the distributed nature of both the mini- and off-grid solutions, and the resulting reduction in other dependencies such as transmission rights-of-way and building new capacity, it will typically be possible to deliver these solutions more rapidly than a grid solution. Rather than relying on the incumbent utility to deliver the grid-based solution, services can be provided by private-sector players. The time benefit is especially relevant when there are shortages in the national grid's generation capacity;
- *Cost of solutions:* each electrification scheme among a range of solutions including on-grid and off-grid, comparing the levelised cost of energy (LCOE) of the mini-grid systems with the long-term marginal costs and extension costs in the national grid system. The cost of technologies will differ according to local conditions and available natural resources, and so the least-cost fuel mix and technology options will also vary for any specific community or area. Cost recovery is essential for the ongoing sustainability of services. Governments need to decide what tariff structures and cost recovery mechanisms (e.g., lifeline tariffs or cross-subsidies; see Information Sheet No.6)
- *Quality of access* provided by technologies: Grid-based solutions should (in theory) provide 24/7 access. However, depending on the generation base of the mini- or off-grid solutions, they are often unable to provide this access 24 hours a day, as the generation of wind and solar energy depends on weather conditions and battery storage is limited and expensive. Advances in battery storage technology (which are likely to be rapid due to the R&D investment in electric vehicles) will, however, improve this over time.
- *Other considerations* (role of area as development centre, topography (mountain area), occurrence in national grid extension plans; climate conditions and climate change impact considerations)

The **private sector** could play an important role in providing initial off-grid electricity supply. For example, mobile phone companies currently use diesel generators to provide power for their antennae in rural areas in Sub-Saharan Africa. By installing solar PV systems, mobile phone operators could be able to generate sufficient power for their requirements and excess capacity, which could be used to power the local health clinic or school. This could be utilized as a charging station for mobile phones, thus providing a commercial incentive for the mobile phone company to invest in the additional capacity.

For all types of electricity access, past successes show that no single **institutional model** reliably provides better success rates than others. Both large-scale vertically integrated utilities and smaller decentralized businesses can deliver the required solutions, using public, private and cooperative approaches, depending on the strength of the existing utilities and local businesses in all cases, however, a degree of central programme-level coordination is necessary. More on mini-grid business and financing models in Information Sheet No.6.

[2] See for example, EUEI-PDF (2012), REN21 (2017)

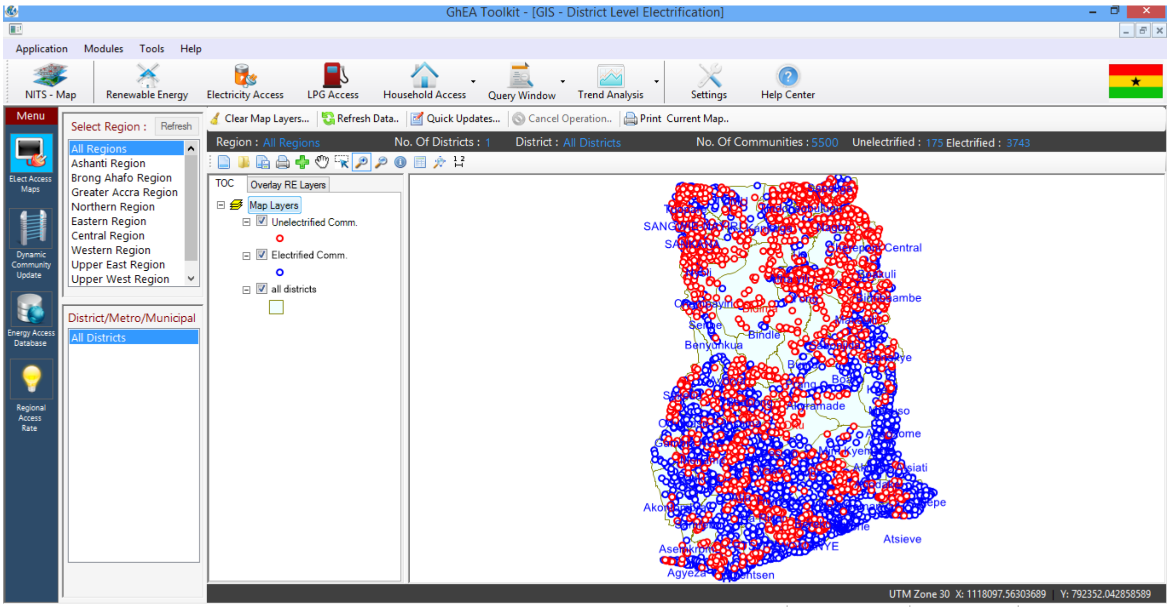
Box 1 Rural electrification planning and GIS

One approach in electrification planning is the identification of priority areas for electrification measures, including areas where off-grid technologies (incl. mini-grids) are to be used. The rural electrification planning exercise usually focuses on spatial analysis of localities, domestic demand, socio-economic activities, load forecast and comparison between various electrification options (grid extension, mini-grids, isolated systems), as illustrated in yellow boxes in the next figures. Another way of prioritization is maximizing the potential direct and indirect impacts of rural electrification by prioritizing the localities with highest development potential.

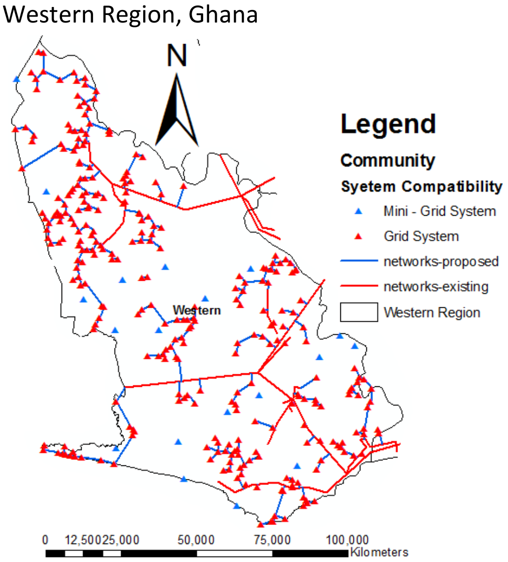
Often, these exercises are hampered by a general paucity of reliable energy-related information and data. geospatial data is largely inexistent, fragmented or inconsistent to allow a strategic planning at the national level. **Geographical Information Systems (GIS)** tools can help to fill such data gaps. Below follows a description of three examples (Eastern Africa, Ghana, Nigeria) of a GIS-based approach in rural electrification planning.

Ghana

Between 2009 and 2011, the EUEI PDF, upon request of the Ghana Ministry of Energy, supported The Energy Center (TEC) of Kwame Nkrumah University of Science and Technology (KNUST) in the implementation of a project aiming at employing and complementing existing policies, strategies and plans to increase access to energy services. This resulted in a) review of energy trends, policies and plans, b) assessment of energy needs, c) development of GIS e-maps for energy services, and d) development of tools, including an electrification cost modelling (Network Planner) and a GIS-based platform that enables users to get information pertaining electrified and non-electrified communities (GIS-based Energy Access review, or GEAR Toolkit). The Ghana Energy Commission had developed a renewable energy tookit (2010) and the two were combined to form the Ghana Energy Access (GhEA) toolkit.

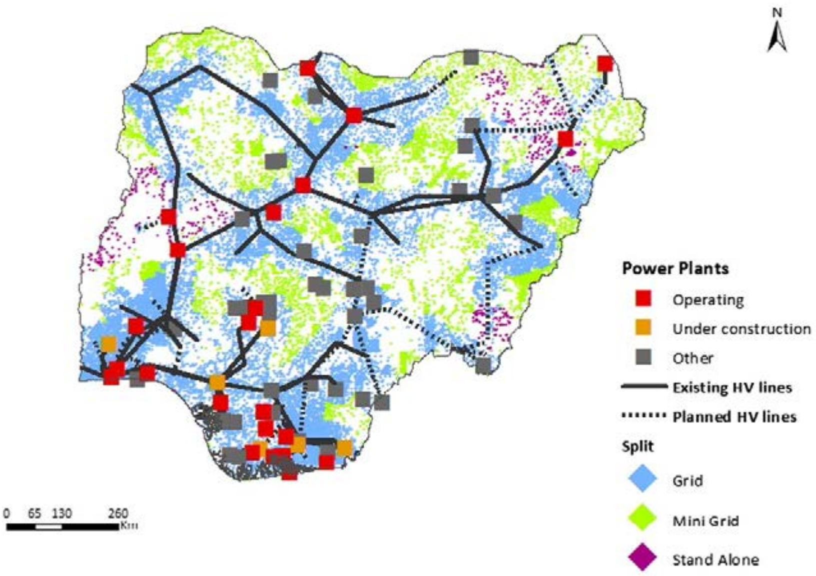


Western Region, Ghana



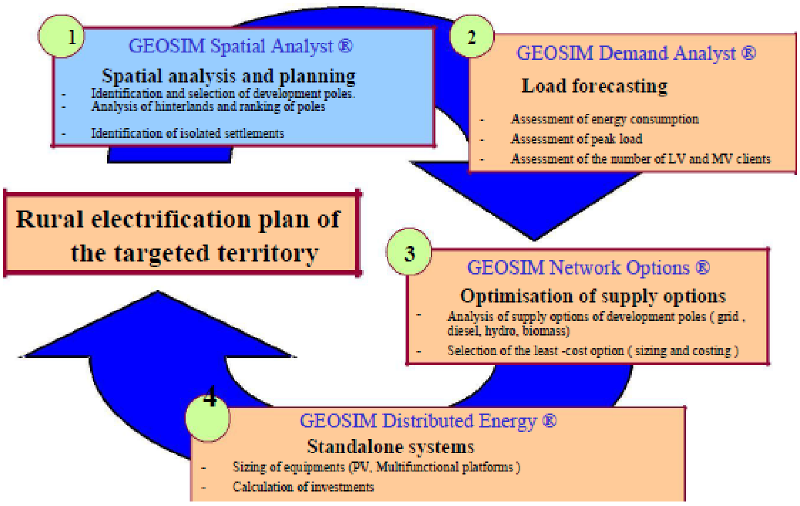
In Ghana, the Network Planner model is used to compare the implications of either extending the national grid, rolling out solar PV household systems supplemented by diesel generators for productive uses, or opting for low voltage diesel-based mini-grid systems. Network Planner is a decision-support tool for exploring costs of different electrification technology options in un-electrified communities. The model combines data on electricity demands and costs with population and other socio-economic data to compute detailed demand estimates for all communities in a dataset. Then, the model computes cost projections of three electrification options and proposes the most cost-effective option for electrifying communities within a specified time horizon. This model links with GIS tools to perform spatial processing and analyses (see Kemausuor et.al., 2014)

Box 1 Rural electrification planning and GIS (cont'd)



Nigeria

IIASA (International Institute for Applied Systems Analysis) and KTH (Royal Institute of Technology) have supported the development of a GIS-based methodology that has been applied in Nigeria in order to identify the optimal mix of electrification options for the entire country for urban and rural areas, ranging from grid expansion (with HV lines), grid extension (with MV and LV lines), mini-grid systems and stand-alone system. The methodology enables the consideration of a set of energy options, including solar, wind, hydro power, diesel and grid connections. The visual representation of results supports policy makers by enabling easy communication of the findings of rather complex least-cost assessments of the various options. This facilitates an outreach to stakeholders engaged in energy planning and power infrastructure investments, such as governmental institutions, energy agencies and utilities. In Nigeria, the OnSSET electrification tool is used. This is a bottom-up optimization energy modelling tool, that estimates, analyses and visualizes the most cost-effective electrification strategy. To do so, OnSSET uses GIS data, such as population density and distribution, proximity to transmission and road network, nighttime lights, local renewable energy potential, etc. (see www.onsset.org).



Eastern Africa

GeoSIM is a decision making tool for rural electrification planning, developed by the French company Innovation, Energie, Développment (IED). The software is based on GIS technology and works with four interdependent modules (Spatial Analyst, Demand Analyst, Network Options and Distributed Energy). The GeoSIM methodology aims at making entire plan of rural electrification at a regional or national scale taking into account the development of social and economic infrastructures, the demand level of households, infrastructures and industries and the development of national grid. The methodology gives electrification options based on a cost-benefit analysis of the best solutions between centralised grid, mini-grid approach and distributed energy, taking into account the importance of village or area as development poles approach. This Methodology has been recently applied in several countries, in Africa, for example, in Tanzania (on six regions) in the Integrated Rural Electrification project (IREP).

There is a need to ensure a proper integration of solar PV and other renewable energy systems into electrification programmes at both national and sub-national levels. The use of GIS-based planning tools can help to determine which areas are best suited for grid electrification, mini-grids and decentralized options. This should be accompanied by more studies to generate a database for determining the pattern of energy access improvement over the years, challenges and prospects as well as the main drivers of energy access in the country. This can be a drawback, since GIS-based methodologies require a long process of data gathering and consolidation, it is only successful if local partners such as rural electrification agencies, ministries and/or utilities are closely involved in the work.

Source: DFID-IED (2013), EUEI-PDF/GIZ Ghana (2012) and Mentis et.al (2015); Kemausuor et.al. (2014)

3. Mini-grid systems: technology overview

Main components

The **main components** of a mini-grid are the power generator (with or without storage), the distribution network, and the service connection.

Generation

Given their low investment requirement, the decentralised mini-grids often use fuel-based gensets in rural areas generating electricity and supplying isolated distribution grids. Most of existing mini-grids in Africa are supplied by fossil fuel-based gensets or in a lesser extent by mini-hydro power plants. Nowadays, given the environmental concern and the significant renewable cost reduction, there is a trend towards the hybridization of existing diesel mini-grids (adding renewable sources) or to design new "green mini-grids" with either hydro, biomass or hybrid (wind, solar, diesel) power systems, depending on the availability of renewable energy sources and on load profile on the demand side. The most common hybrid system is the solar PV generator mixed with a diesel genset and a battery. The various renewable sources of energy (and their applicability in mini-grid systems) are discussed separately in Information Sheet No.4.

The electricity service provided by a mini-grid can be limited to 2-6 hours a day usually when the fuel source (mainly fossil fuels & biomass) has a fuel cost to be supported by the customers; it can be 12-24 hours if the source is "free" and available 24 hours per day (hydro) or if a storage solution is available (solar & wind). Unlike diesel gensets, renewable energy technologies (RETs) require power conditioning units to regulate the power production (controllers, regulators, convertors, inverters, rectifiers, etc.).

Not all renewables do not have the same costs, the same intermittency characteristics, nor the same level of technical maturity and complexity in design and or operations. The hydro potential is actually very site-specific and concentrated in specific locations. Biomass power plants should be close to biomass production areas. Wind and solar are more diffuse resources although sufficient wind speeds are recorded only on specific spots. Solar energy, although the most diffuse (low energy per m², low capacity factor), has the widest coverage and can fit more easily with scattered remote households. Capacity factors of power plants (ratio of actual output to its potential output) vary with RETs: 10-20% for solar PV, 15-30% for wind, 20-50% for micro & small hydro, 10-90% for biomass and >90% for diesel.

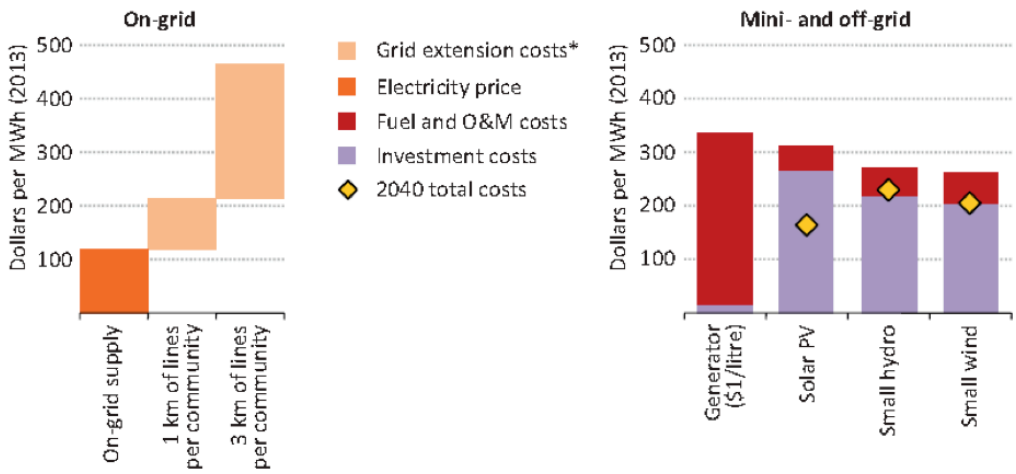
A limited number of publications have analysed the cost of renewable mini-grids. For example, IRENA (2015) mentions costs of solar mini-grids of USD 0.43-0.71/kWh. As indicated in the table below, the reference capital (CAPEX) and operating costs (OPEX) for the different options can vary considerably with type technologies and site location. The mini-grids economics should also take into account realistic load factor and capacity factor to estimate safely the to-be-sold kWh cost (sold kWh are lower than produced kWh), the potential revenues and the financial viability. The figures in Table 1 a crude cost indication; a detailed calculation of the least-cost options and the levelised cost of electricity (LCOE) needs to be done for each specific project and site (see also Information Sheet No. 5 and 6 for more on costs and benefits).

Table 1 Reference cost of mini-grid systems

Technology -based MG	Size range (kW)	Power plant investment ($/kW)	LCOE ($/kWh)	Operating time (h/yr)
Diesel genset	5 – 300	500 – 1500	0.3 – 0.6	On demand
Hydro	10 – 1000	2000 – 5000	0.1 – 0.3	3000 – 8000
Biomass-gasifier	50 – 300	2000 – 3000	0.1 – 0.3	3000 – 6000
Wind hybrid	1 – 100	2000 – 6000	0.2 – 0.4	2000 – 2500
Solar hybrid	1 – 150	5000 – 10000	0.4 – 0.6	1000 – 2000
MV distribution	*33kV*	*13,000 - 15,000*	*$/km (site specific)*	
LV distribution	*380V*	*5,000 – 8,000 $/km*	*A rough estimate of the required length is 30 customers per km.*	
Connection costs	*Ideally $350 per customer (but CAPEX/customer varies $350-3500)*			

Data based on Green Mini-grids (IED, 2013) and IRENA Renewable Power Generation Costs in 2012 (2013)

Figure 3 Cost of grid extension versus off-grid systems



Source: International Energy Agency

Storage

Not all types of mini-grids require storage; for example, well-sized diesel generators and hydropower systems usually run continuously. However, energy storage will be needed in the case of higher penetration of variable renewable energies, i.e. solar and wind. The need for storage over a couple of hours or days will depend on different parameters as the daily load curves & demand peaks, and the renewable energy source intermittency. Usually, well-sized diesel generators, hydropower systems, and biomass generators can run continuously as their "fuel" can be stored (fuel tank, biomass warehouse, water weir/dam). However, with irregular solar & wind resources, energy storage might be needed to increase the penetration (renewable share in the system). In this case, excess electricity will be stored to 'regulate' the generating system while it is in use.

The *lead-acid* battery is made up of plates, lead, and lead oxide (various other elements are used to change density, hardness, porosity, etc.) with a 35% sulphuric acid and 65% water solution. This solution is called electrolyte, which causes a chemical reaction that produces electrons. When the battery is discharged, the sulphur rests on the battery plates and when the battery is recharged the sulphur returns to the electrolyte (80% of all battery failure is related to sulphate build-up that occurs when the sulphur molecules in the electrolyte, the battery acid, become so deeply discharged that they begin to coat the battery's lead plates). *Nickel-metal hydride (NiMH)* batteries use nickel oxide hydroxide and hydrogen-absorbing alloy as electrodes. In small mini-grids (i.e. under 300 kW) lead-acid battery banks are typically used. At an initial investment cost of USD 150-200/kWh capacity and storage unit cost of USD 0.20-0.50/kWh, batteries typically can add more than 50% to the PV system cost.

Power conditioners

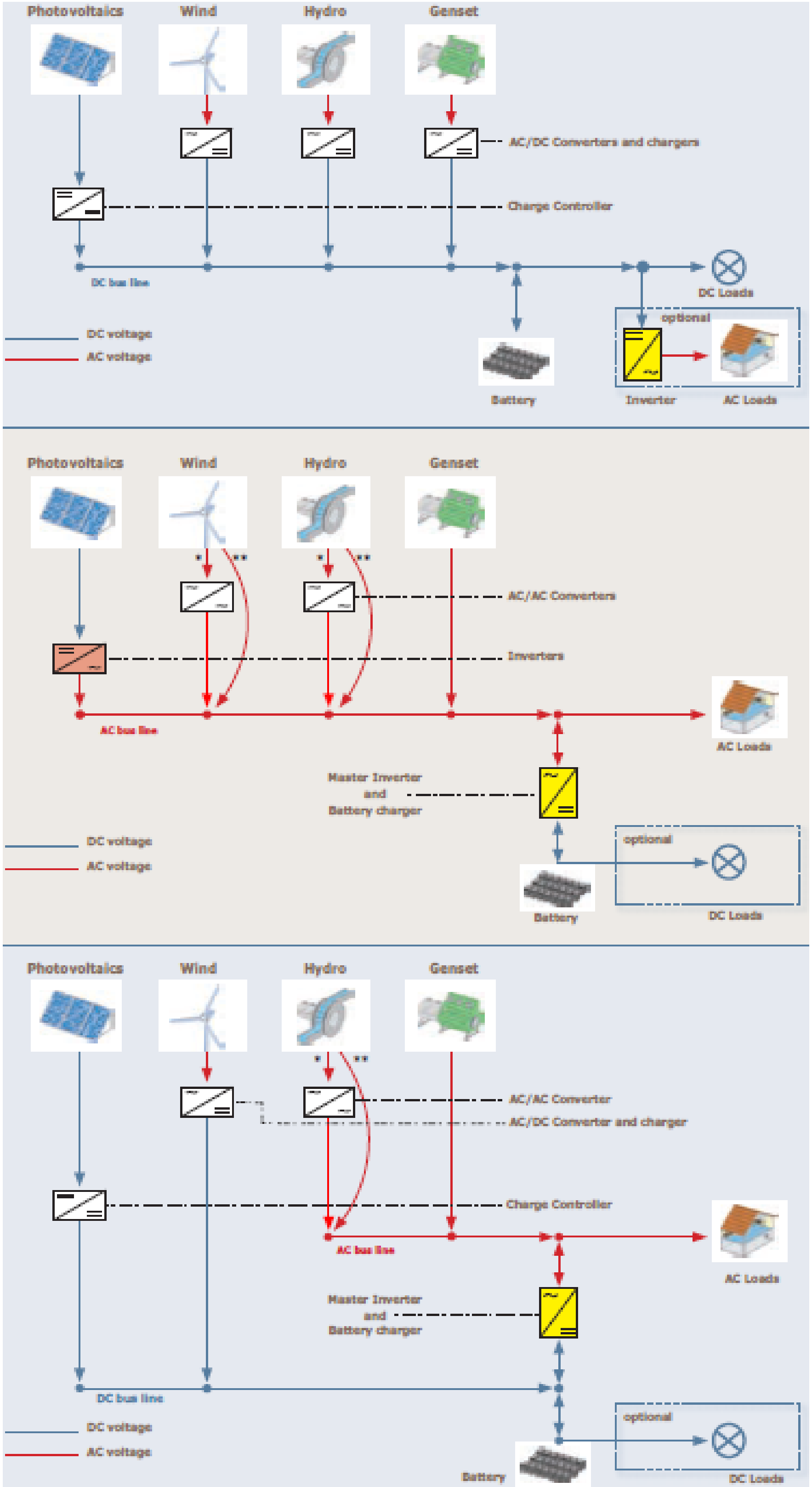
This includes voltage, convertors, rectifiers, and AC/DC inverters. Inverters are devices that transform DC voltage to AC voltage. Single-phase inverters are used in low and medium-size facilities ranging from 300 W to 90 kW. To achieve this level of power capacity, several inverters are necessary. Three-phase inverters are used in medium to large size facilities ranging from 5 kW to several MW.

Distribution

A distribution network (consisting of cables and transformers) carries electricity to the consumers or loads at a limited distance of the generators. The grid system designers shall decide on the type of distribution system, depending on the site characteristics (village size, population density, load profile):

- Alternative or direct current (AC or DC)
- Nominal voltage(s): LV or MV (see below),
- Single or three phases, or single wire earth return (SWER)

Figure 4 Schematic mini-grid system with multiple power source (hybrid configuration)



1. Electricity coupled at DC bus line

All electricity generating components are connected to a DC bus line from which the battery is charged. AC-generating components need an AC/DC converter. The battery, controlled and protected from over charge and discharge by a charge controller, then supplies power to the DC loads in response to the demand. AC loads can be optionally supplied by an inverter.

2. Electricity coupled at DC bus line

All electricity generating components are connected to an AC bus line. AC - generating components may be directly connected to the AC bus line (**) or may need a AC/AC-converter to enable stable coupling of the components (*). In both options, a bidirectional master inverter controls the energy supply for the AC loads and the battery charging. DC loads can be optionally supplied by the battery.

3. Electricity coupled at AC/DC bus lines

DC and AC electricity generating components are connected at both sides of a master inverter, which controls the energy supply of the AC loads. DC loads can be optionally supplied by the battery. On the AC bus line, AC generating components may be directly connected to the AC bus line (**) or may need a AC/AC converter to enable stable coupling of the components (*).

Source: Alliance for Rural Electrification (ARE)

This decision impacts the cost of the project and will determine the types of service and appliances that can be utilised. **Low voltage (LV, or secondary)** distribution network (< 1kV, typically 220-380V) is preferred for technical and economic reasons usually. The lines are usually around 230V in single-phase or 400V in three-phase systems are used to supply customers typically not further than 1-2 km from the power plant to limit the voltage drops and cable size. Some local configurations may require **medium voltage (MV, or primary)** lines (typically 11, 20, or 33 kV) to reach far consuming clusters (usually beyond 1-2 km from the generator, e.g. to remote customers or to several settlement clusters or villages located at several tens of km from the powerhouse. The voltage is usually ranging between 11kV and 33kV. One step-up at the power plant and several step-down transformers are required to deliver LV power to customers at different locations. These MV lines including transformers and specific protections are significantly adding to the distribution costs and can be justified only if the load is high enough. **Three-phase** systems allow higher energy transport and the use of specific appliances as conventional motors for productive uses.

While discussing the issue of mini-grid technologies, the focus is often on the generation side and on which energy carriers its generation should be based on (renewables vs. fossil fuel generation). In reality, the distribution grid and customers' connections often represent as much as 50% of the global investment cost (depending on the generation technology and on grid standard level). For example, investment for simplified LV distribution network can be on average of about 10-20% of the total solar PV mini-grid investment but can rise above 50% with other configurations and standards. Consequently, not enough attention is paid to the issue of reducing the distribution grid per kWh sold cost, by looking at: 1) a better design (layout of the grid), 2) norms which can be simplified at a quality and safety level still acceptable to the utility, and 3) procurement practices.

Typically, LV line costs range from USD 5,000 to USD 8,000/km and MV lines (with MV/LV transformers) cost USD 13,000 to USD 15,000/km. The figures can be lower or higher depending on geo-topographical constraints (hilly or plain) and technology used (poles, cables, accessories, etc.)

Service connection (user subsystem)

The **service drop** includes the cables and accessories to connect the nearest LV distribution pole and the consumer's meter. The **service entranc**e system includes all the equipment located on the end-user side, such as customer board (with meter and protections), grounding, in-house wiring (or a ready board), and electrical appliances (light, radio, TV, fans, motors, etc).

Electricity consumption (**kWh meters)** can be installed as conventional meters that require periodical reading in order to achieve correct billing. This requires a lot of manpower related to the reading and issuing of the bills. Further, it requires the consumers to go to the nearest billing office and pay for the energy already consumed in the previous period. As an alternative, **prepaid kWh meters** can be installed. This has a major advantage since the energy is paid in advance. It is anticipated that payment in advance encourages the consumer to save energy since the time span between payment and consumption is radically reduced. This form of payment, when the customer can pay for a small amount of energy at one time, fits with the peoples' custom to buy rather small amounts of other energy sources for cooking and lighting. The disadvantage of both kWh meter types is the costly procurement. The prepaid meter is the costliest alternative and can range, depending on its sophistication level, from USD 30 to 120 per meter. An alternative is the use of **flat-rate meters.** This device limits the consumed energy per hour and will cut the power when the paid energy is consumed, and the customer must wait for the next metering hour to reconnect the supply. The meter is available in a range of sizes for consumed energy and can be easily changed from one tariff to the next. Unused energy over one hour is credited for the next hour, and so on. The tariff could be introduced as a monthly prepaid scheme.

Mini-grid standards

The International Electro-Technical Commission (IEC) has published **Technical Specifications** IEC 62257, a set of standards covering technical and organisational aspects of mini-grids (design, installation, maintenance, contracting) and a checklist of good practices. A valuable low-cost mini-grid electrification "**Mini-Grid Design Manua**l" was published by the ESMAP programme of the World Bank (2000).

Smart technology

Mini-grids in remote areas are relatively complex to operate efficiently and to manage economically. Very promising devices or smart technologies have emerged and that enable better mini-grid system control (energy generation and distribution) as well as customers' management (fee collection, misuses, thefts, etc.). It also sets the stage for mini-grid

Box 2 Electricity smart technology

Electricity smart technologies are new and innovative technologies, in particular advanced digital technologies (i.e. microprocessor-based measurement and control, communications, computing, and information systems), that can be used to build more efficient, resilient and flexible energy (mini-)grid systems.

Smart technologies can fulfil the following duties:

- *Power production: Control and monitoring of operation, troubleshooting, control of failure, etc.*
  Controller and data acquisition system are required for coupling (synchronisation) with other gensets or with solar/wind generators. Energy management devices in hybrid systems include automatic protections, limitations, switching, built-in data logger (energy flows, solar/wind resources, battery charge status and ageing), AC/DC bus management, communication devices between inverters, load controllers, charge controllers, meters, remote communication for operating data and troubleshooting, and the user's interface (display & data logging).
- *Electricity use: load control and limitation, automatic protection, payments, remote switching, disconnections*
  intelligent electricity meters allow two-way communication through a communication system (GSM with SIM cards, satellite, radio, power line PLC), sending accurate meter readings and energy usage details to the operator (energy supplier) and giving key information to the customers through an energy display. Energy or current limiter: includes various devices as electronic or thermal (PTC) switch, circuit breakers, fuses that can limit the current of each customer at a fixed value.

Especially simple smart meters (e.g. with prepayment or remote payment) have potential for rural mini-grid projects in Africa. In principle, the prepayment management system consists of: a) prepayment meters (tokens, cards, code; combo or split), b) the vending unit (point-of-sales, internet, scratch cards), and c) vending and management servers (operator/utility). Today the expansion of GSM network in rural areas has changed ways to operate and manage electrification infrastructures. The access to mobile network allows in particular remote payment or prepayment. Different approaches of prepayment have been developed:

- Tokens: buying tokens with cash at a point-of-sales or pay-point,
- Reloadable key or card: buying credit with cash at a pay-point with terminal (data from customer can be sent to operator's server) or through a Scratch card: buying credit with cash at a pay-point and reload with code
- Internet: buy credit and get code through (mobile banking),
- GSM: buy credit and get code through mobile banking (SMS)
- Smart meters (with SIM card): buy credit and send data from the meter (SMS)

Source: DFID-IED (2013),

growth, energy efficiency measures and eventual connection to the main grid system. Information and communication technology (ICT) offers attractive options to monitor remotely the mini-grid performances and to assess the demand profile and growth. This will help taking energy efficiency measures, planning mini-grid upgrading or main grid interconnection. For example, smart meters allow the automatization of the tariff collection process by interlinking tariff payments with the widespread telecommunication network, allowing people to pay bills via their mobile phones.

4. Electrification in Malawi

Main electricity grid

Malawi has low levels of electrification with about 10% of the population having access to electricity[3]. Moreover, the national grid almost exclusively serves urban and peri-urban areas, around 37% of urban households have access to electricity, compared to only 2% of rural households. Rural areas currently rely mainly on kerosene for lighting and diesel for mechanical and electrical power.

[3] World Bank (2010), National Statistics Office (2009)

The total installed (national grid) electricity capacity was about 351 MW[4] and is dominated by large hydro (96%) and thermal (4%)[5]. There are 4 major run-of-the-river hydro facilities located on the Shire River in a cascade arrangement. About 63 MW is generated from gen-sets as decentralised power for private use[1]. Supply is already well short of demand leading to widespread power outages. For example, total power capacity requirement in 2014 was 447 MW, thus implicating a shortfall of 96 MW[6]. In fact, if water levels on the Shire river are low, available capacity can drop to 286 MW[7].

In addition, the national power utility Electricity Supply Corporation of Malawi (ESCOM) is unable to meet all demand and is stretched with the regular occurrence of load shedding (power interruptions), as a consequence of:

(a) Many years of under-investment in transmission and distribution infrastructure, with frequent failures, especially during the rainy season, and generally poor quality and unreliable supply[8];
(b) Suppressed demand, i.e. actual (peak)demand for power is higher as the system can provide. With the growing urbanization, power demand grows has grown too and is now estimated at 450-700 MW);
(c) Challenges in transmission due to the country's geographical orientation (long transmission from south to north);
(d) Encroachment and degradation in the catchment area of the hydropower stations.

ESCOM plans to add generation from 351 to 429 MW by 2018 through upgrading hydropower facilities (36 MW), expansion of hydropower (Tedzani, 21 MW) and installation of three diesel generators that will add 45 MW for peak power management. However, as demand increases the shortfall would have increased to 395 MW by 2018. If capacity would stay at 429 MW, the shortfall would be 2,408 MW in 2030.

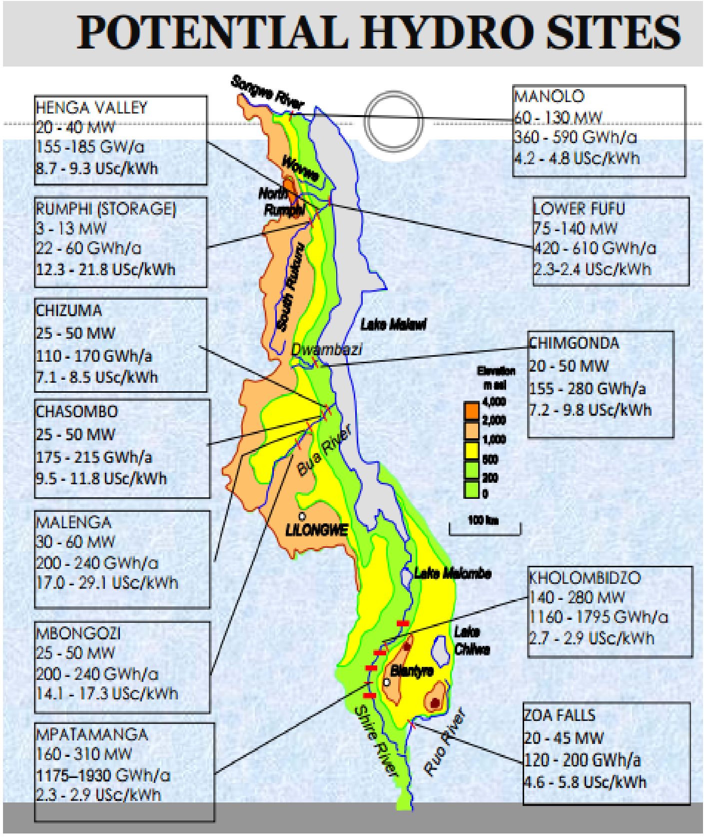
A more drastic expansion of power will be needed therefore in the decades to come. The M&E Plan for the new draft National Energy Policy (2017)[9] an expansion of 1,860 MW over 2015-2025:

- New hydropower facilities (7 stations, totalling 981 MW) by 2022
- New diesel plants (4 plants at 48 MW) by 2018
- New fuels (coal 520 MW), bagasse co-gen (40 MW) and the remainder of geothermal, natural gas, solar PV (270 MW) plus 100 MW reduction to due to energy conservation and DSM efforts.

In addition, interconnecting the grid with Zambia and Mozambique (80 MW) is contemplated, which would tap into SAPP (Southern Africa Power Pool), allowing for new customers and reducing power outages. For the period 2025-2030, expansion of hydropower is planned at about 310 MW.

Box 3 Potential hydropower projects

Taken from SE4All Action Agenda, draft report (2016)



Apart from the Government-backed schemes, there are various donor-supported initiatives to upgrade Malawi's electricity grid:

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4 Hydro: Kapichira falls, 129.6 MW, Nkula, 124 MW, Tedzani, 92,7 MW, small hydro: Wowve: 4.35 MW, Mzuzu diesel 1 MW, Likome islands 9diesel), 1.05 MW and Chizumulu island (diesel), 0.3 MW

5 Kaunda (2013); Support to SE4All Action in Malawi, draft Action Agenda (2016)

6 Business Opportunities in the Malawi Power Sector (2015). Peak demand estimate of 378 plus reserve margin of 69 MW. Demand estimated at 478 in 2015 by ESCOM

7 Only 4.5 MW is located off Shire River (on Wovwe River); Support to SE4All Action in Malawi, draft Action Agenda (2016)

8 www.reeep.org, *Energy Profile Malawi*

9 Support to SE4All Action in Malawi, draft Action Agenda (2016); M&E Plan for National Energy Policy, Appendix 2 (2017) by PWC (National energy policy review)

- The World Bank *Energy Sector Support Project* (USD 84.7 million), started in 2012 and is due for completion in early 2017. The largest part (USD 56.2 million) is for strengthening and expansion of electricity network and for feasibility studies for new generation projects, while the smaller component (USD 6.8 million) is for introducing demand-side management and energy efficiency measures and finally, to build capacity of ESCOM and DEA;
- The US government works with Malawi to deliver the Millennium Challenge Corporation (MCC) Compact (USD 350.7 million) The *Millennium Challenge Account* (MCA) has been set up to implement the programme during 2013-2018, aiming at a) Infrastructure development: upgrading and modernising the power grid system (preserving and stabilizing existing generation capacity, improving capacity of the transmission and distribution network, and increasing the efficiency and sustainability of hydropower generation; b) Policy Sector Reform: strengthening institutions and enhancing regulation and governance of the power sector, including reforming and rebuilding ESCOM, to have independent power utility regulation in Malawi.

The new expansion will not come only from ESCOM, but from independent power producers (IPPs). Currently, there are no IPPs providing power to the grid, but 30 projects have entered into a MoU with the Government (with a total of around 1,230 MW, of which 996 MW in PPA negotiation stage). In realisation of the need for investment by IPPs in Malawi, efforts were initiated to begin to develop an IPP framework in 2013 by the Government, in conjunction with project partners ESCOM, MERA, and MCC. A report (MCA, 2016)[10] was published in April 2016 that outlines the steps that should be taken to develop a functioning, successful IPP framework with cost-reflective feed-in tariffs. The goal is to have a IPP framework ready and PPA process by 2017[11] and a fully functioning IPP framework by 2020.

ESCOM had about 313,000 customers in 2015, constituting the 10% mentioned above. The Sustainable Energy for All initiative (SE4All) Action Agenda calls for 100% access to electricity by 2030, which will be a tremendous task to be achieved. Based on the 2002 Electricity Master Plan study[12], the Government has extended the grid to rural areas to about 376 centres by 2015 in Phase IV to VII[13]. Phase 8 of the **Malawi Rural Electrification Programme (MAREP)** is now underway to cover 173 more trading centres (at a cost of MWK 12 billion)[14]. MAREP is funded as an Electrification Fund, which is replenished by leaving through a 4.5% levy on energy sales. In addition, ESCOM has launched a USD 500,000.00 **Accelerated Electrification Access** Project. MAREP and ESCOM had connected 55,000 households by 2016, and by 2030 aim to have connected and additional 60,000 to 87,000 by 2030[15].

With the support of the US Government through the Millennium Challenge Corporation (MCC), there is ongoing work to improve transmission and distribution, as well as upgrade generation. New transmission lines are planned to be constructed (currently 2,395 km from South to North), adding 370 km by 2018 (with 3,450 MVA substation and 7,180 MVA substations), as well rehabilitating 30.5 km of the Lilongwe ring). Similarly, the distribution network (12,260 km) will be extended with about 75 km by 2018 (at 33 and 11 kV).

he growth in electricity generation capacity has lagged behind the growth in electricity demand for a long period. In the recent past, the Government has expressed the urgency to expand its generation capacity. The National Energy Policy forecasted demand for electricity would be 420 MW in 2015, 1000 MW in 2020, 1750 MW in 2025 and 2550 MW in 2030 under moderate economic growth scenario.

Off-grid electricity

There are a number of private sector companies and community-based organisations that are developing electricity generation initiatives within the country. It is also increasingly common for NGOs to incorporate very small-scale renewable energy technologies (RET) installations into individual projects they are delivering. Given the variety of technologies available and the diversity of organisations that are 'adding on' RETs to their projects, the off-grid micro-generation sector is somewhat fragmented. Although MERA does have powers to oversee the sector, there is no comprehensive map or inventory that describes the extent or capacity of micro-generation in Malawi[16].

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[10] Millennium Challenge Account (MCA, 2016), *Concept Paper for the Energy Sector, Public Private Partnerships on Electricity Generation for Rural Area*

[11] IPP: independent power producers; PPA: power purchase agreement

[12] See the JICA-supported Master *Plan on Rural Electrification in Malawi (2003)*

[13] IV: 97 trading centres; V: 27 , VI: 54 centres, VII: 81 centres ; MCA (2016), *Concept paper for the Energy Sector*

[14] Trading centre should be of a certain size (e.g. have at least 3 maize mills) and at least 8-10 km from the grid

[15] Support to SE4All Action in Malawi, draft Action Agenda (2016)

[16] HIVOS, *Malawi Energy Profile*

A recent survey undertaken by the UK Department for International Development (DFID) and the Business Innovation Facility (BIF)[17] suggests that around 13% of the off-grid households (2 million people) now have access to lighting in the form of solar products in Malawi (portable, 9%, fixed lights, 4%), more than 1.5 times than households connected to the national grid. The majority of households still use torches (63%) and candles (14%). The survey shows that 78% of the non-users of solar lighting product are interested in acquiring such a product as a means for lighting and mobile phone charging. Households annually spend about MWK 11,000 on torches and batteries, MWK 7,500 on candles or MWK 5,500 on kerosene (paraffin), so buying pico-solar products[18] (about MWK 7,000, USD 14) is advantageous with payback times of 8-15 months. Most products have a 5-year lifetime. Note also, that the average user spends MWK 6,000 (USD 9) on phone charging annually. Pico solar products can be bought in some grocery stores or markets.

The EU-funded *SE4RC (Sustainable Energy for Rural Communities*) will give 20,000 Malawian citizens from poor isolated rural communities access to clean electricity for productive use. SE4RC will anchor off-grid energy service delivery to underlying agriculture and socio-economic development. The project aims to establish three Community Energy Service Companies (CESCOs) in Malawi, that will manage mini-grids (serving irrigation schemes, clinics, schools and small agro- and other businesses) and energy kiosks that will provide service for low energy users (small farming households and businesses).

The *Sustainable Off-Grid Electrification of Rural Villages* (SOGERV) Project is funded by the Scottish Government and runs from 2015-2018, led by the University of Strathclyde in partnership with Concern Universal (Malawi) and WASHTED-Polytechnic. The project aims to deploy off-grid sustainable energy projects in Chikwawa district (southern Malawi)[19]. It will target 4 mini-grids in villages in Chikwawa that currently lack access to electricity at homes, schools, health centres and businesses. The projects will provide services such as lighting, mobile phone charging, and supply for refrigeration by means of 2 kilo-watt charging stations, small business solar PV systems, solar PV at schools and health centres for basic services, as well as a mix of pico-solar-products[20].

Despite the awareness of renewable energy (especially solar PV) in the country, the installation of solar PV systems has been limited to off-grid systems (solar home systems) for institutions, especially rural health centres, secondary schools and police units with the typical applications being lighting, cooling (using refrigerators) and water pumping. Despite the high impact, many of these projects have fallen short of sustainability expectations. Maintenance of the solar PV systems and tariff collection has also proven to be a challenge. A recent survey[21] found that less than 50% of installed projects (at schools and health centres) were meeting technical performance expectations and only 15% of all projects had both a bank account and were generating an income. The conclusion was that the relatively high capacity required; the ability to responsibly and manage projects at the community level forms major challenges. Use of solar PV for income generating activities in the rural growth centres (supporting small scale industries) has not been successful so far.

Mini-grids

On-grid and off-grid electrification approaches have been tried for rural electrification with limited efforts at mini-grid based electrification. Clean energy mini-grids can be a viable and cost-effective route to electrification where communities are far from the national grid or where population is not dense enough to justify a grid connection before other communities on one hand, but demand of households and local business is at such a level that cannot be provided by off-grid solar home or pico-solar systems.

In Malawi, a study commissioned by DFID (IED, 2013) suggests that *mini-grids are the most economically viable* technology solution in areas with a population which has a density above 250 inhabitants per km^2 and is situated more than 5 km from the medium-voltage grid line. This represents more than 4.55 million Malawians or 27% of the people currently living without electricity in the country. About 7.72 million could be connected to the grid, and the remaining population would be covered by stand-alone systems.

17 *Off-grid Lighting and Phone Charging Study,* BIF (2016)

18 In Malawi, Sunny Money, a charity and social enterprise, is the biggest PSP seller in Malawi. It channels and markets which will hopefully enable the sector to take-off commercially. Their business model generally uses a vendor system in which local entrepreneurs buy stock from Sunny Money and then sell lights to local communities, along with providing aftercare.

19 The University of Strathclyde managed the Scottish funded *Malawi Renewable Energy Acceleration Programme (MREAP)* from 2012 to 2015 with GBP 2.3 million in funding and the *Community Rural Electrification Development Project (CRED),* 2008-2011. See www.strath.ac.uk/engineering/electronicelectricalengineering/ourinternationalprogrammesprojects

20 SOGERV *Policy Briefing* (2016), University of Strathclyde, WASHTED, Concern Universal Malawi

21 Dauenhofer and Frame (2016)

Table 2 Malawi population density and distance to the MV network

	Population living at less than 5km of MV	Population living at more than 5 km of MV	Total
population living where density < 250hab/km²	2 285 822 14%	4 508 842 27%	6 794 664 40%
population living where density >= 250hab/km²	Extension of MV 5 437 076 32%	Mini grids 4 545 807 27%	9 982 883 60%
Total	7 722 898 46%	9 054 649 54%	16 777 547

Source: Green Mini-grids (DFID-IED, 2013)

ESCOM has little involvement in off-grid power generation. A few diesel-based mini-grid systems are installed at Likoma islands (750 kW) and Chizimulu Islands (300 kW), both owned and operated by ESCOM (and customers paying the regular tariff). DEA supported the installation of three stand-alone solar PV-wind 20.1 kW hybrid electricity generating systems (locally known as solar villages) for demonstration throughout the country (13.1 kW wind and 7 kW solar). Reportedly, these systems are not functioning due to design and battery problems. The site is planned to be connected to the grid, and DEA is contemplating moving and re-installing the equipment to another location (see the Case Study *Powering mini-grids by solar-wind-diesel hybrid systems*).

In particular, the small hydropower potential in Malawi has so far mainly attracted a few actors, such as tea estates or religious missions. For example, the Mulanje area has two mini-hydro plants operated by the Lujeri tea estate (319 and 650 kW). A first hydro-powered mini-grid for rural electrification has been established by MEGA in the Lichenya River. MEGA (Mulanje Electricity Generation Agency) was set up in 2013 and is owned by an NGO, the Mount Mulanje Conservation Trust (MMCT), supported by Practical Action and MuREA (Mulanje Renewable Energy Agency). The basic idea to develop a sustainable business scheme which could achieve expansion and effective provision of electricity to the wider Mulanje area at the same time as ensuring watershed protection on Mount Mulanje through community engagement and action. MEGA obtained a license from MERA to generate and supply electricity (in fact, the first entity other than ESCOM). The facility supplies Bondo village with electricity started to become partly operational in 2013/14 at 56 kW capacity and fully since January 2016[22]. MEGA's now aims to provide the rural, off-grid villages of the Mount Mulanje area with access to affordable and available electricity and energy services, locally generated through a series of 40-100 kW micro-hydro schemes, serving the Bondo, Nessa, and Namainja communities, 4000 people in 810 households (directly connected to the grid), serving another 13,000 people in 2600 households with access to battery-charging facilities, 3 business centres (serving 11 businesses), 6 schools (with 1400 students) and 4 health centres (that cover 29,000 people)[23]. MEGA is the first operational private energy company and operates as a 'social enterprise'. The MEGA business model focuses on making energy available and affordable to its target market – promoting price minimisation, within the parameters of building a financially sustainable business (see Information Sheet No.6 as well the Case Study *Mulanje: pioneering a social enterprise approach in clean energy mini-grid schemes*).

Increasing Access to Clean and Affordable Decentralised Energy Services in Selected Vulnerable Areas of Malawi

The Malawian Government is working in conjunction with the UNDP and a range of other donors on a 3-year project GEF-supported project *"Increasing Access to Clean and Affordable Decentralised Energy Services in Selected Vulnerable Areas of Malawi" (Clean Energy Mini-grid project*) to create opportunities for investment in further mini-grids and to recommend changes to policy and regulations to remove barriers to development in the sector. The project has three components as follow[24]s:

- *Expansion of the Mulanje Electricity Generation Agency (MEGA) Micro Hydro Power Plant and mini-grid scheme:* the project will support the implementation of a second 80 kW micro-hydro powered mini-grid operated by MEGA in the Mulanje district and provide institutional support for the development of several other MEGA micro-hydro schemes to bring the installed capacity of their power production up to 216 kW. The project will also support the institutional capacity of MEGA to help work towards establishing it as a self-sustaining entity;
- *Replication of the MEGA model via piloting of new mini-grid schemes in other areas of Malawi:* the project will aim to initiate an open and competitive mechanism to select and support the establishment of Public-Private-Partnerships (PPPs) for clean energy mini-grids with an emphasis on viable business models. Clean energy mini-grids will be supported.

[22] McKinnon (2013); UNDP *Project Document*

[23] Support to SE4All Action in Malawi, draft Action Agenda (2016)

[24] UNDP: United Nations Development Programme; GEF: Global Environment Facility

- *Institutional strengthening and capacity building for the promotion of decentralized mini-grid applications across the country*: training and capacity building at sub-national and national levels on clean energy mini-grids will be undertaken while a national information clearinghouse will be established to facilitate mini-grid based rural electrification. An analysis of the policy and regulatory changes should take place to make mini-grids part of the mainstream national rural electrification policy (see Information Sheet 1a). Furthermore, there will be support for the development of a toolkit for communities and potential developers to showcase the lessons learned and experiences gained in Malawi so far.

Case studies on mini-grids in Malawi

A number of "Case Studies" have been developed under the UNDP/GEF *Clean Energy Mini-grid project* that seeks to understand the possible role of energy mini-grid systems in Malawi.

- Kavuzi: pico-hydropower schemes, a people's initiative
- Mulanje: pioneering a social enterprise approach in clean energy mini-grid schemes
- Powering mini-grids by solar-wind-diesel hybrid systems (Likoma Island, ESCOM; DoE solar-wind hybrids)
- Solar photovoltaic (PV) mini-grid solutions (Sitolo solar-PV mini-grid; solar kiosks)

Toolkit

The toolkit will be an entry point for the user to the multitude of reports, documents, and tools that today are made available and can be found on the Internet. It will provide links to the project's database of already pre-loaded literature. The interested user can have access by means of a search engine through the web-based Information Clearinghouse

Apart from international literature, development of the toolkit will involve analysing Malawian information and document that shed light on the issue of design, operation, maintenance, and administration of systems. Document gathering will have special attention on these issues so that the toolkit can be used by various practitioners (e.g. government staff, researchers, developers, and investors) in Malawi. The toolkit actually consists of two parts:
- Information sheets (on the webpage and in PDF) that organised around eight main topics (Sections)
- Database of downloadable documents or reports

The toolkit covers the following areas:
1. Energy, electricity, and access; policy and institutional frameworks
2. Rural electrification and mini-grids
3. Renewable energy mini-grids
4. Matching demand and supply; costs and tariffs
5. Cost-benefit modelling
6. Business models, finance, and regulations

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Mentis,	2015	A GIS-based approach for electrification planning—A case study on Nigeria, in: Energy for Sustainable Development 29 (2015) 142–150
World Bank (ESMAP)	2001 2003	Best Practice Manual: Promoting Decentralized Electrification Investment Monitoring and Evaluation in Rural Electrification Projects: A Demand-Oriented Approach

Overview of clean energy and low-emissions energy planning tools

World Bank	Energy Forecasting Framework and Emissions Consensus Tool (EFFECT) http://esmap.org/EFFECT
IAEA	Financial Analysis of Electric Sector Expansion Plans (FINPLAN) https://www.iaea.org/OurWork/ST/NE/Pess/capacitybuilding.html
IED	GeoSIM www.geosim.fr
Energy Commission	Ghana Energy Access Toolkit http://151.80.133.24:90/gheat/
PNNL (USA)	Global Change Assessment Model (GCAM) www.globalchange.umd.edu/models/gcam/
IAEA	Framework of Indicators for Sustainable Energy Development (ISED) https://www.iaea.org/OurWork/ST/NE/Pess/capacitybuilding.html
SEI	Long-range Energy Alternatives Planning System (LEAP) www.energycommunity.org
IAEA	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) https://www.iaea.org/OurWork/ST/NE/Pess/capacitybuilding.html
World Bank	Model for Electricity Technology Assessment (META) https://www.climatesmartplanning.org/dataset/tool-rapid-assessment-city-energy-trace
KTH (Sweden)	Open Source Spatial Electrification Tool (OnSSET) www.onsset.org
IAEA	Simplified Approach for Estimating Environmental Impacts of Electricity Generation (SIMPACTS)
WWI	Sustainable Energy Roadmap http://www.worldwatch.org/sustainable-energy-roadmaps
IEA-ETSAP	The Integrated MARKAL/EFOM System (TIMES) http://www.iea-etsap.org/
IAEA	Wien Automatic System Planning Package (WASP) https://www.iaea.org/OurWork/ST/NE/Pess/capacitybuilding.html

Mini-grid technical design

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Toolkits and guides

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