Technical Aspects of Mini-Grids for Rural Electrification

P. J. Boait

Abstract This chapter aims to provide an overview of the main technical options and decision points that arise when developing a plan for a rural mini-grid. It begins by considering the four potential sources of renewable energy—water, sun, wind and biomass. For each the relevant technologies and methods for quantifying the available resource are considered. Key options for the system architecture are then covered including the choice of AC or DC distribution, network topology, hybrid or single generator systems, and battery technology. Finally, the critical technical factors in system management are summarised.

1 Introduction

The challenge of avoiding catastrophic climate change has motivated governments in many countries to introduce policies aimed at incentivising a transition to low or zero carbon forms of electricity generation. This has stimulated investment in research and development of all forms of renewable generation, whether powered by water, wind, waves, sun or biomass. Because these resources are inherently distributed widely dependent on geography, and are available at every scale from watts to gigawatts, the technologies that have emerged are equally capable of operating at all scales. Increasing manufacturing volumes are also driving down costs making a wider range of technologies accessible to mini-grid designers and investors.

This chapter therefore aims to review the technical options for mini-grid system components and architectures including innovations that have reached, or are approaching, viability for deployment in rural areas of the developing world. This requires proven reliability and ease of installation and support, as well as acceptable

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cost. The discussion of generation options in the next section focuses on methods for assessing the available energy resource using elementary physics and mathematical methods that are amenable to spreadsheet programming. Often these methods are embedded in software tools such as HOMER (covered in "Analytical Frameworks and an IntegratedApproach for Mini-Grid-BasedElectrification"), but an understanding of the underlying physics provides insights into the limitations and data sensitivities of these tools. Later sections cover system architecture and management technologies.

2 Generation Technologies

2.1 Micro-Hydro

Most societies have exploited the power of running water as an energy source for centuries, so generation of electricity forms a natural successor technology to mechanical water mills. Hydro generation is by far the largest source of renewable electricity generation globally reflecting the number of large- and medium-scale plants that have been operating since the first half of the twentieth century. But there remains much potential—the World Small Hydropower Development Report published by UNIDO [1] indicates that in South Asia only 19 % of potential capacity is currently exploited (compared to 95 % in Northern Europe).

An illustration of the key components of a mini hydro scheme is shown in Fig. 1, from Practical Action [2], which also provides videos of a mini hydro in operation. A weir on the stream allows a controlled fraction of the flow to be diverted to the forebay where the water is slowed sufficiently for suspended material to settle. Floating debris is filtered out with a comb of bars (a trash rack) to prevent damage to the turbine. Screening measures to prevent fish entering the system may also be required. The potential energy of the water is converted into a combination of head pressure and kinetic energy in the penstock and delivered to the turbine and generator.

The instantaneous power P kW produced by an ideal hydro generator is given as

$$P = gHQ \tag{1}$$

where H is the head in metres, Q is the flow rate in m^3/s and g is the acceleration due to gravity (9.81 m^2/s). The head is the vertical height between the forebay and the turbine. In practice, P is significantly less due to losses in the flow path, turbine and generator. However, about 70 % is an achievable water-to-wire efficiency [3], so for assessing a potential resource Eq. (1) can be reduced to:

$$P = 7HQ \tag{2}$$

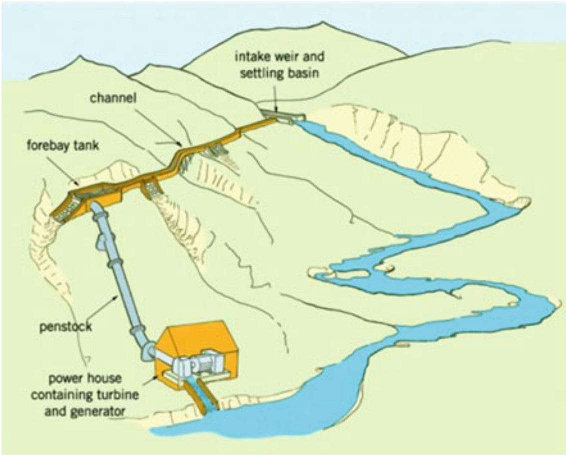


Fig. 1 Components of a mini hydro scheme [2]

The energy that can be produced then depends on the variation in the available flow rate over the year. A simple way of measuring the approximate flow rate is to set up a weir with a rectangular gap in it through which all the water must flow. The flow rate can then be estimated from the depth of water flowing through the gap. It is given as

$$Q = 1.8(w - 0.2d)d^{1.5} \tag{3}$$

where w is the width of the rectangular gap in the weir and d the depth of water, both in metres. If Q is surveyed over a year then this will provide the basis for several key decisions. The first is the proportion of the flow that can be diverted into the hydro system. This will depend on many factors such as the ecosystems to be maintained in the main stream, any local regulatory requirements and the variability of the flow. A typical judgment would be to set the flow rate that is exceeded for 85 % of the year as a minimum flow above which abstraction for hydro generation can take place.

Having determined the system flow rate over a year, the maximum power P_{max} (capacity) of the turbine and generator can be determined. Clearly there is a trade-off between the cost of a larger turbine and generator, and the proportion of the year for which its full capacity will be used. A useful benchmark is the annual mean flow $Q_{mean,}$ which is often a reasonable level to choose to set P_{max} using Eq. (2). For schemes with a head above 10 m, or high flow variability, it may be appropriate to set P_{max} for a flow up to 1.5 Q_{mean}. A factor in this decision will be the ability of the mini-grid consumers to make economic use of seasonal higher levels of power output. If peak river flows correspond with a crop processing task that can profitably use the power, then P_{max} can be chosen accordingly. The relationship between P_{max} and Q_{mean} determines the annual energy output E_a that can be obtained via the capacity factor C_f of the generator. This is a useful metric for all types of generator—it is given as

Table 1 Classification of turbine types

Turbine type	High head	Medium head	Low head
Impulse	Pelton, Turgo	Multi-jet Pelton, Turgo, Cross-flow	Cross-flow, undershot waterwheel
Reaction		Francis (spiral case)	Francis (open flume), propeller, Kaplan
Gravity			Overshot water-wheel, Archimedes screw

Source Compiled by the author

$$C_f = E_a/(8760\,P_{\max}) \tag{4}$$

An approximate value for C_f that can be expected if $P_{\max}$ is set from Q_{mean} is 0.4, so annual energy output will be about 3500 $P_{\max}$ kWh.

To capture the available energy resource as efficiently as possible, the type of turbine employed must be matched to the characteristics of the site. The dominant factor is the available head, which may be classified as high (>50 m), medium (10–50 m) or low (<10 m). The turbine types usable within these head ranges are shown in Table 1. Impulse turbines are driven by the kinetic energy of water jets and have the advantage of being compact and achieving a high rotation rate, which is desirable for efficient generation. Reaction turbines operate completely immersed like the propeller of a ship and can exploit the suction of water falling away from the turbine. Gravity turbines exploit the mass of water falling over the entire head. The choice of device for a given head is a complex trade-off between cost, efficiency at reduced rates of flow and the physical constraints of the site. Okot [4] provides a useful review of these issues, while Williamson et al. [5] examine the options for very low power (<5 kW) installations.

The use of an Archimedes screw for generation is a relatively recent innovation arising from improvements in the cost and efficiency of the gearbox needed to convert its slow rotation rate into a speed suitable for a generator. They are particularly attractive for micro hydro because of their ability to use a low head and tolerate debris and particulate matter in the water. The civil engineering requirements for installation are also relatively simple, and fish can usually pass through safely.

As an energy source for a mini-grid, a micro hydro system on a favourable site has the considerable advantage of producing electricity continuously all year round, though usually with variations in output. This eliminates or minimises the need for backup plant such as batteries and diesel generators. However, they do require sustained maintenance and supervision particularly of the screens and trash rack that filter the water entering the system. These can easily become blocked by seasonal debris and require regular manual clearance.

2.2 Solar Photovoltaic

The universal availability of solar energy makes this an attractive resource for a mini-grid, which may be in a remote location where there are few or no other options. Its seasonal and daily variations lead to the need for energy storage, usually batteries—the system design issues around battery sizing and configuration are covered in a later section. Here, we consider the assessment of the solar resource available at a given site and the technologies for photovoltaic (PV) generation.

The average energy flux S (i.e. power per unit area) reaching the top of the Earth's atmosphere from the sun is 1.367 kW/m^2. When it reaches the Earth this conveniently corresponds to about 1 kW/m^2, which is taken as the benchmark expected value for a clear day on a plane surface with the sun vertically overhead. To turn this figure into the energy resource available in a practical case is a complex trigonometric calculation. There are many free software tools available on the Web to perform this analysis such as the US National Renewable Energy Laboratory's PVWatts [6]. However, these tools do not necessarily have weather data available for a desired location, or contain oversimplifying approximations, or are unable to represent a particular PV system configuration. So this section summarises the calculation from first principles so that readers can cross-check tool outputs. For a comprehensive presentation of the mathematics Duffie and Beckmann [7] is recommended (Table 2).

The sun's angle of elevation α determines the clear sky energy flux on the ground plane—it is simply sin α kW/m^2. But because of the need to separate out beam (i.e. direct) radiation and radiation that is diffused by clouds, it is easier to start with the energy flux impinging on the top of the atmosphere that is directed at the point of interest—this is $S \sin \alpha$. The calculation proceeds by obtaining α for a given time of day, date and location and integrating the energy flux over a day to obtain the extra-terrestrial energy input. This input must be divided into beam and diffuse components at ground level depending on the sunshine hours in the day. Each component must also be modified to take account of the angle of the solar panels, and the sum of the two components provides the energy captured by the panels. From there the efficiency of the panels and subsequent power conversions can be used to find the energy that would actually be presented to a mini-grid.

The first step is to calculate the sun's declination δ for a given day n where $n = 1$ on 1st January:

$$\delta = 23.45 \sin\{360(284 + n)/365\} \tag{5}$$

Then $\sin \alpha$ can be found for a latitude ϕ and time of day ω:

$$\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \tag{6}$$

Table 2 Nomenclature for estimation of solar energy resource

Symbol	Represents
α	Solar elevation
β	PV panel angle of elevation to horizontal
δ	Solar declination
ϕ	Latitude of location for PV system
ω	Solar hour angle—noon is zero
ω_s	Solar hour angle of sunrise, sunset is $-\omega_s$
A	PV panel area m^2
B	Solar beam energy on unit horizontal area over given day and location
D	Solar diffuse energy on unit horizontal area over given day and location
e_m	PV module efficiency
e_p	PV output conditioning plant efficiency
G	Total solar energy on unit solar panel area over given day and location and panel angle of elevation
H_o	Extra-terrestrial energy directed at a unit horizontal area over a given day and location
K	Clearness index for day
n	Day number in year, n = 1 on 1st January
N	Number of integer hours of daylight for given day and location
r_b	Factor expressing the effect of panel angle β on incident beam radiation
r_d	Factor expressing the effect of panel angle β on incident diffuse radiation
s	Number of sunshine hours in the day
T_0	Reference temperature for PV panel performance, usually 25 °C
T_a	Average ambient temperature during daylight
t_{cp}	Coefficient of PV panel power variation with temperature
S	Solar radiation power constant 1.367 kW/m^2
w	Weighting factor when calculating daily average r_b

Sunrise ω_s and sunset ($-\omega_s$) times are also needed for daylight duration and are given as

$$\omega_s = \arccos(-\tan\phi\tan\delta) \tag{7}$$

H_o can now be found with adequate accuracy by summing the energy in each of the integer daylight hours (1:N hours):

$$H_0 = \sum_{i=1}^{i=N} S\sin\alpha_i \tag{8}$$

Suehrcke's method [8] as validated by Driesse and Thevenard [9] can be used to divide this energy into beam and diffuse components depending on the amount of cloud cover. This begins by calculating the clearness index K from sunshine hours data using the empirical relationship:

$$K = 0.65\sqrt{[3]}s/N \tag{9}$$

where s is the number of sunshine hours in the day and N the number of integer hours of daylight. If s is small giving a K value below 0.2, Eq. (9) is less accurate as shown by Driesse and Thevenard, so a better approximation is obtained setting $K = 0.2$. The beam and diffuse components B and D of the radiation at horizontal ground level are then found using two more empirical relationships:

$$B = 1.11 H_0 K^2 \tag{10}$$

$$D = H_0 K - B \tag{11}$$

The empirical constant 0.65 in Eq. (9) provides a good fit for a relatively cloudy climate similar to that of northern Europe. Increasing it to 0.75 provides a better result for consistently sunny climates.

In general the amount of solar energy collected over a year can be optimised with respect to the location, climate, battery capacity and service reliability by placing the panels at an angle to the horizontal. A common decision is to orient the panels for maximum output during the month containing the winter solstice. The modification factor r_b (an improvement for most of the day) on beam energy flux caused by positioning the PV panel south facing with an elevation angle β can be calculated as for a given date, location and time of day as

$$r_b = \frac{\cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)}{(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta)} \tag{12}$$

To obtain the effect of this modification on a day's energy collection an average value of r_b is taken, with the value for each hour weighted by the normalised fraction of H_o expected in the hour. Because of the ill-conditioned nature of (12) it is best to constrain the upper limit of daylight duration N to 12 h, i.e. 6 h either side of noon. The weighting factor w_i is given as

$$w_i = \sin\alpha_i / \sum_{j=1}^{j=N} \sin\alpha_j \tag{13}$$

Then

$$\overline{r_b} = \frac{1}{N}\sum_{i=1}^{i=N} r_{bi} w_i \tag{14}$$

The effect of the panel angle β is however to reduce diffuse energy flux by a factor r_d:

$$r_d = \frac{1}{2}(1 + \cos\beta) \tag{15}$$

The day's total solar energy incident on the panel G for unit area is thus equal to

$$G = \overline{r}_b B + r_d D \tag{16}$$

Table 3 Commercial photovoltaic technologies

Technology	Typical efficiency e_m (%)	Typical temperature coefficient of power t_{cp} (%)	Comments
Cadmium telluride thin film	11	−0.25	Good performance in hot climate
Copper-indium-gallium-selenide (CIGS) thin film	12	−0.45	Potentially low cost
Silicon amorphous	8	−0.2	Low cost per unit area
Silicon polycrystalline	14	−0.44	Widely used for small scale systems
Silicon monocrystalline	15	−0.5	Also widely used for small scale systems
Silicon heterojunction with intrinsic thin layer amorphous (HIT)	18	−0.3	Highest output per unit area

Source Compiled by the author

The conversion of this energy into useful electricity then depends on the PV module efficiency, the operating temperature and the efficiency of the electronic plant matching the PV output to the grid. Typically, this is a maximum power point tracker (for a DC grid) or an inverter (AC grid). The PV module efficiency e_m and temperature coefficient of power output t_{cp} are usually given on manufacturer's data sheets, while the plant efficiency e_p will be dependent on plant loading and so must be selected as a reasonable approximation off the manufacturer's efficiency curve. The electricity output E kW h for the day will then be given as

$$E = e_m e_p A G \{1 + (T_a - T_0) t_{cp}\} \tag{17}$$

where A is the panel area, T_a is the average ambient temperature during daylight, and T_o is the panel reference temperature (usually 25 °C). If temperature varies considerably during a day the average should be weighted similarly to that performed in Eqs. (13) and (14). By repeating this calculation over a year using local meteorological records providing sunshine hours and temperature an annual profile of the expected output can be obtained.

Table 3 provides a summary of the photovoltaic module technologies that are readily available commercially with typical efficiencies and temperature power coefficients with respect to a T_o of 25 °C.

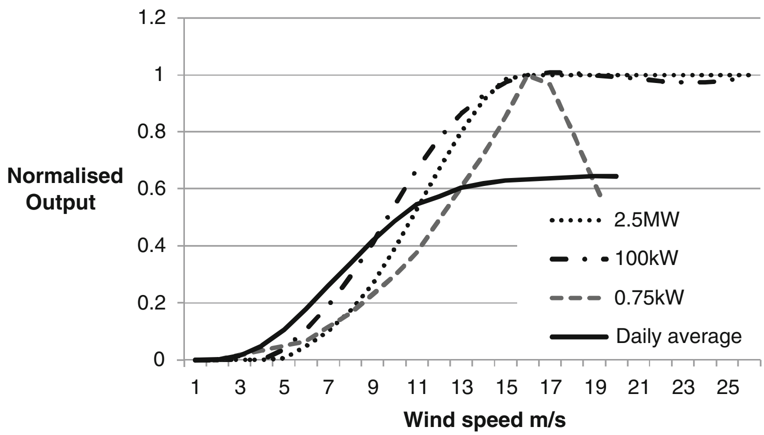


Fig. 2 Normalised wind turbine power curves

2.3 Wind

Like solar energy, some level of wind energy can be found everywhere and it has the merit of not being limited to daylight hours. However, the highly nonlinear relationship between wind speed and the energy that can be collected implies that coastal and hilly locations will always be preferred. Because wind generation is usually higher in winter or during a monsoon season, it can partly complement PV generation in a hybrid system so that the battery capacity required for a given level of reliability can be reduced.

The power P that can be generated by a wind turbine with swept area A in a wind speed v is given as

$$P = e_t \frac{1}{2} A \sigma v^3 \tag{18}$$

where e_t is the efficiency of the turbine, which has a theoretical limit of 0.59 [10] and σ is the density of air (about 1.2 kg per m^3). In practice, the efficiency of a wind turbine varies depending on the wind speed and the manufacturer's optimisation, and is typically between 0.35 and 0.5 including the conversion from mechanical to electrical energy. In Fig. 2 three manufacturer's power curves are shown for turbines with widely differing peak power ratings of 2.5 MW, 100 kW and 0.75 kW. The output is normalised with respect to the peak power to allow comparison. All exhibit to some extent the cubic relationship in Eq. (18). Output also flattens or falls away over 16 m/s for all three devices.

Meteorological records typically provide average wind speeds which do not directly provide a reliable indication of average power output because of this nonlinear relationship between wind speed and output. However, the statistical properties of wind can be used to estimate the expected output of a wind generator.

The Weibull distribution provides the most general model of wind speed variation (Justus et al. [11]), but when the Weibull shape factor (which controls the evolution of the distribution from an exponential form to a bell curve) is set to 2, it simplifies to a Rayleigh distribution. This shape factor is appropriate for a wind turbine that is employed for a rural mini-grid because it is intermediate between a mainly exponential function applicable to sheltered situations given by shape factor 1 and a bell curve distribution given by shape factor 3, which is more applicable to locations such as offshore with a sustained high average speed [12].

A Rayleigh distribution of wind speed v with mean μ is given as

$$f(v) = \frac{\pi v}{2\mu^2} e^{-\frac{\pi v^2}{4\mu^2}} \tag{19}$$

If this distribution of wind speeds during a day with average μ is applied to the appropriate manufacturer's power curve then the energy output for the day can be calculated. The 'Daily average' curve in Fig. 2 takes the power curve for the 2.5 MW turbine (chosen because its shape is intermediate between the other two) and plots the resulting average normalised daily power obtained by applying to it the Rayleigh distribution of wind speeds from a given daily average wind speed. It can be seen that the higher wind speeds that occur at low average wind speeds push up the energy output over the day, while at higher averages the capping of power at 16 m/s limits the daily energy output. Carillo et al. [13] provide a useful database of the key parameters for this calculation for a wide range of turbines. Noumi et al. [14] use this method to evaluate the annual output expected from a specific model of 1 kW wind generator (Unitron H80) at 19 locations in India with results ranging from 297 kWh at Malwan to 1769 kWh at Muppandal with an average of 839 kWh.

Depending on the size of the wind turbine envisaged for a given project, it may be desirable to adjust wind speeds from historic data, which are likely to be collected at about 10 m above ground level, to give wind speeds at the actual hub height (i.e., height of the centre of rotation of the turbine). Wind speed rises with height, following approximately a power law relationship:

$$\frac{v_h}{v_r} = \left(\frac{z_h}{z_r}\right)^{\alpha} \tag{20}$$

where z_r is the reference height at which data were collected, z_h is hub height, v_r is the observed wind speed and v_h is velocity at hub height. The exponent α is an empirical constant depending on the local topography and surface roughness from vegetation and dwellings. A value of 0.14 for α is often used and is suitable for a level open field. Because of the sensitivity of wind turbine output to wind speed, it is desirable to make the hub height as high as is reasonably practical.

Technological innovation in wind generator design has generally been concerned with refinement of methods for driving the generator from the turbine and within the generator itself. The horizontal axis turbine, with 2 or 3 blades, remains

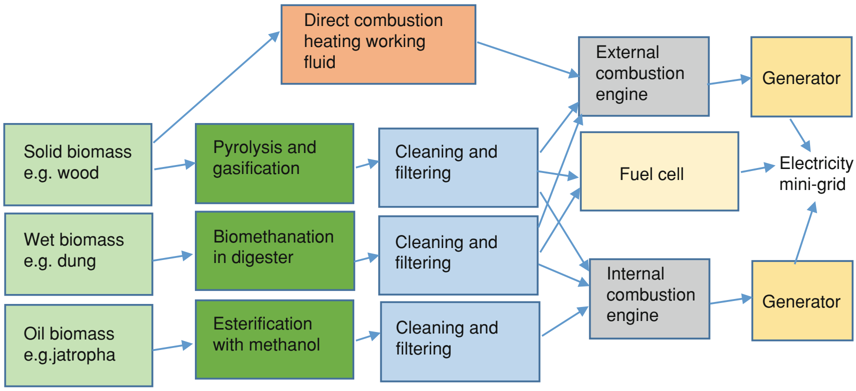


Fig. 3 Processes for conversion of biomass into electricity (*source* this study)

dominant. There are manufacturers producing other designs such as vertical-axis turbines, which allow the generator to be conveniently located at ground level, but the design trade-offs have not resulted in radical improvements. Kjellin et al. [15] provide a useful analysis of performance from a simple 12 kW H-rotor vertical axis wind turbine.

A potentially useful aspect of wind as a resource is that it is possible to build a wind generator from scrap materials. This usually relies on finding a suitable low speed permanent magnet motor that can be recycled, but given access to good quality magnets it is possible to wind alternator coils by hand and build the generator. There are many Internet sites giving details for this; a book reference is Bartmann and Fink [16].

2.4 Biomass

In this section, we consider all forms of biological energy resource, even though they may be liquid or gaseous at some or all stages of processing. This covers a wide range of potential sources and processes to arrive at generated electricity. The considerable potential for biomass generation is illustrated by the case study given in "Viability of Husk-Based Mini-Grids in South Asia" which describes the rice husk fuelled mini-grid systems deployed in South Asia. Figure 3 summarises the process options, which derive from the three main forms of biomass:

- Solid material, such as wood and crop residues, which can be subjected to direct combustion, or converted into a gas via a pyrolysis process.
- Wet material, such as food waste, animal dung and urine, which provides a good basis for anaerobic digestion to produce biomethane.

Table 4 Example data on energy content of biomass

Biomass type	Water content (%)	kW h/m^3	kW h/kg	Source
Jatropha oil	<5	9,460	11	(a)
Willow wood	12	3,816	4.4	(b)
Eucalyptus	15	Not given	4.3	(c)
Bamboo	11	1,062	4.2	(b)
Rice husks	10	729	4.2	(b)
Rice straw	11	448	3.7	(b)
Sewage sludge	57	319	1.2	(b)

Sources (a) Koh and Ghazi [38] (b) Chiang et al. [39] (c) Pérez et al. [40]

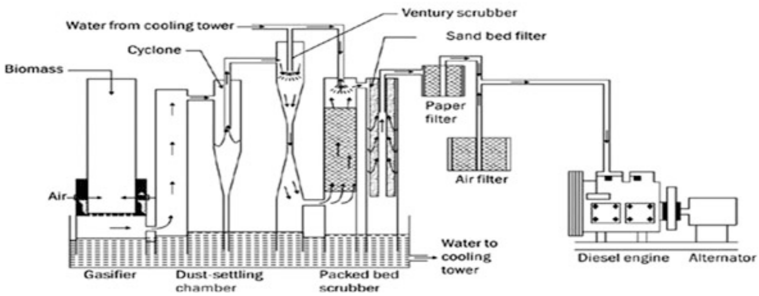


Fig. 4 Schematic of a gasifier system for power generation (*Source* www.teriin.org)

- Oils obtained from crops, such as rice bran and jatropha, by pressing. This is readily converted into an oil suitable for a diesel engine through a chemical process (transesterification).

The process steps to convert each of these biomass forms into a usable form of chemical energy are described in the next three sections, followed by consideration of the technologies required to transform that chemical energy into electricity. Table 4 provides example figures for the energy content of various forms of biomass. These are highly dependent on the particular plant varieties and handling methods assessed in the data sources indicated. The process efficiency then determines the proportion of the biomass energy content that can be converted into electricity.

2.4.1 Solid Biomass Processing

Where solid biomass will be used for direct combustion (e.g. in a log-fired boiler) processing need only consist of air drying to a suitably low moisture level (below 20 %) and cutting or pressing the material to the required size for the fuel feedstock. Otherwise, gasification by pyrolysis is the preferred process. Figure 4 illustrates the components of a mini-grid scale gasifier system.

This involves heating the biomass with a limited amount of air in a reactor vessel, which causes the volatile organic compounds to be driven off and a series of complex reactions to take place. The carbon content remains as char creating a reducing environment that converts water vapour to hydrogen and carbon dioxide to carbon monoxide. The resulting gas (known as producer gas or syngas), which also contains methane and other hydrocarbons, must then be cooled and cleaned to remove dust and heavier organic compounds that condense to form tar. This process has been employed for many decades to convert wood into a gas suitable for internal combustion engines, so it is a mature and low cost technology for which plant is available at scales from small gasifiers that can feed a tractor engine to industrial plant capable of generating several MW.

2.4.2 Wet Biomass Processing

This process employs a tank or chamber containing bacteria in a wet and warm environment from which air is excluded, hence the name anaerobic digestion. The feedstock comprises the biomass mixed with water to form a slurry with about 8–11 % of solid material by weight. This slurry is consumed in a batch process with each batch taking 40–100 days, at the end of which the spent slurry must be removed and can be used as a fertiliser. The breakdown of the chemical chains of the input biomass material to produce methane is complex, involving four different bacterial processes. Hydrolysis is the first stage, which breaks down the chemical bonds of fats, carbohydrates and proteins to form sugars, fatty acids and amino acids. Acidogenesis breaks down the products of hydrolysis, degrading them into carbon dioxide, hydrogen, alcohols and organic acids including acetic acid. Some of these products (e.g. acetate, hydrogen and carbon dioxide) can be directly used by the methane-producing bacteria in the fourth stage of anaerobic digestion (methanogenesis). Other products, such as some alcohols and organic acids, need to be degraded into acetates by acetate-forming bacteria (acetogenesis) before they can be used as a substrate for the methane-forming bacteria.

For sustained production of methane, the digestion vessel must be kept at a constant temperature between 32 and 45 °C and the slurry should be stirred so that all four bacterial processes take place simultaneously. The output gas typically contains about 50–65 % methane, 30–40 % carbon dioxide and a variable balance comprising water vapour, nitrogen, hydrogen and hydrogen sulpfhide. For use as a fuel the moisture content is reduced by condensing the water vapour, and the hydrogen sulphide is absorbed by chemical ‘scrubbing’.

2.4.3 Oil Biomass Processing

The first step for oil-bearing biomass is to mechanically press the material, with application of heat in some instances, to extract the oil. From then on the objective is to prepare the oil for use in a diesel engine. This requires the viscosity to be reduced so that it can be vaporised by the engine injectors and will ignite under compression. There are a variety of methods possible for achieving this, including blending with solvents and forms of pyrolysis, but the preferred method for producing a reliable fuel is transesterification. This is a chemical reaction, which typically employs methanol and sodium hydroxide as a catalyst to convert the input oil into a mixture of esters with the desired properties and glycerol as a by-product. The process is easy to operate on a small scale; detailed instructions for plant construction and operation are available on the Internet such as Addison [17]. A comprehensive review of transesterification process techniques and issues is provided by Demirbas [18].

2.4.4 Generation of Electricity from a Biofuel

To convert the chemical energy from a biomass-derived fuel into electricity, there are two routes. The first and potentially the simplest and most efficient is a fuel cell, which oxidises the fuel with oxygen from the air in a controlled catalytic process similar to a battery that generates electricity directly. In current practical and relatively low-cost implementations such as the BlueGen offered by Ceramic Fuel Cells [19], this operates with a gas fuel, such as hydrogen or methane, which could in principle be obtained from a biological source. However, there are two related issues, which make this technology unlikely to be viable for rural electrification in the immediate future. The first is the need for the fuel gas to achieve a high level of purity and stability in its chemical makeup so that the operating conditions and catalysts of the fuel cell can be chosen accordingly. The second is the long-term reliability of the catalysts, which has proved difficult to achieve even with gas with a tightly controlled specification from a main gas grid. But given the high energy conversion efficiency of fuel cells (about 60 %) and because hydrogen fuel cells are seen as a possible approach to de-carbonisation of transport (in effect replacing diesel and petrol engines) a considerable research and development effort is in progress, which in time should deliver devices with the required durability and low cost. Biomethane from anaerobic digestion is the most suitable biomass-based feedstock for a fuel cell because of its relative purity. NREL [20] provides a good summary of the state of the art in biogas-powered fuel cell systems including descriptions of demonstration plant.

The commonplace alternative to the fuel cell is some form of thermodynamic heat engine, which uses heat from combustion of the fuel to create mechanical motion that can drive a generator. A primary choice with respect to the heat engine is between internal and external combustion. An internal combustion engine is just a conventional gas or diesel engine. These are available often with integrated generator for a wide range of capacities and fuels. The constraint they apply is that the quality of the fuel must be reasonably well controlled to ensure reliable operation. Even then, they tend to require quite a lot of maintenance but at least the required skills are widely available.

External combustion has the big advantage that the fuel can take any form and its chemical composition will not be critical, so extensive preprocessing such as gasification is not essential. Mechanical reliability is also considerably improved because the internal components of the engine do not suffer from the corrosive effect of combustion by-products. Historically, the most common form of external combustion engine has been the steam engine. These were often used to drive mechanical agricultural processes, such as sugar cane crushing or palm oil milling. The waste biomass from the process (bagasse or nut shells) provided fuel for the boiler and the exhaust steam from the engine could be used for process heat. Because steam engines have largely been abandoned in the developed world their merit for rural development has possibly been overlooked. Sookkumnerd et al. [21] found steam engines a valid solution for electricity generation in Thailand from rice husks, while Teixera et al. [22] evaluated a range of engine options for electricity generation from biomass in the Amazon region, and found a steam-driven option the most cost-effective. Small steam engines complete with generator sets are still manufactured, for example in India, by Aadhunik Global Energy [23]. For electricity generation, the disadvantage of solid-fuelled small-scale steam power is the relatively low efficiency, possibly in the range 10–20 %, and the manual labour associated with stoking the boiler, which will be difficult to sustain continuously. These issues are a trade-off from the simplicity of fuel preparation.

Other forms of external combustion engine are organic Rankine and Stirling cycle devices. A Rankine engine is similar to a steam engine in principle, but uses a volatile organic compound as the working fluid in a similar way to refrigeration plant. The Stirling engine operates with a stable and sealed volume of gas such as nitrogen as the working fluid. Advantages of both are being able to operate with a low temperature differential and without the high pressure boiler needed for steam, which can be hazardous. Corria et al. [24] examine the merits of a Stirling engine for rural electricity generation in Brazil. From a purely technical perspective, these external combustion technologies are more suitable than internal combustion engines as prime movers driving generation for a remote rural mini-grid because of the simplicity and reliability of the complete process chain. But because they are not manufactured on the same scale as internal combustion engines their cost tends to be higher.

3 System Architecture and Performance

In this section, we consider the main system design issues and decisions that arise once the energy resources to be exploited have been determined. These may be summarised as:

- The selection of direct current (DC) or alternating current (AC) for distribution, the operating voltage and the voltage tolerance at supply points.

- The central system architecture that can deliver the planned service capacity, availability and reliability. This defines the requirements for hybrid generator configurations and batteries.
- Distribution network cable sizing and topology.
- Technical options around balance-of-plant items, such as maximum power point trackers and inverters.

3.1 Selecting DC or AC Distribution

This choice may be simple if the primary source of electricity is predetermined to be a conventional diesel generating set equipped with an AC generator. If this is not the case, then DC operation should be considered first to see if the constraints it imposes are acceptable. The reason for evaluating DC distribution first is the proliferation of electricity-consuming devices and appliances that are designed to operate on DC and require an internal or external power conversion module to use AC. The shift to DC within appliances is not confined to light-emitting diode (LED) lighting and electronic devices such as computers and peripherals. It is also taking place wherever electric motors are required because DC operation allows precise control over motor speed and torque resulting in energy savings and improved reliability. Converting AC to DC has both an initial and continuing cost—Garbesi et al. [25] estimate that eliminating these conversions reduces energy consumption by about 14 %.

There is therefore an emerging initiative in developed countries to migrate electricity distribution in homes and offices to DC. At the time of publication this is still at the stage of pilot and demonstration projects. However, standards are being drafted, published and implemented, in particular, by the Emerge Alliance [26]. It seems likely that the 24 and 380 V standards promoted by this body will be widely adopted, initially by warehouses, supermarkets and data centres where the savings are most significant. The 24 V standard will also be taken up in homes and small offices where eliminating the clutter of ‘black plug’ power converters will be attractive alongside the energy and cost savings. Once large-scale adoption occurs, then lower level components, such as connectors and circuit breakers, will be manufactured in the volumes needed to be competitive with AC components.

For a mini-grid that is primarily powered by PV or wind energy there is the additional advantage in DC distribution of eliminating the cost and losses of AC inverters. The present critical limitations of DC distribution are:

- Operation at 24 V limits the area covered by the mini-grid before voltage losses, or the cost of suitably low resistance cable, becomes unacceptable. However, the availability of useful light from a 3 W LED lamp combined with a 2 W mobile phone charger allows a household to benefit from service as low as 5 W. Table 5 shows the possible distribution cable distance for different service loads

Table 5 Distribution cable length for 1 V drop on a 24 V DC system

Total consumer load (W)	Length (m) 1 mm^2 cable	Length (m) 1.5 mm^2 cable	Length (m) 2.5 mm^2 cable	Length (m) 4 mm^2 cable
5	109	166	267	436
10	55	83	133	218
15	36	55	89	145
20	27	41	67	109

Source Author

Table 6 Distribution cable length for 10 V drop on a 230 V AC system

Total consumer load (W)	Length (m) 1 mm^2 cable	Length (m) 1.5 mm^2 cable	Length (m) 2.5 mm^2 cable	Length (m) 4 mm^2 cable
10	5227	7931	12,778	20,909
20	2614	3966	6389	10,455
50	1045	1586	2556	4182
100	523	793	1278	2091
500	105	159	256	418

Source Author

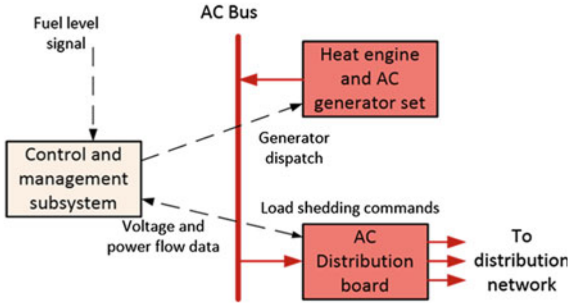
and cable conductor sizes, assuming an acceptable voltage drop of 1 V, which corresponds to distribution losses of about 4 %.

- Some types of electrical plant important to a rural mini-grid, for example, refrigeration appliances and small industrial equipment, such as grinders and mills, are currently more expensive or not readily available in DC-powered form.

Once the components and operational safety practices associated with 380 V DC distribution become well known it will be possible to overcome the distance limitation. DC plant, and the cost savings associated with it, will also become accessible to rural mini-grid projects as developed world migration to DC proceeds. But Table 5 (based on IET Wiring Regulations) [27] shows that 24 V operation does permit safe distribution for a compact village if household provision is mainly lighting; and higher power requirements, such as computers, televisions and agricultural process plant, are co-located with the generator and balance of plant such as batteries.

If a DC system cannot provide the coverage or choice of load devices needed, then a 220–240 V AC system is the logical alternative. The exact operating voltage will depend on the plant chosen and any national regulations for the location. Table 6 provides distribution of cable lengths for a 10 V drop on a 230 V system, against the higher consumer loads likely to be offered. For a system with industrial plant in the kW region and generation of 20 kW and above, a three-phase AC system will be preferred. This extends possible distribution distances

Fig. 5 Simple central system with heat engine and AC generator



further but requires greater attention to safety because of the 400 V interphase voltage.

For other voltages and consumer loads, a useful formula for the length l m of cable that will cause a 1 V drop is

$$l = 22.7AV/W \tag{21}$$

where A is the conductor area in mm^2, V is the distribution voltage and W is the consumer load in Watts. This is an approximate equation for high quality copper cable and assumes 2-wire distribution with a margin of about 30 % to allow for cable heating. Longer lengths may be achievable in cool climates with overhead cable distribution.

3.2 Central System Architecture

A mini-grid central system can be as simple as a diesel generator set supplying a distribution network via a distribution board that provides current limiting for safety on the various network feeder lines and central voltage and current metering for system management purposes. This is a practical option where fuel can be stored to buffer variations in the supply chain allowing the generator to be dispatched on a schedule or operated continuously. It also applies for mini-hydro systems where the water flow is reliable or there is an upstream reservoir that can be used to regulate the availability of the water resource. But where the energy resource is uncontrollably variable or intermittent, more complex configurations are needed to ensure a supply commitment can be given to the electricity consumers.

Figure 5 shows a simple central system as used, for example, by the rice husk-fuelled systems described in "Viability of Husk-Based Mini-Grids in South Asia". Some form of control and management subsystem is needed even at this level to avoid the need for continuous operator attention and to collect data allowing performance to be monitored. This could comprise just a time clock scheduling the dispatch of the generator with an interlock ensuring enough fuel is available. The

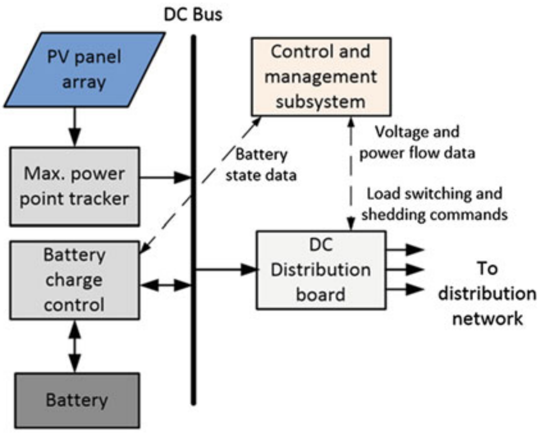


Fig. 6 Central system architecture for PV generator with DC distribution

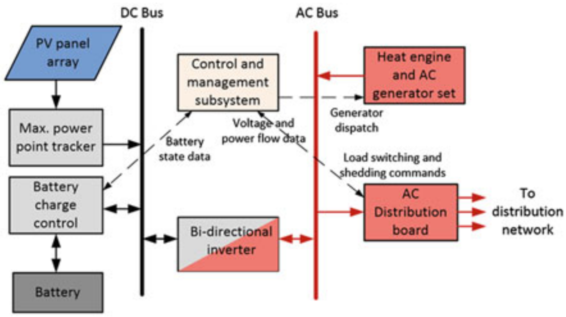


Fig. 7 Central architecture for a dual bus hybrid system

data collected could be simply fuel consumed, voltage levels and metered energy outgoing to the network. Fuel consumption data will allow the efficiency of the heat engine to be monitored, while aggregate output metering in addition to household level metering will allow electricity theft to be detected. There should preferably also be some ability for the control subsystem to respond automatically to overload conditions by shedding load at the distribution board in a predetermined priority order.

The simplest possible central system for a mini-grid with PV generation and DC distribution is shown in Fig. 6. Key additional components are the maximum power point tracker (MPPT) and battery with charge controller. The MPPT has the function of adjusting the load seen by the PV panel so that the voltage and current it produces are optimised and the collected power flow is converted to the DC bus voltage, which will be set by the state of charge of the battery. The role of the control subsystem is similar to that in Fig. 5, but because battery capacity will be the dominant constraint on the service that can be provided, the construction of an operating schedule by which different segments of the distribution network are energised at certain times becomes critical. The management subsystem should ideally provide software tools to assist this task. The issues and techniques around

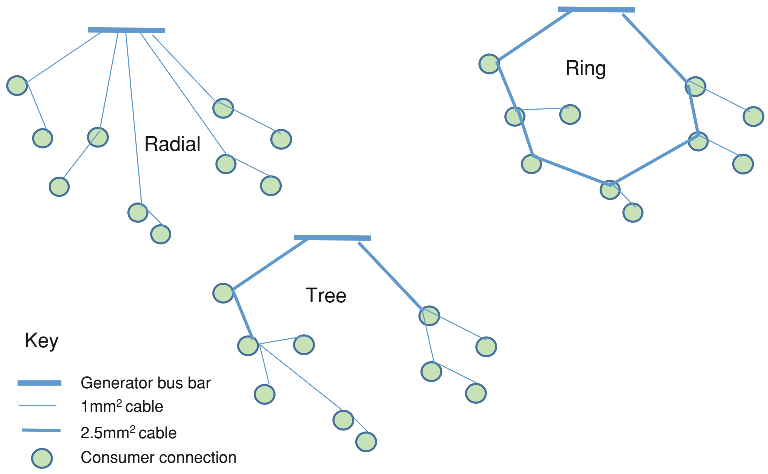


Fig. 8 Mini-grid distribution network topologies

matching supply and demand for a mini-grid are considered in "Demand Management for Off-Grid Electricity Networks".

An illustrative architecture for a dual-bus system designed to provide a 24-h AC electricity supply is shown in Fig. 7. To achieve this level of service without an extremely costly amount of battery capacity, a fuel powered electricity generator, such as a diesel generator set or a fuel cell, is needed. Such systems are usually referred to as hybrid. The bi-directional inverter is able to convert DC from the PV panels and/or battery to AC to supply the loads and can also accept any surplus AC generator capacity to recharge the battery. The control subsystem ensures the generator is dispatched whenever it predicts that the battery charge will not sustain the service until PV production resumes, or when PV production is inadequate. These dispatch decisions must take account of the need to operate the generator over a sufficient period and with a sufficient load so that its reliability is not compromised. In a suitable location, PV hybrid systems of this type are capable of scaling-up to meet the needs of a small town—Léna [28] provides a good review of the scaling trade-offs.

There are many possible variations on the dual-bus architecture of Fig. 7. A common simplification for small systems is to omit the fuel-powered generator and supply AC power from the inverter alone. Where fuel supplies are ample, it is possible to build a system with multiple generators that can be dispatched according to the level of demand, and reduce the battery capacity to the minimum level required for bridging between PV and generator operation. If the location has a useful wind resource, then combining wind generation and PV can work well as a hybrid system since wind speeds are often higher in winter months when PV output is low.

3.3 Network Topology

In general, it is always possible to connect the consumers of a mini-grid to the central plant using different network topologies. Figure 8 illustrates radial, tree and ring options for a simple case of a 24 V system with 5 W loads in each dwelling (a total of 10 dwellings) and a maximum cable distance of 55 m to the most remote dwelling. In many cases, the options are restricted by the geography of the settlement or location allowing a selection from the remaining alternatives by inspection, taking account of factors such as the need to separate out loads of different priority on different feeders to facilitate load shedding. It is also important where three-phase AC distribution is adopted to design the network so that the load is balanced across the three phases. In some situations a ring solution is preferred because the available capacity at any point on the ring is doubled potentially giving scope for expansion, while reliability of service is enhanced because a single break in the ring will not deprive any consumer of supply. Sebitosi et al. [29] show that in the absence of other constraints a tree structure is most efficient for an even distribution of consumers and provide a simple design method.

For larger networks with hundreds or thousands of consumers, it may be preferable to use more automated methods to find a preferred topology that minimises cable cost, constrains voltage drop and satisfies other requirements that arise. This is a classic problem for which a range of discrete optimisation techniques as applied to graphs can be employed. Genetic algorithms are probably the most suitable for mini-grid topology optimisation because they generate a range of promising solutions from which the best can be chosen taking account of human factors that are not easily encoded in a fitness function. Coley [30] and Silva et al. [31] describe how to apply genetic optimisation methods to this type of problem. Genetic algorithm add-on programmes are available for established mathematical software, such as Matlab and Excel.

3.4 Batteries

A battery will be required in every mini-grid, if only for starting an engine driving the generator. The sizing of its capacity will depend on the system architecture and reliability as discussed in Sect. 3.2. Here we consider the performance options arising from the battery chemistry. Lead-acid batteries are the established technology, but for mini-grid use they must withstand regular deep discharge cycles to 80 % of capacity. The sealed valve regulated type (VRLA) can provide this, with wet, gel and AGM (absorbed glass matt) variations in the medium holding the electrolyte. Gel types generally have the best performance with charge efficiency (i.e. discharge energy as a proportion of charge) of 90–95 % and a life of up to 1,200 deep discharge cycles for individual 2 V cells with tubular construction.

Flat plate batteries similar to those for automotive use have a shorter life of around 500 cycles. Hence, these batteries receive less preference in mini-grid applications.

In wider applications where weight and energy density are critical factors, batteries based on lithium-ion chemistry have emerged as the preferred solution. These are not important for mini-grid applications, but the lifetime and deep discharge tolerance of lithium batteries have also benefited from the extensive research and manufacturing volume now deployed for this technology. Krieger et al. [32] performed a thorough comparative evaluation of four different battery types when charged by a wind turbine. This is a challenging test because of the bursty nature of wind generation. The battery types are flat plate lead-acid (VRLA), lithium cobalt oxide (LCO), LCO-lithium nickel manganese composite (LCO-NMC), and lithium iron phosphate (LFP). Lithium iron phosphate is clearly the most durable technology to the extent that the authors believe it is a cost-effective alternative to VRLA even though the cost per Ampere-hour is about 4 times higher. This is justified because the LFP battery can be taken close to complete discharge, whereas the VRLA would normally be sized for 50 % discharge in normal operation. The LFP will also last more than twice as long at 2,000 discharge cycles. If costs of shipment, maintenance and recycling are taken into account, LFP is clearly the preferred technology if the capital cost can be supported.

4 System Management

The management challenge for an operational mini-grid of matching demand to available electricity supply has already been mentioned. "Demand Management for Off-Grid Electricity Networks" examines this issue in detail and reviews the technologies and devices that may be installed at the consumer's connection point to manage demand. In this section, we briefly consider the information systems that may be deployed to assist operators. These are generally closely tied to payment mechanisms, which are not covered here. However, two technical factors have a strong influence on practical options. The first is the availability of mobile phone coverage at the mini-grid location. This allows data collection and control to be performed remotely. Bit-harvester [33] uses text messaging for this purpose, while Gram Power [34] provide a smart meter and switch that is enabled via the mobile phone network, and used for load prioritisation and monitoring as well as revenue collection.[1] The ability to supervise a mini-grid remotely allows more complex solutions in all aspects of mini-grid design than is possible for systems that have to be totally self-sufficient.

The second key technical factor is whether a mini-grid is power or energy limited. Biomass-fuelled or mini hydro systems are typically power limited in that

[1] These examples are given for illustration purposes only. This is not, in any way, an endorsement of these products.

the maximum generator power provides the dominant limit on demand. Where PV or wind generation is the main resource, battery energy capacity becomes the critical limit on demand as the instantaneous power available from batteries and inverters will be higher than the level that can be sustained. For power limited systems, careful consideration has to be given to the population of electricity-consuming appliances that are likely to be connected and active at any given time. To manage the service, the types of load operating at different times of day need to be categorised and prioritised, so the information system needed to support these decisions must capture data on the loads in use and their timing.

For energy-limited systems, the constraint that must be applied to consumers is a daily energy budget. This limit will vary from day to day and seasonally because of the weather dependence of PV or wind generation. The technology for equitable allocation of variable energy budgets is still emerging at the time of writing. Devices such as the Urja Bandu (CAT [35]) and the Dispensador [36] can enforce a daily energy budget for each consumer and provide feedback on its status. The information system then needed for management must be able to monitor and predict the state of battery charge and facilitate decisions on energy budget allocation by the operator.

5 Conclusions

With the levelised cost of PV-generated electricity at or near ‘grid parity’ in many locations including India [37] it is likely that innovation in mini-grid technology will be more rapid for system components that make use of the solar energy resource. Combined with the evolution to highly efficient DC-powered lighting, entertainment and information systems this should enable PV powered systems, augmented where necessary with biomass-fuelled generators, to have enough capacity to support small-scale industrial and commercial uses of electricity. Development of information systems that are easy to operate and allow flexible allocation of daily energy budgets would complete the portfolio of technology needed to bring electricity to every rural area.

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