Clean energy and mini-grid toolkit

Module 4

Matching demand-supply; costs and tariffs

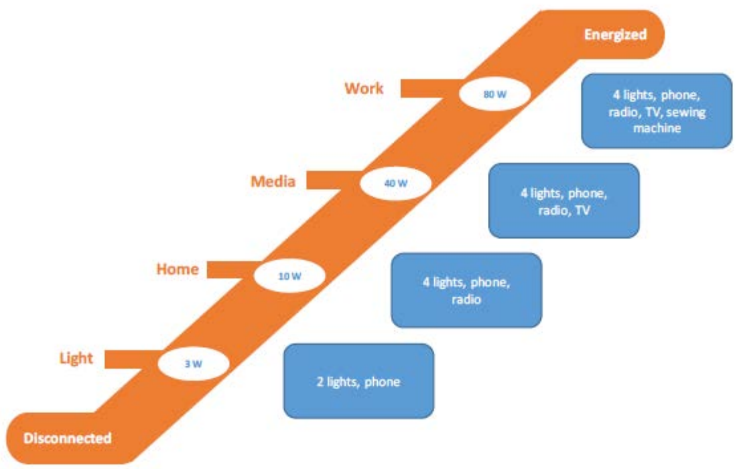
1. Access to modern energy

Access to electricity contributes to poverty alleviation and to sustainable human development of educational and health services and of water supply. It has also tremendous positive impacts on rural households, particularly on children and women who bear the responsibility and hardship of main household work. Electric lighting in homes enables both adults and children to study after their daytime activities, and thereby increases the likelihood that women will read and children will attend school regardless of their income class. It also enables mobile phone charging.

Access to electricity is one of the essential pre-conditions for improving the living conditions in rural areas through the creation of job and income opportunities. The energy demand of the productive uses is, for example, the operation of machinery for agricultural production and agro-processing, water pumps, and tools for small shops and workshops. Electricity is essential for the provision of quality community services. The demand for energy in services covers energy use for health care services (such as hospitals, clinics, and health posts), education (such as schools, universities, and other education services), public institutions (such as government offices, religious buildings), and infrastructure services (such as water supply and street lighting).

The SE4ALL initiative (www.se4all.org) is proposing the use of a **multi-tier framework**, as opposed to the binary definition of 'having access' or 'not having access'. To track the progress towards one of the SE4All/Sustainable Development Goals, universal energy access by 2030 (see Information Sheet No.1), various levels of access are distinguished, i.e. tiers based on the attributes of people's energy supply, the services they use based on that supply, and the energy consumption involved.

The indicative frameworks for household electricity proposed in the *SE4ALL Global Tracking Framework* report have **six energy access tiers**: each defined by electricity supply attributes such as quantity, duration, evening availability, affordability, quality of supply, and legality of connection. A higher tier represents an electricity supply with better attributes and the possibility of access to more modern energy services, which can translate to improved well-being for users. The technologies likely to deliver these attributes range from kerosene/candles (Tier 0), through to intermediate electricity technologies such as solar lanterns that enable lighting, radio, and mobile phone charging, to a reliable grid supply that allows all electric applications (Tier 5). The typical benchmark for rural electrification consists to compare each rural electrification approaches, i.e. on-grid connection, off-grid mini-grid, off-grid stand-alone for the broad range of uses on the energy ladder.



The level of revenue per customer on the energy ladder starts at around USD 10 per year for Tier 1, increases to USD 100-500 per year for tier 2 and 3 and exceeds USD 1000 per year for tier 4 and 5. The level of investment ranges from USD 70 for tier 1, increases to USD 300-1000 for tier 2, and peaks at USD 3,000 for Tier 3, 4 and 5 (see Table 1).

Figure 1 Energy ladder. Source: Azuri Technologies

Table 1 Definition of levels of energy demand and energy access

Attributes	Tier 0	Tier 1	Tier 1	Tier 1.5	Tier 2	Tier 2.5	Tier 3	Tier 3	Tier 4	Tier 5
Continuous Spectrum of improving Electricity supply Attributes										
Service Description	Kerosene lighting	Task lighting and phone charging (or radio)	Task lighting and phone charging (or radio)	4 lights, phone charging and radio	General lighting and TV or fan (if needed)	General lighting and TV and fan (if needed)	Tier 2 and any low power applicances	Tier 2 and any low power applicances	Tier 3 and any medium power applicance	Tier 3 and any high power applicances
Peak available capacity (W)	-	1	5	10	20	50	200	500	2000	2000
Duration (hours/day)	-	4	4	4	4	4	8	8	16	22
Evening supply (hours/day)	-	2	2	2	2	2	2	2	4	4
Average annual consumption per household										
Load factor		17%	17%	17%	17%	17%	18%	20%	20%	25%
annual consumption (kWh/year)		1,5	7,3	14,6	29,2	73	315	876	3504	4380
Price of electricity (US$/kWh)		5,0	4,8	4,0	4,0	3,0	1,0	0,50	0,30	0,25
annual cost (US$/year)		7,3	35	58	117	219	315	438	1051	1095
Average costs (US$/household)										
Least cost		70	110	166	288	500	1800	3200	1600	1600
Likely electricity supply technology	None		Solar lanterns		Stand-alone home systems			Mini grid	on grid	

Source: EU SE4All Technical Assistance Facility (TAF) and World bank ESMAP *Beyond Connection, Energy Access Redefined* (2015)

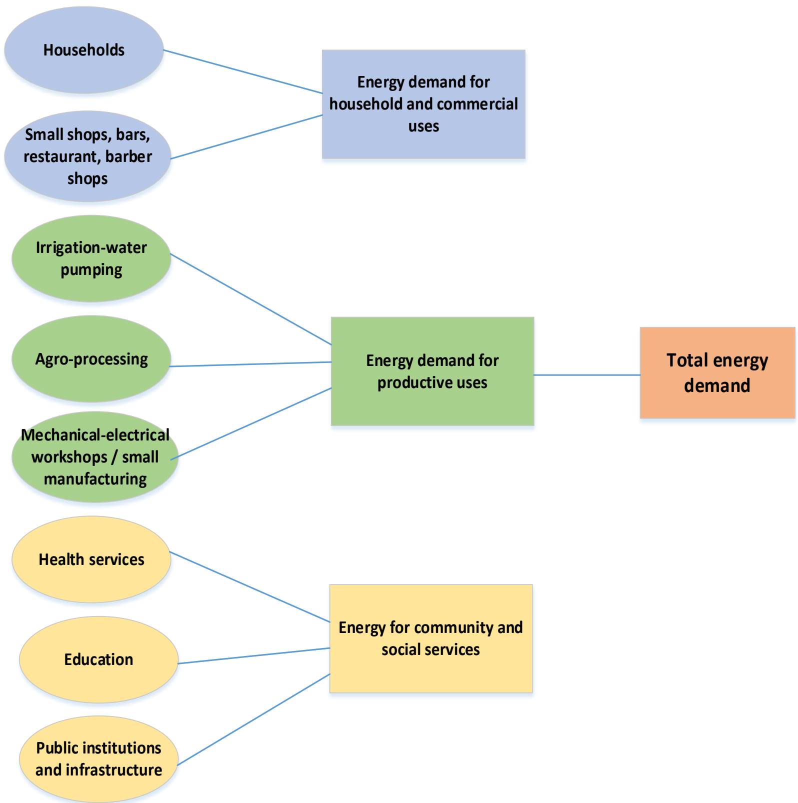
2. Customers of mini-grids

Assessing energy service needs in a village or area involves assessing the energy demand of households for consumptive and small commercial uses of energy, as well as the energy demand for productive uses and community services.

Households

Rural people aspire to gain access to affordable modern energy services (with applications like mobile phone charging, televisions, and fans) in their homes and increase their standard of living. Electric lighting is often the best option as it is safer than an open flame such as in kerosene, paraffin stoves or burning grass Low-income rural households without access to grid electricity usually pay USD 2.5-10 per month for traditional sources of energy (candles, kerosene, disposable batteries, and battery charging). Unelectrified electricity customers in Africa can pay USD 20-80 per kWh for cell phone charging, and USD 40 to 80 per kWh for dry-cell batteries[1].

Figure 2 Energy demand



[1] WB-ESMAP (2008)

Thus, batteries are used in torches is in effect a relatively expensive form of providing electricity. After LED lighting and mobile charging, televisions, radios, refrigerators, and fans are ranked third, fourth, fifth, and sixth most popular household (or small commercial) appliance in terms of anticipated off-grid consumer demand[2]. The total wattage of a rural household, once connected, maybe 0.15-0.30 kW with a daily energy demand of about 2 to 5 kWh (depending on the usage of the appliances). Households that may consume electricity from small, inefficient petrol or diesel gensets with an extremely short lifetime and low efficiency, pay USD 0.35-1.50 per kWh.

Table 2 Energy consumption of selected for households and small shops

Appliance	Typical power rating (watt)	Typical usage per day (hours)
CFL light bulb	12-20	6 (indoor)
LED light bulb	9-15	12 (outdoor)
Radio	6-20	12
Stereo equipment	100	6
TV	30-100	5
DVD player	30	5
Refrigerator	150	10-24
Phone charging	5	2-5
Fan	15-75	4-5
Kettle	350-2000	1
Iron	1000	0.5
Sewing machine	100	2-3
Cooker (2 plates)	2000	2
Cooker (plate)	500	2
Microwave oven	1300	1

Data compiled from:
CES/MuREA (2014) *Toolkit* (2014), CES *Sitolo Review* (2017), CEM-Global LEAP (2016)

Small commercial and productive uses

Productive-use customers will employ electricity for the same uses as households, e.g. lighting, radio/TV, as well as for different purposes that depend on their business' activity and can be categorised as follows:

- Commercial loads (e.g. shops, bars, ice-makers, battery charging and renting, lantern renting)
- Agricultural loads (e.g. irrigation pumps)
- Productive loads (e.g. milling, rice de-husking, oil pressing, wood and metal workshops)
- Anchor loads (e.g. telecom towers, mines, hotels)

Often, these productive users already use diesel engines to power their machines and appliances. Exchanging existing diesel-run machines with electric machines can be economical if the electricity cost is less than the cost of locally available diesel. GIZ has produced a good catalogue on (DC-AC) appliances for small productive uses (GIZ, 2016).

Table 3 Energy consumption of selected appliances in productive uses of electricity

Appliance	Typical power rating (Watt)
Laptop	60
Computer (desktop)	230-300
Printer	15-600
Overhead projector	300
Speaker	400
Keyboard	70
Cooker (4-plate)	7000
Microwave oven	660-1500
Clothes iron	150-2000
Hair drier	400-1500
Sewing machine	60-230
Refrigerator/freezer	350
Saw	700
Drill	250
Welder	2000
Soldering iron	200
Compressor	600
Washing machine	3000
Huller	2000-15000
Wheat flour mill	2000
Wheat/maize mill	15000-20000

Source:
CES/MuREA (2014) *Toolkit* (2014), CES *Sitolo Review* (2017), GTZ *Chitral* (2005), GIZ *DC Appliances* (2016)

Both small and medium enterprises are boosted when energy is used to add value. Small businesses need electricity. A village barber shops will have outdoor and lighting, a shaver, a radio/DVD/VCR combination load, a TV and a fan, and will have a load of about 250 W and energy consumption of 1-3 kWh per day. A hair salon using a power-consuming hair drier will have a higher load of 1.5-3 kW and daily energy usage of 6-13 kWh/day). With 6 lights, TV/radio, phone charging, and refrigeration, a shop will typically have a load of 0.3-1 kW and energy consumption of 4.5-8 kWh/day. Village mall bars/restaurants will need power for indoor and outdoor lighting, refrigeration, a cooker, DVD/VCR combination load and/or stereo equipment, a TV and a fan, with a total load of around 0.3-0.4 kW and daily energy consumption of 5.5-6 kWh. A small guesthouse cum business centre may have a load of 3 kW and daily electricity use of 10-30 kWh. A small carpentry or welding workshop may have a load of about 3 kW and an energy consumption of 9-12 kWh/day.

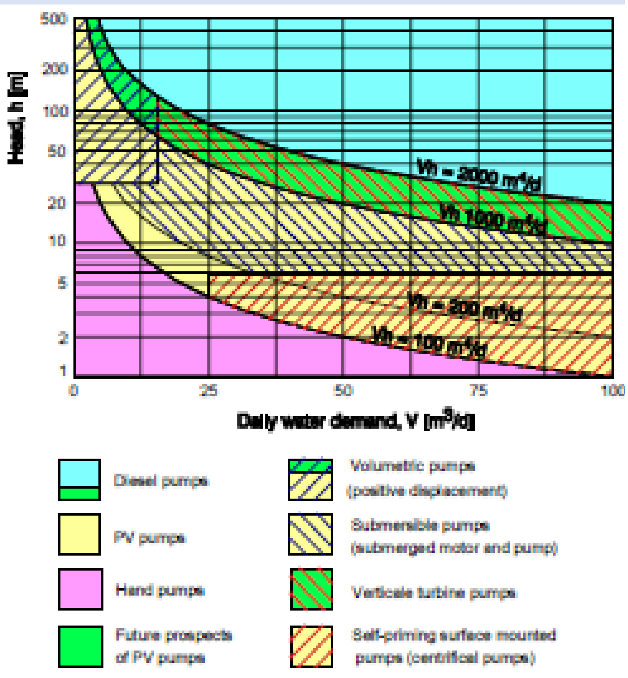
[2] CEM-Global LEAP (2016)

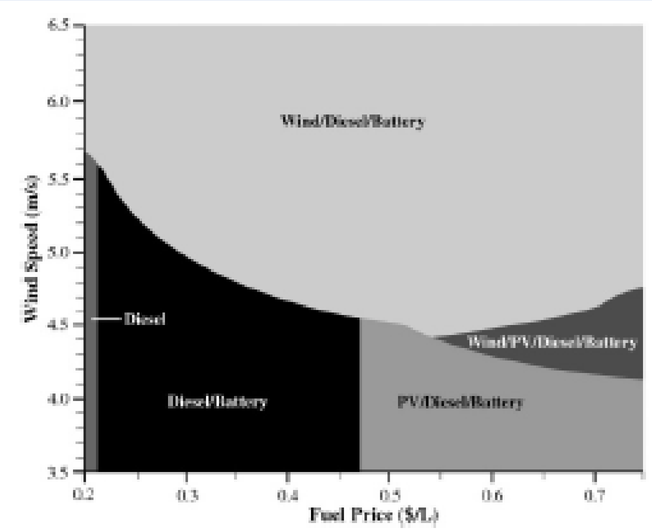
Box 1 Energy and water pumping

The available water resource is an important criterion for choosing the kind of energy sources for any given water pumping application. Water can come either from surface water or groundwater. Water demand is another important criterion for designing rural water supply systems (see Table 5).

Unlike demands for domestic and livestock water supplies, water demand for crop irrigation is seasonal. Because some crops require a maximum water supply for a relatively short growing season, all irrigation systems need to be designed for peak water demands. Irrigation water pumps are characterized by the need for large quantities of water. For this reason, wind- and PV-powered irrigation pumps are usually recommended for surface water resources or for shallow wells for high yield. In this case, producing high-value cash crops is advantageous, making such systems economically viable. Generally, water demand for irrigation varies from crop to crop and changes with the type of soil, soil preparation and irrigation methods, rainfall regimes, and other meteorological factors (temperature, humidity, wind speed, and cloud cover).

Various types of pumps and motors are available for water pumping application depending on the daily water requirement, the pumping head, the suction head (for surface mounted units), and the water resource. The water demand and the total pumping head the main criteria for sizing any water pumping system. An undersized system will frustrate its users; an oversized system is a waste of financial resources. Sizing a system for the worst seasonal variation of the energy resource (solar and wind) and the seasonal variation in demand (e.g. in the case of irrigation) is recommended to ensure that users have enough water. In the case of renewable energy pumps special attention needs to be given to the design of water tanks.





Figures: sizing of renewable energy-hybrid pump systems.
Left: Types of pump sets for different heads and flow rates
Above: Hybrid system configuration for an average daily load of 20 KWh for different fuel prices and wind speeds

Source: NREL *Renewable Energy for Water Pumping Applications in Rural Villages* (2003)

Larger productive uses

Larger productive uses include agro-processing and water pumping. The three main areas of need are village water supply, water for livestock and water for irrigation. A water pumping system must be sized carefully and realistically (see Box 1).

A maize milling facility uses electricity for the mill, lighting and small equipment at a load of about 15-20 kW and daily demand of 80-250 kWh depending on the hours of operation). A small coffee processing facility (using a coffee huller and washing/refinery) may have a load of 30-230 kW. In estimating annual energy consumption, it should be noted that the use of agro-processing machinery is often seasonal.

Social and health services

Schools need power for indoor and outdoor (safety) lighting, laptops/computers, and printers, fans, teaching aids (TV and radio/DVD/VCR and slide projectors. With such appliances, a village school may consume about 5-10 kWh per day at a load of 0.5-1.6 kW. Some schools may need refrigeration, communication equipment (short-wave radio, Internet), and water pumps. In some schools, refrigeration is necessary for preserving food and some medical supplies. Given the remoteness of the school, and the necessity to undertake minimal repairs, it may be useful to provide electricity to run some simple power tools, such as electric drills, sanders, and portable saws.

A refrigerator/freezer will consume about 1 to 3 kWh per day. Water may have to be pumped from a well or surface source or it may flow by gravity from a spring. A water pump (that produces 1500 litres a day lifting water 40 m up) has a load of 100 W and during 6 hours will have consumed 0.6 kWh.

Table 4 Indicative water needs

	Water consumption (litres/day/head)
Human consumption	5-10
Personal hygiene	20-50
Animals	
Dairy cows	80
Beef cows	50
Calves	30
Sheep and goats	10
Pigs	20
Chicken	0.1
Crops	**Daily water need (m^3/ha)**
Rice	100
Cereals	45
Sugarcane	65
Cotton	55

Source: NREL (2001) and NREL (1998)

Table 5 Load profile for rural clinic equipped with conventional medical devices

Appliance	**Typical power rating (watt)**	**Typical usage per day (hours)**
Refrigerator (vaccines)	60	5-12
Refrigerator (non-medical)	300	5-10
Centrifuge	250	2-4
Microscope	20	1-6
Blood analyser	75-100	4
Haematology analyser	230	4
CD4 machine	200	
Oxygen concentrator	300	1-4
Vaporizer	40	1-4
Communication VHF radio - standby - transmitting	 2 30	 12 1
TV	1000	1-4
Radio	30	2-12
Light (LED-CFL-tube)	15-20-32	8
Overhead fan	40	4-12

Source: UNF *Malawi Country Summary* (2015) and WHO-ESMAP (2015)

The most common applications needed at **rural health care** facilities require some form of energy. Immunization programs depend upon reliable refrigeration to preserve vaccines. The vaccines need to be stored for up to one month and require a stable temperature between 0-8°C, but once the vaccines have been exposed to temperatures outside this range their potency is lost. Electric light greatly improves emergency treatment, birthing, maternity care, surgery, administrative tasks, and other medical functions. Emergency medical treatment is greatly facilitated with reliable communications to other health clinics and facilities in the region. Common means of chemical disinfection include chlorine and iodine. There are more sophisticated means of water treatment that generate higher volumes of potable water and are effective for a wider variety of types of contamination. These processes require electricity, such as ozone treatment, reverse osmosis, ultraviolet disinfection.

Table 6 Load profile for rural clinic equipped with conventional medical devices

	Tier 1	**Tier 2**	**Tier 3**	**Tier 4**	**Tier 5**
Peak power capacity (Watt)	5-69	70-199	200-1999	2000-10000	>10000
Daily energy capacity (Wh per day)	20-279	180-1599	1600-3199	32-220 kWh/d	> 220 kWh/d
Duration of supply	> 4	> 4	> 8	> 16	> 23
Evening peak hours supply	-	> 2	> 2	4	4

Source: WHO-ESMAP (2015). Based on the WB-ESMAP Global Tracking Framework (see Table 1 in this Information Sheet), the table presents a multi-tier definition of energy access in health facilities, An energy needs assessment has been conducted for 79 healthcare facilities in Malawi, carried out by African Solar Designs (ASD) and commissioned by the United Nations Foundation (UN Foundation)[3], The sample consisted of 4 dispensaries, 1 health post, and 74 health centres. In 2010, Malawi had 37 community/rural hospitals (> 14 beds), 423 health centres (8-14 beds), 17 maternities (8-10 beds), 77 dispensaries (0-2 beds) and health posts[4]. Of the 79 health facilities assessed, 73 were off-grid and six were grid-connected. PV systems were found in 96% of the sites visited, however only 57% of solar PV systems assessed were functional, emphasizing the need for increased attention to power and associated maintenance needs at health clinics. Firewood was the most common source of thermal energy (found at 92% of facilities surveyed), mainly used for cooking and water heating. The results of the assessment highlight that off-grid energy sources provide critical services where the grid cannot reach.

However, these off-grid energy systems, particularly PV, have a high failure rate. The most common cause reported of system failure has been dead batteries. As is often the case with off-grid PV systems, this is linked, caused and/or exacerbated by a. faulty design (demand-supply mismatch, unhealthy battery depth of discharge), b. lack of after-sales service (b1. lack of relationship between the equipment supplier, health centre, and health centre staff, and b2. no arrangements in place for equipment inspection and servicing, spare parts of battery replacement), c. lack of knowledge on maintenance of equipment by (new) staff, and d. lack of funds for maintenance (health facilities do not have their own operational budget; technically the responsibilities of the District Health Offices, these are often unable to provide funds for spare parts and battery replacement). Thus, the UNF report concludes that "it is the technology business model and management, not the technology itself that is often at fault". The report recommends that six sites continue to use the national grid, 22 sites should be connected to the national grid, one site use a stand-alone approach and 50 sites use clinic-level micro-grids (that cover several medical and/or staff buildings).

A small rural clinic will typically need electric power for interior, outdoor and operation lighting (about 5-6 lights), refrigeration (1-2), ICT (two notebooks. printers and phone chargers), and medical equipment (1-2 microscope, 1-2 CD4 machine, and depending on the clinic, an oxygen concentrator, centrifuge, and a suction machine). In addition, electricity may be needed for water pumping (about 0.15 kWh/m^3, but depending on the pumping head) and staff housing units (0.5-0.6 kWh/day). See Table 5 for more details on load and energy consumption.

Impacts and benefits of rural electrification

Access to electricity contributes to poverty alleviation and to sustainable human development. Electricity is essential for the provision of quality community services especially of educational and health services and of water supply. It has also tremendous positive impacts on rural households, particularly on children and women, who bear the responsibility and hardship of main household work. Access to lighting, information, and communication **improves the living conditions** of each household, reduces migration to the urban centres and improves the attractiveness of the community for well-educated and professional service people like teachers, doctors, etc.

Access to electricity is one of the essential pre-conditions for improving the living conditions in rural areas through the creation of **job and income opportunitie**s; initiating local economic activities for a sustainable rural development; improvement of health and education; and for poverty reduction. Skilled jobs are created through operation and management of power station, the demand for installations in houses and the repair of electric appliances and machinery. Services like barber shops, restaurants, workshops (e.g., machinery repair, welding, or carpentry) also create jobs and improve the access to local services (which often results in additional benefits due to the saving of transport cost and time). Electricity can operate irrigation pumps to increase agriculture production, change from subsistence to cash crop production or add value by further processing.

Thus, energy supply plays an important role in **poverty alleviation**. Besides the provision of power, it also creates skilled job opportunities directly in the mini-grid power supply system and in village workshops for electric appliances and for electrical house installations. A typical impact chain may be as follows: the mini-grid system provides electricity of sufficient quality and quantity for consumer and productive use. The electricity is used to process local products, to run small shops and other services. Accompanying measures provide business and technical skills, know-how and start-up capital to start business activities. Thus, local markets are initiated providing job and income opportunities to the local population. The economic activities are self-driven and therefore sustainable. This finally, contributes to poverty mitigation in the project area.

[3] *Malawi Country Summary,* UN Foundation "Energy for Women's and Children's Health Project", by African Solar Designs (Kenya), 2015

[4] *Malawi Health Sector Strategic Plan, 2011-2016*

Box 3 Benefits of rural electricity

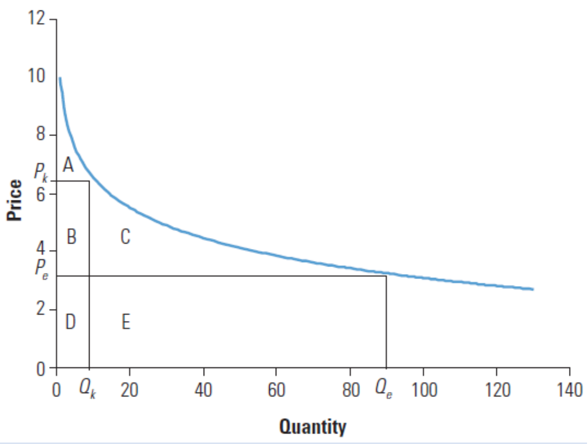
- Lighting benefits
- Education and communication
  - ICT: Radio/TV/internet
  - Ability to charge mobile phone
  - Light for studying at night
  - ICT devices (e.g. PC) at school may increase school attendance
- Health and hygiene
  - Better health due to avoided toxic fumes from i.e. kerosene lamps
  - Improved quality of service at health facilities (improved lighting increases the ability to perform medical operations, ability to store medicine and vaccine, etc.)
  - Improved quality of lighting (less straining on the eyes)
  - Improved health and hygiene through improved education/communication
- Environmental benefits
  - Avoided local air pollution (from e.g. diesel, kerosene)
  - Avoided greenhouse gas emissions
- Time use
  - Hours saved (i.e. not having to walk to nearest town to charge mobile phone)
  - Improved lighting provides the ability to work in the evening (resulting in either more work hours available, and thus more income; or more flexibility as to when work is carried out, i.e. can avoid working during the hottest periods of the day, or attend to children/family chores during the day, and work in the evening)
- Productive uses
  - Local industry
  - Household/micro enterprise

Source: NORPLAN (2012)

Box 2 Quantification of benefits of electrification

Benefits are often defined by calculating the avoided cost of displaced sources of energy, such as kerosene, candles or diesel. This avoided cost method generally underestimates the actual benefits (mainly because the quality of the service from electrification is far superior to what was replaced, and thus individuals are prepared to pay more for high-quality service. Another way is the **consumer surplus approach**. The blue line in the figure shows the demand curve for lumens. Data from an energy survey give two points on the demand curve: price of lumens and the quantity consumed using either kerosene (Pk,Qk) or electricity (Pe,Qe). The amount the consumer is willing to pay for a quantity Q is the area under the demand curve from 0 to Q. Hence, the consumer is willing to pay A+B+D for consumption of Qk, but actually pays just B+D (= Pk Qk), leaving a consumer surplus of A. Once electricity becomes available, the consumer surplus is A+B+C, so the increase in consumer surplus as a result of electrification is B+C. This consumer surplus has two parts: that arising from the reduction in the price of the Qk units already being consumed and the consumer surplus associated with the new consumption, Qe - Qk

In the example in this box, we calculate the benefit of lighting, which is measured in lumens. A lumen is a measure of light emitted: a candle emits around 12 lumens, a kerosene lamp from 30 to 80 lumens, and a 60-watt lightbulb emits 730 lumens. So, by using a single 60-watt lightbulb for four hours a day for one month (30 days), a household is consuming 88 kilolumen-hours (klh) (=4 x 30 x 730/1,000). Electricity consumption is 7.2 kWh per month (=4 x 60 x 30/1,000). Suppose electricity costs the consumer $0.05 per kWh; then she has a monthly lighting bill of USD 0.36, equivalent to a cost of USD 0.004 per klh. In contrast, burning a kerosene lamp for four hours a night yields just 6 lumens, but costs about the same as the monthly electricity bill, giving a cost of USD 0.06 per klh. Moving from kerosene to electricity cuts the cost by more than a tenth and increases consumption more than tenfold.



Source: World Bank, *The Welfare Impact of Rural Electrification* (2008),

3. Sizing mini-grid systems

The demand for electricity does not only need to be properly assessed but also sufficiently matched during mini-grid operation in order for mini-grids to be economically sustainable. It has to be highlighted that every village and community differs in terms of needs and conditions. The design of a mini-grid directly affects the cost structure of the project and determines not only the price of the energy produced, but also its quality. Lack of knowledge about the load conditions, electrical demand and future load growth during the sizing process can result in a) oversized mini-grid systems (with increased investment and thus higher payback times, as well as higher operational costs and lower overall efficiency or b) undersized mini-grids (with unreliable supply, leading to blackouts and reduced service quality, and low consumer satisfaction). The quality of electricity provided by the mini-grid can be equivalent to that of the national electricity network. Nevertheless, for initial rural electrification, lower service levels (e.g. 4-8 hours of supply per day) can be considered in order to reach the first tiers of electricity supply (see Table 1).

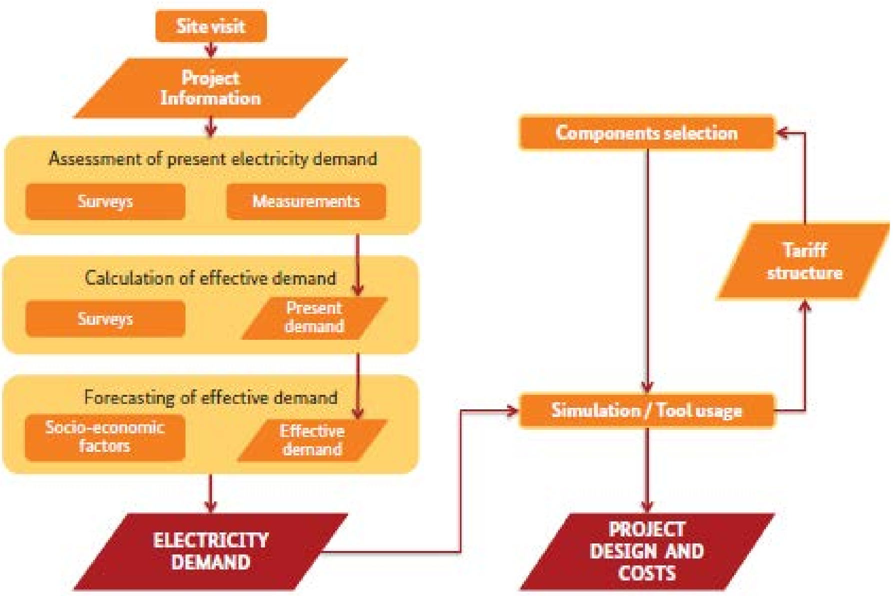
Demand assessment has a direct impact on the size of the components and thus the investment costs. Mini-grids need accurate predictions of electricity demand. Considering the characteristic of the assessed demand profile, peak demand hours (see Figure 4) and load profile characteristics (see tables 2,3 and 4) can be evaluated. The assessment starts with an analysis of community- and customer based data, which are specific to every project location, have to be gathered from statistics, report, and GIS data; customer-based information also needs to be gathered and is best done in an on-site survey. Classifying potential customers into the categories residential (households), small productive uses and social services (as in section 2) is very helpful to determine the market characteristics, the economic activities of the area. The **assessed electricity demand** is the amount of electricity that customers state they would use if there was electricity at this moment (and is different from the current power demand). Demand may differ per season (influenced by crop cycles for farming-related productive loads, such as irrigation and milling); as well as occasional events like festivals and weddings causing ad hoc increases in demand. The **effective demand** is the assessed demand that is influenced by the "willingness to pay" (i.e. the maximum amount that an individual indicates that he or she is willing to pay for a good or service) and "ability to pay"

The **effective future demand** is the demand forecast over the near future (10 to 20 years), which is influenced by various socio-economic factors, such as population growth, economic productivity and changes in consumption patterns, and energy demand. The challenge with this demand prediction is to assess the power demand not only at present but for the near future in rural areas where people do not have personal experience with electricity, and then to accurately estimate demand growth over time (as the village grows and may attract other people as a development pole, increasing productive uses of energy, while households may use more appliances as power becomes available and possible incomes increase). The mini-grid must be sufficiently flexible (technically and in its revenue/ tariff model) to meet these seasonal changes and future growth.

Once the data assessment of electricity demand is successfully completed, the data needs to be processed, and the average daily load profile can be calculated, the **peak load** in kW (which is required for the load forecasting and plant sizing, as well as the **energy demand** in kWh (needed to forecast power sales and delivery) can be retrieved. The load profile is needed for choosing the right components (solar, wind, diesel, battery, other) and determining the operation mode of the mini-grid.

Matching customers' electricity demand with the electricity supply is another critical element in mini-grids from both a

Figure 3 Flowchart of the mini-grid sizing process



Source: GIZ *Mini-grid sizing manual* (2016) technical and an economic perspective. From a **technical perspective**, like in all electricity grids, mini-grid electricity supply has to meet electricity demand at all times as much as possible. Yet, as mini-grids have fewer customers and less varied consumer types than national grids, the concurrency of demand is higher and load profiles are more volatile. A typical mini-grid load curve with mainly residential customers can be seen in the graph in Figure 4, with some productive use during the day, a peak from lighting and TV during the evening hours, and little demand at night. The technical solutions for meeting demand at all times do come at higher (investment) costs.

From an **economic perspective,** *the more electricity produced in a system can be sold, the lower the tariffs for the customers can be***.** Thus, mini-grid economics mainly depend on the electricity demand, the electricity supply and cost, and the potential revenues (see also the Information Sheet No.5 for calculation examples).

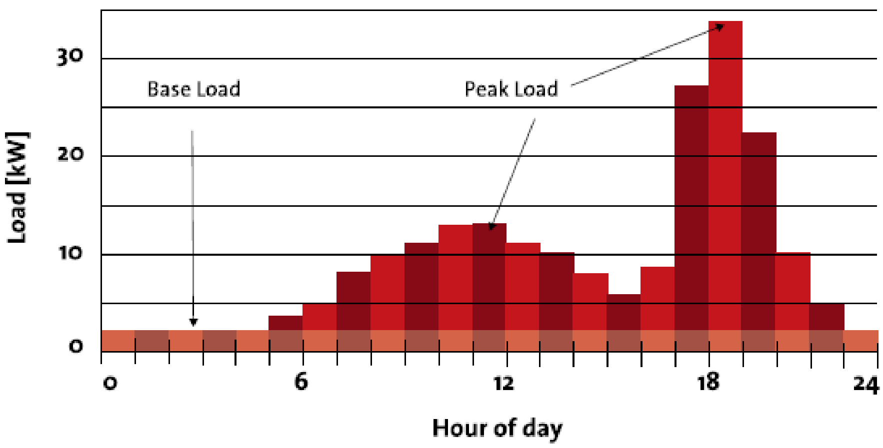
Validating the steps of electricity demand assessment and the technical and financial analysis is necessary to increase the success and viability of the project. For mini-grids there are a variety of **tools** available with different functionalities, based on complex algorithms, some of which are introduced below:

- The **HOMER Pro** microgrid software by HOMER Energy is the global standard for optimising mini-grid design in all sectors, from village power and island utilities to grid-connected facilities. Originally developed at the National Renewable Energy Laboratory (NREL), and enhanced and distributed by HOMER Energy, the HOMER (Hybrid Optimisation Model for Multiple Energy Resources) nests three tools in one software product, so that engineering and economics work side by side (see www.homerenergy.com)
- The **Mini-grid Builder** is a tool developed by GIZ. Its scope is to deliver a standardised approach towards the load assessment, sizing of generation capacity and financing aspects of mini-grid projects (www.minigridbuilder.com)
- **Sunny Design** was developed by SMA Solar Technology AG and allows the user to receive an optimum PV system configuration based on the required data entered (www.sunnydesignweb.com)
- **RETScreen** is a software package, developed by Natural Resources Canada (NRCan), that can be used to determine whether or not a proposed renewable energy, energy efficiency, or cogeneration project is financially viable (www.nrcan.gc.ca/energy/software-tools/7465), based on input demand and supply data and technology cost.

4. Economics of mini-grids

The costs of energy technologies include equipment, organization & installation, and operating & maintenance. Financing expenditures are part of the costs (see Information Sheet #6). However, in comparing technologies financial costs should in principle be left out of the initial cost assessment. The idea is that costs of technologies are compared on their merit (benefits vs costs). Often the financial sector may have a bias towards new or innovative technologies as opposed to the proven ones. If projects or technologies need funding, criteria are often applied that disfavour these technologies.

Figure 4 Typical load curve of a mini-grid



Source: EUEI-PDF Toolkit

Four cost metrics are frequently referred to in reports:

- *Investment cost* or *capital expenditure* (CAPEX), which includes the total cost of project development, installation & construction, including equipment cost. In the annual cost sheets, these appear as depreciation (i.e. distributed over the lifetime of the assets).
- *Operating expenditures (OPEX*), are the annual (variable and fixed) expenditures for operation, administration, maintenance. Fixed costs include interest on debt and fixed taxes. Other fixed costs are overhead and transaction costs (administration, reporting, fee collection, mini-grid staff, regular maintenance). Overhead and transaction

costs are often underestimated. Examples are fuel and lubrication costs (in the case of diesel or biomass-based mini-grids) and include battery depreciation.

- *Capacity factor* or load (utilization) factor is the ratio of the net energy production in a given year that could have been generated at full-capacity operation (i.e. at 8,760 hours). The generation capacity may not be fully used due to non-availability (scheduled maintenance and overhaul work), resource limitations (variability and unavailability at certain time per day or seasonally) and low demand (when capacity is idle);
- *Levelised cost of energy* (or electricity) – LCOE: the value of lifecycle costs (e.g. in USD/MWh) of producing a unit of energy (MWh) of a specific technology. One can also say the LCOE is the price that must be received per unit of output to reach a financial return (break-even) over its lifetime

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : investment expenditures in the year *t*

M_t : operations and maintenance expenditures in the year *t*

F_t : fuel expenditures in the year *t*

E_t : electrical energy generated in the year *t*

r : discount rate (often taken as 10%)

n : expected lifetime of system or power station

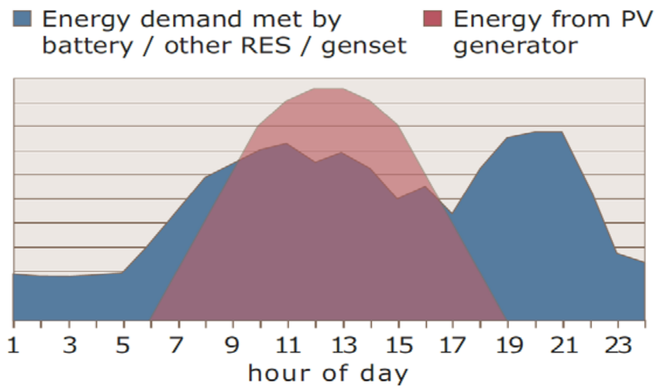
The instantaneous demand (kW) of a village can easily vary over the day from 10% to 100% of the peak power demand. Thus, the so-called "load utilization factor" can be rather low in rural off-grid systems (15-30%). Matching the daily demand and the fluctuating renewable energy production is a key issue in off-grid systems and the recourse to storage systems (e.g. batteries) has to be considered to increase the share of variable renewables, such as solar and wind.

The right mix between thermal fuel oil generator (diesel engines) and renewable energy generators (solar PV, wind, biogas, biomass gasifier) determines the least-cost solution for the local generator:

- 100% diesel-fed systems have lower capital costs, but higher running costs due to pricy fuel purchase, supply scarcity and the substantially lower lifetime of the generator. A renewable energy-based generator would generate electricity at a levelised cost that is lower than the marginal cost of generating this electricity with fuel oil.
- 100% renewable energy systems have much lower running cost, but higher capital cost due to renewable energy technologies (RETs). Adding a small diesel genset can avoid expensive over-capacity of renewable sources and storage systems for a reliable power supply.

The optimum configuration of a hybrid generator is somewhere between these two extremes, depending on a) the characteristics of the renewable energy sources that determines the availability of the renewable generators, and b) he aggregated load duration curve on the demand side (see figure 4). Biogas generators with gas from gasification or digesters can provide power flexibly. Also, hydropower stations are flexible as long as their capacity and the water flow are adequate. Other technologies like solar PV modules and wind turbines only produce electricity when the sun shines or the wind blows. Up to a certain percentage of solar and wind energy can be introduced into the mini-grid without providing for costly storage systems.

Figure 5 Rural demand profile and solar production profile



Source: ARE (2013)

Although electricity generation from renewable energy usually entails high fixed costs and related risks, renewables can play an important role in mini-grids as prices have decreased within the last few years, in particular, the price of solar panels have dropped considerably. Nowadays, for most sites in Africa, renewable energy and hybrid solutions have a lower levelised cost of electricity (LCOE) than diesel generators. Given the standard RET costs (see

Information Sheet No.3) the least-cost generating solutions usually start with hydro, followed by biomass, then hybrid systems using wind and/or solar energy.

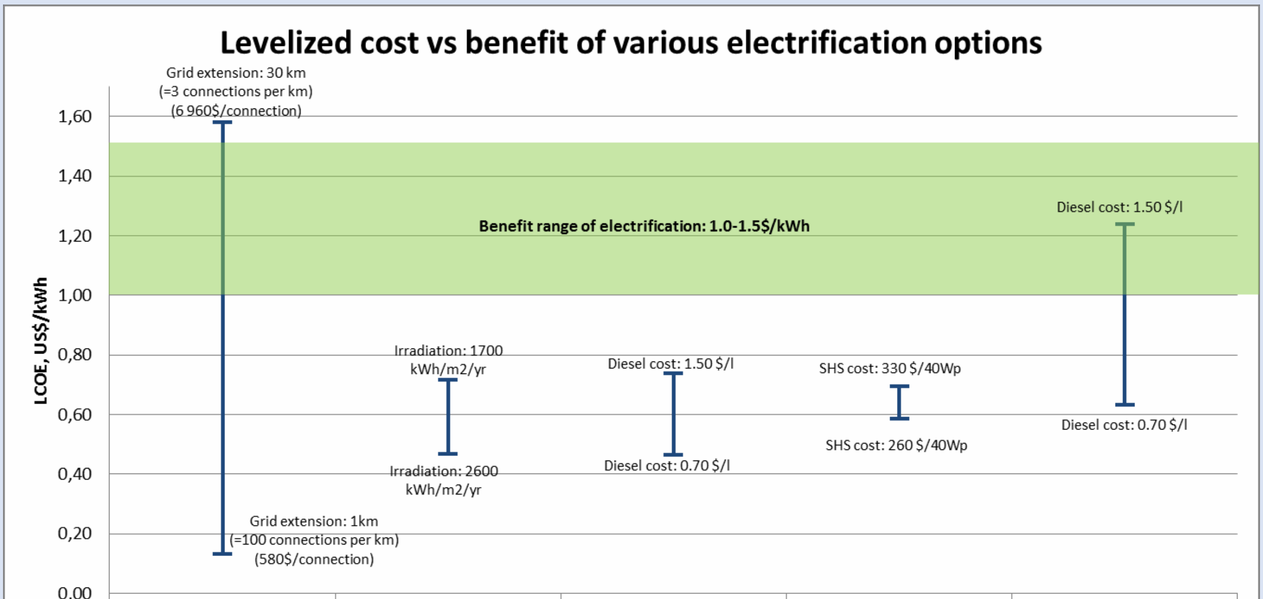
Whenever a system combines different sources, it is recommended to evaluate its performance using computer simulation tools like HOMER to find an optimal configuration. The financial performance of the system can either be reviewed using the same tool or by introducing the technical output data into a financial model. One such a financial model (with Excel-based support tools) are available for download at www.minigridpolicytoolkit.euei-pdf.org/tools.

The economics of a mini-grid system can be improved, if it has one or more stable and reliable anchor and business loads (industrial or institutional) that have most of their electricity demand during off-peak hours. In this, so-called A-B-C model, there are:

- **A**nchor customers, such as agro-industry, tea factories, telecom tower or pumping station ensure continuous and predictable load improving the bankability of the mini-grid,
- **B**usinesses, such as rice mills, shops, crafts, ensure large loads which increase the amount of sold electricity and reduces the unit cost of supply,
- **C**ommunity, which requires affordable (cross-subsidised) electricity at lowest prices and that supplements the revenues from the first two customer groups.

Box 4 Cost comparison of electrification options

This Box reviews various electrification options, namely grid extension, solar PV mini-grid, solar PV- diesel hybrid mini-grid, solar home systems (SHS), and diesel based mini-grid, in terms of their levelised cost of energy (LCOE) over the life time of each option.



	Grid extension	Solar PV mini-grid	Solar PV-diesel hybrid mini-grid	Solar Home System	Diesel mini-grid
High	1,579	0,714	0,738	0,695	1,237
Low	0,132	0,467	0,463	0,585	0,633

Some key assumptions for the LCOE calculations include:

- Installation costs: Grid extension: USD 22 000/km (for transmission line only), solar PV: US$7 230/kWp, Generator costs: USD 13,200 (30 kVA) and USD 6,000 (7 kVA)
- A distribution grid of 2km at a fixed cost of US$18 000/km is assumed for each option (except in the case of SHS) with 100 connections, each consuming an average of 50 kWh/month
  Cost of diesel: an additional 50% has been added to the diesel price to take account transportation cost in remote rural areas as compared to urban diesel distribution
- Discount rate: 10%
- Varying factors are: for grid extension: length of extension; for solar PV: irradiation; for PV-diesel hybrid: irradiation and diesel price; for SHS: low vs high price (developed vs undeveloped SHS market) for a 40 Wp system and for the diesel system: diesel price

Source: NORPLAN *Policy Brief: Cost-benefit analysis of rural electrification* (2012)

5. Tariffs

Revenues can be acquired through connection fees, subsidies, and tariffs. **Connection fees** are an important measure to guarantee the commitment of electricity customers and cover the cost of connection. These can be in the order of USD 60-250 (which is usually the cost of connection and in-house installation). In practice, many rural village customers will be unwilling or unable to pay such a one-time connection charges. Thus, reducing the one-time connection charge, for example by spreading 50% or more of the connection fees over a certain time period (e.g. by including them in the tariff charge) is an effective way to gain more customers.

Tariffs are either **f**lat rate (fixed) prices (regardless of electricity consumption) or energy-based energy prices (which are tariffs based solely on the consumed amount of energy) or a combination of both. **Energy-based tariffs** depend on the actual electricity consumed and are thus based on measured kWh.

Power-based (fixed, or flat-rate) tariffs are based on the expected power consumption, which in turn determines the maximum power available for the consumers. These tariffs are calculated on a Watt basis. A basic tariff would limit consumer consumption to e.g. 60 W and charge each consumer USD 6 each month. It might also be **service-based** (when consumption levels of consumers are very small) or device-based linked to the number of light bulbs and appliances that the consumer proposes to use. Flat-rate tariffs are easier to administer and reduce connection cost (no need for energy meter, except for a load limiter) and are often used in pico and micro-grids. However, a customer may cheat by connecting appliances above the maximum power consumption threshold. Also, a fixed tariff does not incentivise customers to use electricity efficiently.

These tariffs can be either **pre-paid** (pay-as-you-go) **or post-paid**. Pre-payment tariffs give both mini-grid operators and consumers more planning security. In Sub-Saharan Africa, these prepayment systems are often viewed positively because of the good experience with a similar payment scheme for mobile phones. However, these are less suited for off-grid electricity systems with high fixed costs such as PV- and battery-based mini-grids. In such systems, the operator must try to sell all the electricity produced before it gets lost, which occurs when the battery is full. The lower the amount of available/produced electricity that is sold the lower are the revenues and the higher is the tariff per kWh. For PV-based mini-grids, flat-rate or take-or-pay contracts may be more suitable than pay-as-you-go.

Tariffs can further be distinguished between breakeven tariffs or profitable tariffs. Break-even tariffs are designed to ensure cost-coverage (often used in community mini-grids). Profitable tariffs, which are usually higher, are designed to generate sufficient return on investment to appeal to private sector investors or to allow to build up financial reserves for future large overhaul or expansion of the system. Tariffs typically cover all system costs (fixed cost, including annualised investment, and fixed and variable O&M cost) and should be flexible and be revised regularly.

Tariffs can be different according to the type and level of consumption of the consumer. **Customer class tariffs are** set according to consumer groups, e.g. residents, institutions, and businesses. These are mostly used to cross-subsidise residents, with commercial tariffs typically being higher than the residential and the social institution tariffs. **Stepped tariffs** reflect the difference in consumption level of the consumers. These are progressive, that is, consumers pay low tariffs for the first kilowatt-hours (often called *lifeline* tariff), or Watts, and higher tariffs for further consumption, effectively a form of cross-subsidisation from high to low-consumption customers.

Time-based tariffs: variable tariffs based on the time (and/or per seasonal availability of the renewable energy resource) They are mostly applied for commercial and industrial consumers and are also used for load scheduling (demand-side management), aiming at improved energy efficiency. A completely **flexible tariff** structure includes tariffs that change according to electricity demand or power demand, providing incentives for electricity usage when surplus energy is available. Here, advanced metering systems are needed (see 'smart meters' in Box 2 in the Information Sheet No. 2).

Private mini-grid operators in Africa expect a project Internal Rate of Return (IRR) (a margin of revenues over fixed and variable cost) of at least 12% and an equity IRR of 16%. These are considered to be adequate by social entrepreneurs but not by purely profit-oriented companies and investors. The calculated margin can only be realised by selling a certain amount of electricity (kWh) per year. Any kWh sold beyond the planned electricity sales volume will generate an extra margin. From a mini-grid point of view, the risk would be lowest if the tariff would have a combination of both fixed and flexible prices, where revenues from the fixed basic tariff exactly covered the fixed costs and energy prices are slightly higher than variable costs. A tariff consisting of the energy tariff component only, like in a pay-as-you-go scenario, results in the highest possible risk for the mini-grid operator (see the discussion on finance and risks in Information Sheet 6).

6. Malawi

Studies on rural energy demand in Malawi have been carried out, but usually, are linked to a particular rural energy project in a particular area or village. Often, these are done as part of the feasibility study of the rural electrification project and may not be published separately or not at all due to confidentiality clauses. Sometimes studies or information on demand appear on the particular project's website and then disappear again when at project's end the website is abandoned. This is a pity because such studies give valuable insight into the current and future energy demand of rural households, social services and productive uses in Malawi. A list of studies available to the authors of this Toolkit is given in the Bibliography section. The information in Tables 2 to 5 is based on these reports and therefore is tailored as much as possible to the typical circumstances of Malawian villages.

Box 5 Feasibility assessments of solar PV and hybrid mini-grids in Malawi

A limited number of studies have been carried out on the viability of renewable energy based mini-grids in Malawi, using the Hybrid Optimization Model for Electric Renewables (HOMER) software.

In 2014, a techno-economic feasibility study was carried out (doctoral thesis research (Zalengara, 2015) on solar and wind-generated electricity on Likoma Island in Lake Malawi. Supplying electricity for 24-hours with diesel generators would raise the operation and lifecycle costs by 44% compared to the costs of the current 14-hours supply schedule. The study shows that the power provided at a 24-hours basis by a solar PV-diesel-battery (with or without wind turbine) would be cheaper than the 14-hours electricity supplied today. The cost of producing photovoltaic and wind-based electricity could be between USD 0.44 and USD 0.56 per kWh, depending on the interest on capital finance, which is considerably less compared to USD 0.89 per kWh for diesel-fired electricity. Thus, PV-wind-diesel hybrid systems could reduce the subsidy spent by the government on grid electricity on Likoma Island from USD 0.80 per kWh by about half. The result of the comparison analysis between 24-hrs solar/wind-based and 24-hrs diesel-based with existing 14-hrs diesel-based power supply, Likoma, is summarized in the table below:

	System configuration					Financial indicators		
Type of system	PV (kW)	Wind (kW)	Diesel (kW)	Batteries (number)	Converter (kW)	Initial capital (USD million)	LCOE (USD/kWh)	Net present cost (USD million)
Diesel gensets, 14 hrs/day	-	-	600	0	0		0.888	10.18
Diesel gensets, 24 hrs/day	-	-	600	-	-		0.883	14.64
PV-wind-diesel-battery	1250	150	400	1710	500	4.02	0.441	7.30
PV-diesel-battery	1500	-	400	1900	500	3.60	0.452	7.49
PV-wind-battery	2000	150	-	4180	500	6.89	0.535	8.86
PV-battery	2500	-	-	4750	500	7.07	0.569	7.07

Annual power production (at 24 hrs per day availability) of 1.825 million kWh per year. Peak demand (based on 2012 population data): - 375 kW (maximum). Batteries are 1150 Ah. Source: C. Zalengera, Ph.D. thesis, Loughborough University (2015).

Sitolo village in Mchinji District has 300 households and 1 primary school and 1 clinic. A 45-kW solar-PV mini-grid has been proposed that will initially connect 100 households, grocery shops, a salon and barber shops, one bar, a maize mill, the local school and health clinic as well as six street lights. The Project will involve the installation of a 45-kW solar mini grid complete with a 3-km radius transmission (11 kV) and distribution (400/230 kV) system targeting 100 households. This project is supported by UNDP (working in close collaboration with Department of Energy Affairs) with Community Energy Malawi offering on-the-ground implementation supervision of the deliverables. Mzuzu University has carried economic viability assessment of photovoltaic powered mini-grid for Sitolo Village in Mchinji, Malawi. The analysis made use of the HOMER software. Based on the findings, the recommended system for the target load in Sitolo village is a 45 kW PV system with 2 strings of 82 batteries (2 V, 3300 Ah) and a 30 kW inverter. The recommended system would have a capital cost of about USD 300, 000 including equipment, accessories and installation. The total net present cost (NPC) of operation and maintenance for the system is estimated at USD 44,000.00 over 25 years with a breakeven cost of energy generation of USD 0.084 per kWh. However, such a system would not be able to meet all of the peak load (84%), even if the maize mill is not included. To have zero capacity shortage all the time would require to meet the estimated load of 234 kWh per day would require a solar PV system of 70 kW. Such a system would have a net present cost of USD 600,000 and and LCOE of about USD 1.00 per kW. This example shows the importance of sizing a mini-grid system in view of expected load and energy demand, availbale resource, LCOE and realistic tariff setting.

Source: Technical and Economic Viability Analysis of Photovoltaic Powered Mini-grid for Sitolo Village in Mchinji, C. Zalengara (Mzuzu Universirty)

The studies indicate that productive uses of energy are key to the sustainability of energy systems and should build on already existing development initiatives among the rural communities. For example, there is evidence from recent solar projects that barbershops and selling cold drinks, mobile phone charging and video can bring in significant income. Malawi has a mainly agriculture-based economy and, as a result, the agro-processing potential is very high. Water pumping for irrigation and domestic use is important in the dry season, in particular in years when droughts occur. Maize is the staple crop in Malawi and all rural Malawians require milling services to process the maize they grow at home.

The Government considering a number of regulations and policies that will facilitate the development of more mini-grids across the country. The current regulatory framework requires mini-grid operators to comply with largely the same regulations as a large grid-connected development, which results in transaction costs that are often too high for small developers with a social objective. One area to have distinct regulations is **tariff setting**, i.e. the mini-grid regulations allow for cost-recovery by suppliers of electricity. This allows independent suppliers to charge higher prices than those paid by consumers of electricity from the national grid. This reflects the additional costs of mini-grid developments such as the need for construction of a distribution network and the high construction costs for schemes in remote areas.

The first private mini-grid that has pioneered this is the Mulanje Electricity Generation Agency (MEGA). MEGA has installed a 65-kW mini-hydro mini-grid in the Mulanje area serving Bondo village and is planning to install a second 80 kW plant. MEGA is a social enterprise and the first operational private energy company in Malawi. Its business model focuses on making energy available and affordable to its target market, promoting price minimisation, rather than 'traditional' profit maximisation, but within the parameters of building a financially sustainable business. MEGA is therefore applying tariffs that are above the (subsidised) tariffs that the national utility ESCOM would apply. For more on the MEGA business model and experience, the reader is referred to the Case Study *Mulanje: pioneering a social enterprise approach in clean energy mini-grid schemes.*

Comparison between MEGA and ESCOM pre-paid tariffs

	MEGA	ESCOM	
(tariff in MWK/kWh)	**Single phase**	**Single phase**	**Three phase**
Community institutions	32	38.56	59.57
Households	64	38.46	59.57
Commercial	106	66.21	79.45

Source: MEGA, ESCOM (2016-17 tariffs).
USD = MWK 720 (Apr-Oct 2017, www.oanda.com)
MEGA has now introduced a connection fee for their consumers. Each new household applicant is required to pay MWK 5,000 whereas each business applicant is required to pay MWK 6,500.

Information Sheet No. 5 shows simulation results of a hydro and PV-based mini-grid system based on data collected from real life examples in Malawi, including the technical design, capital structure, cost summaries, financial indicators and tariff design.

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