COURSE HANDBOOK

MINI-GRID DESIGN

Focus on Solar Photovoltaic and Micro Hydro

European Union

german cooperation
DEUTSCHE ZUSAMMENARBEIT

USAID
FROM THE AMERICAN PEOPLE

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Mini-Grid Design

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1. RENEWABLE ENERGY OVERVIEW

About this module

To be able to effectively employ renewable energy to tackle rural electrification, it is essential to understand and appreciate the global outlook of energy sources with particular focus on renewable energy.

Learning outcomes

At the end of this module, the participant is able to

- Understand the global challenge with respect to fossil fuel reserves and climate change
- Appreciate the challenges facing electricity supply and distribution in Nigeria
- Outline and give a brief description of different renewable energy (RE) technologies
- Have a broad appreciation of potential applications of RE technologies
- Gain an appreciation of issues and barriers with respect to achieving universal energy access in rural areas

1.1. GLOBAL ENERGY RESOURCES

CLASSES OF ENERGY

Energy is one of the major inputs and drivers of the economic development of any country. In developing countries, the energy sector assumes a critical importance in terms of ever-increasing energy needs and the huge investments they require. Global energy consumption is increasing at an annual rate of 1.5% while available resources remain limited. Fossil fuels, particularly crude oil, are currently the primary energy source that fuels our planet, accounting for some 80% of global energy consumption. Energy consumption has a significant impact on our natural environment. There is clear evidence that climate change is caused by human activity mostly related to the use of energy, above all fossil fuels.

Energy that we use can be classified into several types based on the following criteria:

- Primary and secondary energy
- Renewable and non-renewable energy
- Commercial and non-commercial energy

» Primary and secondary energy

Primary energy refers to all types of energy extracted or captured directly from natural resources. Primary energy can be further divided into two distinctive groups:

- Non-renewable (fossil fuels, e.g. coal, crude oil and its products, natural gas; nuclear, etc.)
- Renewable (solar, wind, geothermal, tidal, biomass, hydro, etc.)

The energy content of all fossil fuels is expressed by the unit "tonne of oil equivalent" (toe), i.e. the energy released by burning one tonne of crude oil, which is based on the following conversion factor:

1 tonne of oil equivalent (toe) = 10 x 10^6 kCal = 11,630 kWh = 41,870 MJ

Primary energy sources are converted in industrial utilities into secondary energy sources; coal, crude oil or natural gas, for example, can be converted into steam and electricity. Primary energy can also be used directly. Some energy sources have non-energy uses, such as the use of coal or natural gas as a feedstock in fertiliser plants. Thus, primary energy is converted into more useful forms of energy such as electricity, steam, transportation fuels, etc. These output forms are called secondary energy. The figure below illustrates the relationship between primary and secondary energy sources.

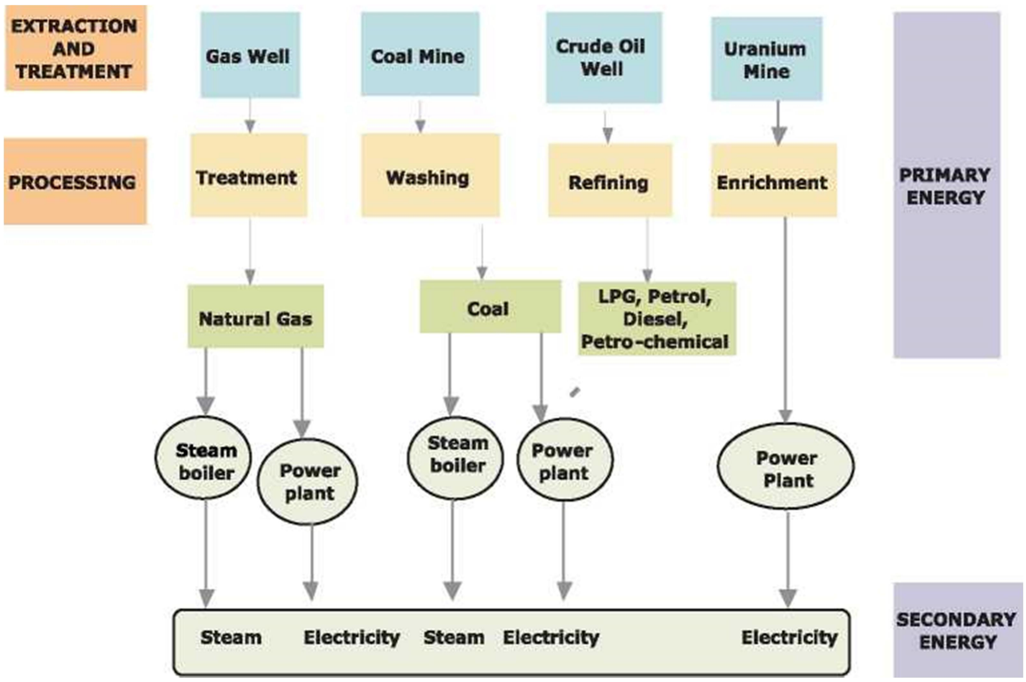


Figure 1.1: Relationship between primary and secondary energy

» ***Commercial and non-commercial energy***

Commercial energy is energy available in the market for a defined price irrespective of the method of production. All forms of energy that are traded as commodities, whether from fossil fuels, nuclear or renewable sources, can be classified as commercial energy.

By far, the most popular forms of commercial energy are electricity, coal, refined petroleum products and natural gas. Commercial energy forms the basis of all industrial, agricultural, transport and commercial development in the modern world. In industrialised countries, commercial fuels are the predominant sources of energy not only for industrial use, but also for many household needs. Examples include electricity, lignite, coal, natural gas, etc.

On the other hand, energy which is sourced within a community and its surrounding areas, and which is not traded in the commercial market is termed non-commercial energy. Non-commercial energy sources include fuels such as cattle dung and agricultural (green) wastes, which are traditionally gathered and used mostly in rural households. These are also called traditional fuels. Non-commercial energy is often ignored in compiling a country's energy statistics. Examples include firewood and agro-waste in rural areas, solar energy for water heating, animal power for transport, pumping water for tasks such as irrigation and crushing sugarcane, wind energy for pumping water and electricity generation.

» ***Non-renewable and renewable energy***

Renewable energy is the energy obtained from natural sources which are essentially inexhaustible and are replenished on a human timescale. Examples of renewable resources include wind, solar, geothermal, tidal and hydroelectric power (see Figure 1.2). The most important feature of renewable energy in terms of its consequences is that it can be harnessed without the release of harmful pollutants.

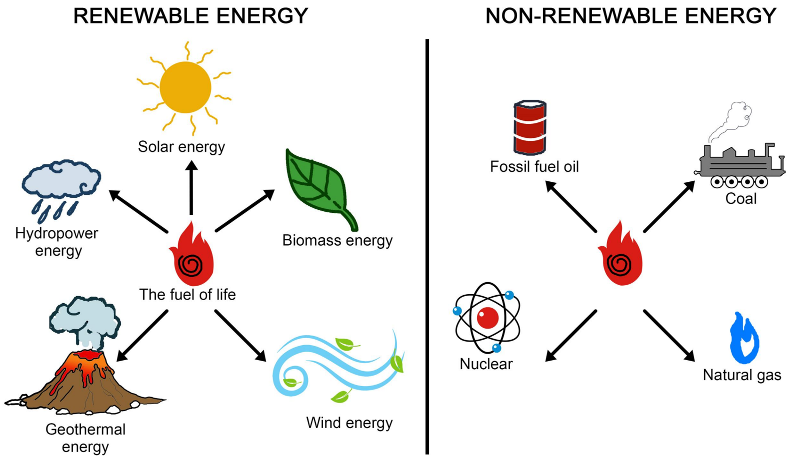


Figure 1.2: Various sources of energy. Renewable energy (left) Conventional (right)

Non-renewable energy resources are naturally occurring resources that cannot be produced, grown, replenished or used on a scale which can sustain their consumption rate. These resources often exist in a finite amount or are consumed much faster than nature can create them. Natural resources such as coal, crude oil and natural gas take millions of years to form naturally and cannot be replaced as quickly as they are being consumed at present. These resources will be depleted with time.

ENERGY AND THE ENVIRONMENT

» *Global warming and climatic change impact*

Increasing carbon emissions from human activities and a reduction in the ability of the natural environment to absorb carbon dioxide result in an accumulation of greenhouse gases (GHG) in the upper atmosphere, which has led to a phenomenon called climate change. These GHGs trap more and more heat in the upper atmosphere, ultimately leading to increased atmospheric temperatures worldwide. Global warming produces the following effects:

- ***Increasing ocean temperatures and rising sea levels:*** During the twentieth century, data show that the average sea level increased by about 20 centimetres. The largest contribution to this rise is from the thermal expansion of ocean water as the ocean's warmer water expands and the sea level rises. Coastal flooding will increasingly occur with rising sea levels. In low-lying countries like Bangladesh, where poverty and overcrowding are common, people may be forced from their homes. Even developed countries such as the Netherlands may lose land. Since one half of the world's population currently lives near the coastal zones, human vulnerability to rising sea levels is very high.
- ***Melting snow and ice:*** Ice is already melting worldwide, especially at the Earth's poles, which contain mountain glaciers, ice sheets covering West Antarctica and Greenland, and Arctic sea ice. Melting snow and ice will contribute to rising global sea levels and also disturb the ocean ecosystem. Fresh water from melting ice caps will most likely desalinate the oceans and throw ecosystems out of balance. Ocean

currents, which regulate the temperatures, would then be disturbed. Furthermore, white ice caps have a cooling effect, as they reflect heat back into space. With their loss comes a further warming of the Earth. In other areas, as glaciers continue to shrink, summer water flows will drop sharply, disrupting an important source of water for irrigation and power in many locations that rely on mountain watersheds. Monitoring of Himalayan glaciers indicates that the recession of glaciers has occurred in some regions, though not consistently across the entire mountain chain.

- ***Altered rainfall patterns:*** Rainfall patterns would be altered, with some areas getting more rainfall and others suffering more droughts. On warmer days, more water evaporates from the soil and trees into the air leading to more clouds and rainfall. However, water can also evaporate from dry soils, depriving them of already limited moisture.
- ***Extreme weather events:*** Cyclones, storms, hurricanes are already occurring more frequently, and floods and draughts are more intense than before. This increase in extreme weather events is not considered to be random.
- ***More severe heat waves*****:** Heat waves and periods of unusually warm weather are already happening and are expected to increase with global warming. Presently, many cities in India are experiencing increasing heat waves due to global warming. Temperatures that would be considered normal in hotter climates can be termed a heat wave in a cooler location whenever they fall outside the normal pattern for that area. Severe heat waves have caused catastrophic crop failures, thousands of deaths from heat stroke and widespread power blackouts due to the increased use of air conditioners.
- ***Loss of biodiversity:*** Ecosystems will change – some species will move farther North and successfully migrate; others that cannot move will face extinction. Most of the world's endangered species may become extinct over the next few decades as warmer conditions alter the forests, wetlands and rangelands on which they depend, with human development preventing them from migrating elsewhere. The oceans, which are a source of great biodiversity, would also be affected. For example the coral reefs, which have a limited tolerance for warm waters, would be severely affected.
- ***Increased diseases:*** Infectious diseases currently restricted to existing hot regions may move into the newly warming regions. Malaria is one such disease, spread by mosquito vectors, infecting and killing millions each year in warm climates. With rising temperatures in currently temperate regions, mosquitoes and other insects are expected to move in, while in regions where they are already present, the transmission windows for disease could expand. In addition, indigenous disease organisms that were previously killed by winter cold will be better able to survive milder winters.
- ***Dwindling freshwater supply*****:** A higher sea level also means salty water can infiltrate fresh groundwater in coastal areas, thus reducing the freshwater supply and rendering it undrinkable. This is a major concern, since billions of people on Earth already lack access to fresh water. Higher ocean levels already are contaminating underground water sources in many parts of the world. Climate change is projected to decrease water availability in many arid and semi-arid regions. One third of the world's population is now subject to water scarcity.
- ***Food shortages:*** Food production will need to double to meet the needs of an additional three billion people in the next 30 years. Water resources will be affected as

precipitation and evaporation patterns change around the world. This will affect agricultural output. Climate change is projected to decrease potential crop yields in the tropics and sub-tropics for almost any amount of warming. Food security is likely to be threatened and some regions are likely to experience food shortages and hunger.

» *Impact of coal mining*

Coal mining, the first step in the dirty life cycle of coal, causes deforestation in open cast mines and releases toxic minerals and heavy metals into the soil and water. The effects of coal mining persist for years after coal is removed.

METHODS OF MINING

Poor mining practices can result in methane accumulation and fire outbreaks at a coal mine. These fires can burn for decades, spewing fly ash and smoke laden with greenhouse gases as well as numerous chemicals. Mining releases methane gas, which is 30 times more potent as a greenhouse gas than carbon dioxide. Coal dust inhalation causes black lung disease among miners and those who live nearby, and mine accidents kill thousands every year. Coal mining also displaces whole communities, forced off their land by expanding mines, coal fires, subsidence and contaminated water supplies. The two most widely used mining techniques today are open cast or strip mining and underground mining.

Open cast mining **-** also known as strip, mountain-top or surface mining, this mining technique involves scraping away earth and rocks to get to coal buried near the surface. In many cases, mountains are literally blasted apart to reach thin coal seams within and permanent scars are left on the landscape as a result. Strip mines account for 40% of coal mining activities worldwide and even 80% in countries that are heavily dependent on coal exports, such as Australia. Even though it is highly destructive, the industry often prefers strip mining as it requires less labour and yields more coal than underground mining. Impacts of strip mining include:

- Destruction of landscapes, forests and wildlife habitats at the site of the mine when trees, plants and topsoil are cleared from the mining area.
- Removal of vegetation also leads to soil erosion and destruction of agricultural land.
- When rain washes the loosened topsoil into streams, sediments pollute waterways. This can hurt fish and smother plant life downstream, and cause disfiguration of river channels and streams, which leads to flooding.
- Increased risk of chemical contamination of groundwater sources, due to seepage of minerals and chemicals into the water table
- Noise and dust pollution

Although many countries require reclamation plans for coal mining sites (i.e. undoing all the environmental damage to water supplies, habitats and air quality), reclamation is a long and problematic task, which is also capital intensive.

Underground mining **-** although strip mining is more frequent, the majority of the world's coal is obtained through underground mines. While underground mining, which allows coal companies to extract deeper deposits of coal, is viewed as less destructive than open cast mining, it still causes widespread environmental damage. For instance, in room-and-pillar mines, columns of coal are left to support the ground above during the initial mining process, then they are often taken out and the mine is left to collapse, which is known as subsidence. Impacts of underground mining include:

- Huge amounts of waste earth and rock to be brought to the surface – waste that often becomes toxic when it comes into contact with air and water.
- Subsidence as mines collapse and the overlying land starts to sink. This causes serious damage to buildings.
- Lowering of the water table, changing the flow of groundwater and streams
- Release of greenhouse gases

OTHER IMPACTS

Coal mine methane - coal mine methane, which is released during the coal mining process, is less prevalent in the atmosphere than CO_2 but 30 times as potent as a greenhouse gas. Most coal mine methane comes from underground mines. While this methane is often captured and used as a town gas, industrial fuel, vehicle fuel and chemical feedstock, it is rarely consumed in its entirety.

Coal fires - coal fires are often caused by using improper mining techniques. When they occur underground, these fires can burn for centuries, filling the atmosphere with smoke laden with carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), sulphur dioxide (SO_2), nitrous oxides (NO_x) and other greenhouse or toxic gases.

Acid mine drainage - when water mixes with coal or other rocks unearthed during mining, it could become toxic. This toxic water could seep through the soil structure to contaminate groundwater, streams, earth, plants, animals and humans. Sources of acid mine drainage can remain active for decades or centuries after a mine closes.

» Crude oil and natural gas mining

Petroleum or crude oil may exist as a combination of liquid, gaseous, sticky, and tar-like substances. Crude oil and natural gas are cleaner fuels than coal, but they still have many environmental disadvantages.

Crude oil deposits are usually small pockets of liquid or gas trapped within rock layers deep underground (often under the sea floor). Extracted crude oil is refined and used to manufacture gasoline (for transportation) and petrochemicals (for the production of plastics, pharmaceuticals and cleaning products).

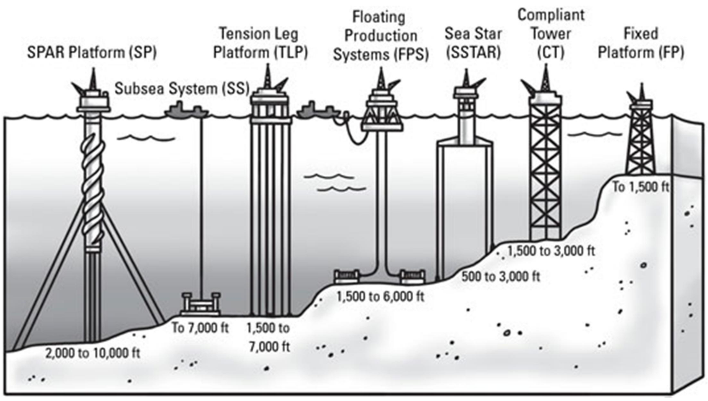


Figure 1.3: Commonly used oil mining platforms – *Courtesy: Illustration by Lisa Reed in Environmental Science for Dummies*

Extraction companies pump liquid oil out of the ground by using drilling rigs and wells that access the oil pockets. The oil fills the rock layers the way water fills a sponge – spreading throughout open spaces – instead of existing as a giant pool of liquid. This arrangement means that to pump out all the oil, drillers have to extend or relocate the wells after the immediate area has been emptied. Oil drilling rigs set on platforms in the ocean to access oil reserves below the sea floor must therefore employ a series of more technically complex drill rigs built to access oil reserves in deeper water. The figure below illustrates some of the most commonly used ocean drilling rigs and platforms as well as the water depths for which they are best suited.

FRACKING

The demand for natural gas has increased in the last few decades as concerns about carbon emissions and global warming have grown. The push for cleaner fuels as well as energy independence from traditional exporters has led the oil industry to explore the extraction of natural gas locked in reservoirs separate from petroleum as a source of clean fuel. The method by which this gas is released and captured is termed hydraulic fracturing, or fracking. Fracking for natural gas requires injecting a liquid mix of chemicals, sand, and water into the gas-bearing rock at extremely high pressures – high enough to crack open the rock and release trapped gases. The gas is then pumped out of the rock along with the contaminated water.

IMPACT OF CRUDE OIL AND NATURAL GAS MINING

Oil is a cleaner fuel than coal, but it still has many disadvantages, such as the following:

- **Air pollution:** Refining petroleum creates air pollution. When crude oil is transformed into petrochemicals, toxins which are detrimental to human health and the ecosystem are released into the atmosphere.
- **Toxicity:** Crude oil is a mixture of many different kinds of organic compounds, several of which are highly toxic and cancer causing (carcinogenic). Crude oil, when released into the atmosphere (air, land or sea), increases toxicity due to the presence of harmful substances. Burning gasoline releases CO_2. Although crude oil does not produce the same amount of CO_2 as coal burning, it still produces greenhouse gases and increases global warming.
- **Incomplete combustion:** When oil or petroleum distillates are burned, the combustion does not usually run its full course. This means that in addition to water and carbon dioxide, the combustion process generates incompletely burned compounds. These additional compounds are often toxic to life. Examples include carbon monoxide and methanol. Also, fine particulates of soot blacken the lungs of humans and animals and can cause heart problems or even death.
- **Acid rain:** High temperatures created by the combustion of petroleum cause nitrogen gas in the surrounding air to oxidise into nitrous oxides. Nitrous oxides, along with sulphur dioxide from the sulphur in the oil, combine with water in the atmosphere to create acid rain. Acid rain causes many problems such as dead trees and acidified lakes with dead fish. Acid precipitation caused by acid rain is also killing coral reefs in the world's oceans on a large scale.
- **Oil spills and environmental damage:** The term oil spill refers to the release of a liquid petroleum hydrocarbon into the environment, especially marine areas, due to human activity, and is a form of pollution. The term is usually applied to marine oil spills, where oil is released into the ocean or coastal waters, but spills may also occur on land. Oil spills may be due to the release of crude oil from tankers, pipelines, railcars, offshore platforms, drilling rigs and wells, as well as the spill of refined petroleum products and their by-products, heavier fuels used by large ships such as bunker fuel, or the discharge of any oily refuse or waste oil. Major oil spills in recent history include the Kuwaiti oil fires and lakes, the Lakeview Gusher, the Gulf War oil spill and the Deepwater Horizon oil spill. Although large oil spills with catastrophic envi-

ronmental effects such as the 1989 Exxon Valdez in Alaska or the 2010 BP Deepwater Horizon in the Gulf of Mexico have received significant media coverage, most of the oil spilled into ecosystem actually leaks from cars, airplanes, and boats or is caused by illegal dumping. In Nigeria, oil spills have diminished fish and bird populations, poisoned local vegetation and contaminated natural water sources. Spills may take weeks, months or even years to clean up.

» *Global primary energy reserves and commercial energy production*

Figure 1.4: Some effects of oil spills: Bird unable to fly (left), degraded environment (centre), local farmer covered in crude oil (right)

CRUDE OIL

The global proven oil reserve (of conventional crude oil) was estimated to be 1.5 trillion barrels[1] by the end of 2015. Almost 60% of the world's proven oil reserves are in the Middle East. Saudi Arabia has the largest share of the reserve with about 21%. Saudi Arabia is the largest oil producer in the world (as of 2012). With almost one-fifth of the world's proven oil reserves, some of the lowest production costs, and an aggressive energy sector investment initiative, Saudi Arabia is likely to remain the world's largest net oil exporter for decades to come. Russia is another major world oil producer, sometimes surpassing even Saudi production. Although the United States ranks third in terms of oil production, it only ranks eleventh in terms of proven oil reserves. Figure 1.4 provides an overview of the top oil producing countries in 2012. If production continues at today's rate, in less than 20 years many of the current top ranking producers such as Russia, Mexico, US, Norway, China and Brazil will have their oil fields largely depleted, and as a result, will have a much smaller share in the oil market. At that point in time, the world will have to depend mostly on the Middle East for crude oil.

Apart from the conventional oil reserves quantified above, another 800 to 900 billion barrels of unconventional oil reserves comprised of oil sands (or tar sands) and heavy oil are located in Canada and Venezuela.

Although crude oil still dominates the energy mix, environmental concerns related to global warming and air pollution have increased the need for a switch to cleaner energy sources like natural gas, nuclear, solar and wind power.

COAL

Coal is the most abundant and geographically widespread fossil fuel and exists as peat, brown coal (lignite), sub-bituminous, bituminous and anthracite coal.

[1] www.opec.org/opec_web/en/data_graphs/330.htm

It is estimated that there are over 826 billion tonnes of proven coal reserves worldwide. Around half of the world's proven reserves are bituminous and anthracite coal, the latter being the grade of coal with the highest energy content. There is enough coal to last around 122 years at current rates of production.

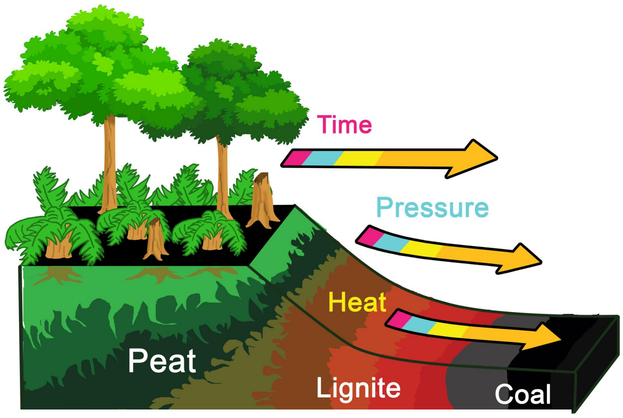


Figure 1.5: Formation of coal

NATURAL GAS

Natural gas is a gaseous fossil fuel consisting primarily of methane but also small quantities of ethane, propane, butane and pentane. Before natural gas can be used as a fuel, it undergoes extensive processing to remove almost all constituents except methane. It is the third most heavily consumed form of primary energy worldwide after crude oil and coal. Over the past three decades, natural gas has been seen as an alternative to the dirty crude oils and coal used in most countries.

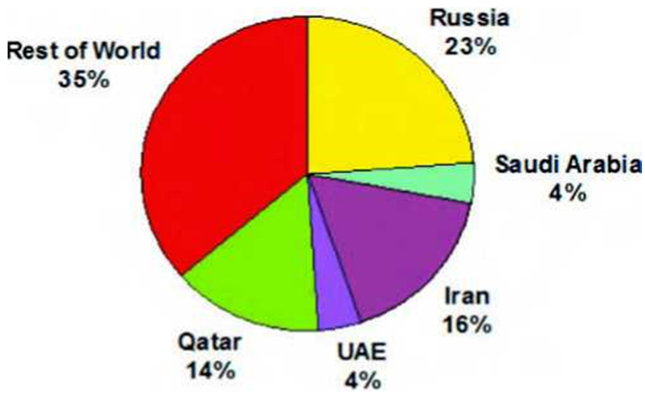


Figure 1.6: Global distribution of proven natural gas reserves

Natural gas resources are large, but, like oil, they are highly concentrated in a few countries and fields. The global proven gas reserve was estimated at 185 trillion cubic metres in late 2008. At current production levels, this reserve will be available for around 60 more years. The US is the world's largest natural gas consumer with a share of 22%, followed by Russia with 14%. Other top gas consuming countries include Iran, Canada, UK, Germany, Japan, and Saudi Arabia. Gas is used extensively for power generation, transportation and heating buildings in most countries.

1.2. RENEWABLE ENERGY RESOURCES AND ENERGY EFFICIENCY

By 1873, concerns of running out of coal prompted experiments using solar energy with the development of solar engines, which ceased at the outbreak of World War I. The importance of solar energy was recognised in a 1911 Scientific American article: "in the far distant future, natural fuels having been exhausted, [solar power] will remain as the only means of existence of the human race".

In the 1970s environmentalists promoted the development of renewable energy for two main reasons: firstly as an alternate source of energy for the eventual depletion of crude oil and secondly for an independence from crude oil, which was mostly found in regions prone to political instability. These concerns caused a political push in Western countries to develop mature technologies to harness the energy stored in sunlight, wind, water and geothermal sources.

Economic trends - renewable energy technologies are becoming more affordable thanks to technological advancements and the benefits of mass production and market competition. A 2011 report by the International Energy Agency (IEA) states: "A portfolio of renewable energy technologies is becoming cost-competitive in an increasingly broad range of circumstances, in some cases providing investment opportunities without the need for specific economic support", and adds that "cost reductions in critical technologies, such as wind and solar, are set to continue".

Hydropower and geothermal energy produced at favourable sites are now the cheapest methods of generating electricity. Renewable energy costs continue to drop, and the levellised cost of energy (LCoE) is declining for wind power, solar photovoltaic (PV), concentrated solar power (CSP) and some biomass technologies.

The levellised cost of energy indicates the minimum price at which electricity generated by a specific source must be sold to break even over the lifetime of the generating source. This is usually represented in unit currency per unit of electricity (e.g. NGN/kWh, USD/kWh). It gives a quick economic assessment of the total cost of an electricity generating system, which includes all capital and operational costs over the system lifetime. It is calculated using the formula below.

$$\mathrm{LCoE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Carbon-neutral and carbon-negative fuels: Carbon-neutral fuels are synthetic fuels (including methane, gasoline, diesel fuel, jet fuel or ammonia) produced by

- Hydrogenation of waste carbon dioxide recycled from power plant flue-gas emissions
- Recovery of automotive exhaust gas
- Extraction and subsequent processing of carbonic acid from seawater

Fuels retrieved using these methods are considered carbon-neutral because they do not result in a net increase in atmospheric greenhouse gases.

Renewable energy and energy efficiency are the backbone of sustainable energy policy and are high priorities in the sustainable energy hierarchy. Renewable energy is the energy obtained from sources that are essentially inexhaustible. Renewable energy systems convert the energy found in sunlight, wind, falling water, ocean waves, geothermal heat, or biomass into a useable form of heat or electricity. Another important feature of renewable energy is that it can be used without the release of harmful pollutants.

Energy efficiency refers to the utilisation of energy in the most cost-effective manner to carry out a manufacturing process or provide a service, whereby energy waste is minimised and the overall consumption of primary energy resources is reduced.

RENEWABLE ENERGY

» Solar energy

Solar energy, defined as radiant light and heat from the Sun, is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaics, concentrated solar power and solar architecture. In nature, solar energy is harnessed by plants through photosynthesis.

Solar technologies are broadly characterised as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Passive solar techniques include orienting a building at an advantageous angle to the Sun, selecting materials with favourable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air. Active solar technologies can be divided into solar thermal energy, which uses solar collectors for heating, and solar power, which involves converting sunlight into electricity either directly using photovoltaics (PV) or indirectly using concentrated solar power (CSP).

A photovoltaic system converts light into electrical direct current (DC) by taking advantage of the photovoltaic effect. Concentrated solar power systems combine lenses or mirrors with tracking systems to focus a large area of sunlight into a small beam. Commercial concentrated solar power plants were first developed in the 1980s.

» Hydropower

Energy in water can be harnessed and used. Since water is about 800 times denser than air, even a slow-flowing stream or a moderate sea swell can yield considerable amounts of energy. There are many classifications for hydropower, which can be based on dam/weir size, flow rate, power output, etc.

Table 1.1: Classification of small hydropower schemes

Family	*Type*	*Power output*	*Connection*
Large hydropower	Large	>10 MW	Grid connection
Small hydropower	Small	<10 MW	Grid connection
	Mini	<1 MW	Possible grid connection
	Micro	<200 kW	Partial grid connection
	Pico	<10 kW	Island grids

Small hydropower schemes (SHP) typically require less time and effort than large hydropower plants in terms of their construction and integration into local environments. For this reason, the deployment of SHPs is increasing in many parts of the world, especially in remote areas where other energy sources are not viable or are not economically attractive.

» Wind power

Wind power refers to energy extracted from an air flow using wind turbines or sails to produce mechanical or electrical power. Historically, humans have harnessed wind power for activities such as milling grain (windmills), pumping water and propelling ships with sails.

» Biomass and biofuels

Biomass is biological material derived from living or recently deceased organisms. It most often refers to plants or plant-derived materials. As an energy source, biomass can either be used directly via combustion to produce heat or indirectly after converting it to various forms of biofuel. Conversion of biomass to biofuel can be achieved by different methods which are broadly classified as thermal, chemical, and biochemical.

Biofuels include a wide range of fuels derived from biomass. The term covers solid biofuels, liquid biofuels and gaseous biofuels. Liquid biofuels include bio-alcohols, such as bioethanol, and oils, such as biodiesel. Gaseous biofuels include biogas, landfill gas and synthetic gas. Biodiesel uses primary materials such as vegetable oils, animal fats or recycled greases. Biodiesel can be used as a fuel for vehicles in its pure form but it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide and hydrocarbons from diesel-powered vehicles.

» *Geothermal energy*

Geothermal energy is from thermal energy generated and stored in the Earth. Geothermal energy originates from the original formation of the planet (20%) and from the radioactive decay of minerals (80%). The geothermal gradient, which is the temperature difference between the planet's core and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface.

At the core, temperatures may reach over 5,000°C. Heat conducts from the core to surrounding rock. Extremely high pressures and temperatures cause the partial melting of rock, commonly known as magma. Magma convects upward since it is lighter than the solid rock. This magma then heats rock and water in the crust, sometimes up to 371°C.

ENERGY EFFICIENCY

Energy efficiency is defined as the ratio of energy output to input. For instance, the energy efficiency of an electric motor is the ratio of mechanical output (that is, the work done using the motor) to the electrical input commonly expressed as a percentage. This approach can be used widely for various types of equipment such as motors, pumps, compressors, furnaces and boilers.

The technical definition provided above is seldom used to analyse energy efficiency. In many real situations, energy efficiency is most often expressed as a surrogate, the ratio of energy input to the output from a specific activity.

Efficient energy use, sometimes simply called energy efficiency, reduces the amount of energy required to provide products and services. Improvements in energy efficiency are generally achieved by adopting a more efficient technology or production process or by applying commonly accepted methods to reduce energy loss. Some of the reasons for adopting energy efficiency measures include reduction in energy costs thereby improving profits, corporate social responsibility and reduction in global levels of CO_2 and other GHG emissions.

» *Energy efficiency in industry*

Industrial plants require large amounts of energy to power various manufacturing and resource extraction processes. Most industrial processes require heat and mechanical power, which is primarily delivered as natural gas, petroleum fuels and electricity. In addition, some industries generate fuel from waste products that can be used to provide additional energy.

Due to the wide variety of industrial processes, it is impossible to describe all possible opportunities for energy efficiency in industry. These options depend on the specific technologies and processes in use at each industrial facility. There are, however, a number of processes and energy services that are widely used across many industries. For example, various industries generate steam and electricity for subsequent use within their facilities. When electricity is generated, the heat that is produced as a by-product can be captured and used for process steam, heating or other industrial purposes. Conventional electricity generation has an efficiency of about 30%, whereas combined heat and power (also called co-generation) converts up to 90% of the fuel into usable energy.

» *Energy efficiency in buildings*

A building's location and surroundings play a key role in regulating its temperature and illumination. For example, trees, landscaping and hills can provide shade and block wind. In cooler climates, designing Northern Hemisphere buildings with south-facing windows and Southern Hemisphere buildings with north-facing windows increases the amount of sunlight (ultimately heat energy) entering the building, thus minimising energy use by maximising passive solar heating.

Figure 1.7: The Empire State Building is the tallest and largest LEED certified building in the western hemisphere

A deep energy retrofit is a whole-building analysis and construction process that is employed to achieve much larger energy savings than conventional energy retrofits. Deep energy retrofits can be applied to both residential and non-residential ("commercial") buildings. A deep energy retrofit typically results in energy savings of 30% or more, perhaps spread over several years, and may significantly improve the building's value. The Empire State Building underwent a deep energy retrofit process that was completed in 2013. The applied retrofits led to a 38% (USD 4.4 million) reduction in annual energy use. The Empire State Building is the tallest Leadership in Energy and Environmental Design (LEED) certified building in the United States. It received a gold rating from the organisation in September 2011.

» *Energy efficiency for appliances*

Modern appliances, such as freezers, ovens, stoves, dishwashers, clothes washers and dryers, use significantly less energy than older appliances. Current energy-efficient refrigerators, for example, use 40% less energy than conventional models did in 2001. Modern power management systems also reduce energy usage by idle appliances by turning them off or putting them into a low-energy mode after a certain time. The impact of energy efficiency on peak demand depends on when the appliance is used. For example, an air conditioner uses more energy during high-temperature afternoon hours. Therefore, an energy-efficient air conditioner will have a larger impact on peak demand than off-peak demand. An energy-efficient dishwasher, on the other hand, uses more energy during the late evening when people run the machine after dinner. This appliance may have little to no impact on peak demand. To facilitate comparison, many countries require manufacturers of electronic appliances to identify the energy consumption of the products on their packaging. An example of one such label is shown below.

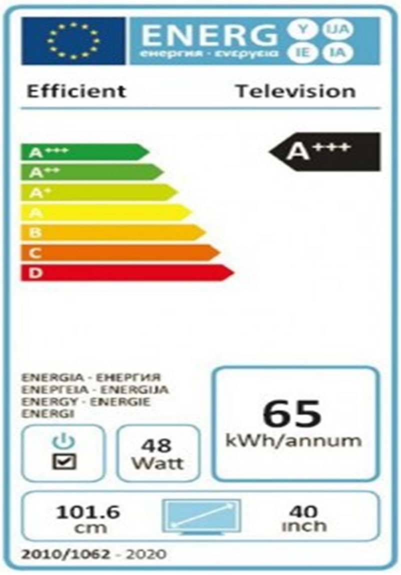


Figure 1.8: EU energy label for a 40-inch television

» *Energy efficiency in transport*

There are several ways to enhance a vehicle's energy efficiency. Engines and transmission components provide the largest scope for improvements. Other factors such as improved aerodynamics also matter as they minimise drag to improve fuel efficiency. Vehicle weight reduction can also improve fuel economy, which is why composite materials are increasingly used in car bodies. Another way to enhance efficiency is through the use of alternative fuels. Non-conventional or advanced fuels are any suitable fuel materials or substances other than conventional fuels. Some well-known alternative fuels include biodiesel, bio-alcohol (methanol, ethanol, butanol), chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, etc. The mainstream trend in automotive efficiency is the rise of electric vehicles (all electric or hybrid electric).

1.3. RENEWABLE ENERGY IN NIGERIA

Basic human needs such as cooked food, comfortable room temperature, adequate lighting, the use of appliances, necessary health care (refrigerated vaccines), educational utilities, agricultural and trading activities, transport services, etc. rely largely on energy. Therefore, sustainable access to clean energy is essential for achieving socio-economic advancement and poverty eradication. Renewable energy has the potential to create jobs, improve livelihoods and open up the market in rural areas.

SOURCES OF RENEWABLE ENERGY IN NIGERIA

Renewable energy resources – especially solar energy, biomass, small and large hydropower – are present in varying amounts in different parts of Nigeria. The Federal Government of Nigeria envisions and promotes the initiative on rural electrification through renewable energy sources most notably through its "Operation Light-Up Rural Nigeria", which targets rural communities not connected to the national grid.

» *Solar*

Nigeria's location between the latitudes of 3°N and 14°N ensures that it receives an average of 2,100 kWh/m^2 of global horizontal irradiation annually. If harnessed using solar PV, only 1% of Nigeria's land area could theoretically produce 207,000 GWh of electricity. This is equal to ten times the current electricity production (national grid) in Nigeria[1]. However, the potential for concentrated solar electricity is limited to the northernmost region of the country due to its semi-arid climate.

In light of this potential, various solar photovoltaic projects are being planned, ranging from kilowatt-scale mini-grids to multi-megawatt utility-scale plants. For example in July 2016, power purchase agreements (PPAs) worth USD 2.5 billion were signed by Nigerian Bulk Electricity Trader (NBET) with 14 firms[2].

» *Wind*

At present, wind energy makes up a minor share of national energy consumption, with no commercial wind power plants connected to the national grid as of 2015. The only notable wind energy project under construction is the 10 MW wind farm situated in Katina state.

[1] Nigerian Energy Sector Study, GIZ-NESP, 2015
[2] www.vanguardngr.com/2016/07/solar-power-devt-investors-commit-2-5bn-14-projects/

» ***Hydro***

Nigerian's hydropower potential is high and hydropower currently accounts for about 32% of the total installed electric power generation capacity. It is estimated that the large and small hydro reserves are 11,500 MW and 3,500 MW, respectively. Nigeria's installed hydro-electric power generation stands at 1.9 GW, distributed across three plants, namely, Shiroro at 600 MW, Kainji at 760 MW and Jebba at 500 MW.

» ***Biomass energy***

While there is a huge potential (estimated 11 million hectares of forest, 28.2 million hectares of arable land and 112 million farm animals) for biomass-based energy production in Nigeria, this resource remains largely untapped. Biomass sources such as municipal solid waste generated by households and areas of concentrated population, as well as agricultural waste which is very common in the form of rotting farm produce, have not been harnessed even though there are several proofs of concept and academic papers stating the viability of biomass energy as a fuel source for large power plants.

1.4. ENERGY ACCESS AND POVERTY ALLEVIATION

DEFINITION

The term "energy poverty" refers to the lack of affordable and reliable access to modern energy services. Very low energy consumption, use of dirty or polluting fuels, and excessive time spent collecting fuel to meet basic needs affects the overall well-being of individuals and populations. While it is inversely related to access to modern energy services, improving access is only one factor in efforts to reduce energy poverty. Energy poverty is distinct from fuel poverty, which focuses solely on the issue of affordability.

According to the Energy Poverty Action (EPA) initiative of the World Economic Forum, "Access to energy is fundamental to improving quality of life and is a key imperative for economic development. In the developing world, energy poverty is still rife. Nearly 1.6 billion people still have no access to electricity."[1]

» ***Domestic energy poverty***

Domestic energy poverty refers to a situation where a household does not have access or cannot afford to have the basic energy or energy services to meet day-to-day living requirements. Requirements change from country to country and region to region. The most common energy needs are lighting, cooking and ventilation or cooling. In most countries, a household is said to be in energy poverty if it does not receive a minimum of 1 unit of electricity (kWh) per day.

Until recently, energy poverty definitions took only the minimum required energy quantity into consideration when defining energy poverty, but a different school of thought is that not only energy quantity but also the quality and cleanliness of the energy used should be taken into consideration when defining energy poverty. Practical Action, an international NGO with a focus on technology use to combat poverty in developing countries has laid out the following definition:

"A person is in 'energy poverty' if they do not have access to at least:

[1] EPA brochure

- The equivalent of 35 kg liquefied petroleum gas (LPG) for cooking per capita per year from liquid and/or gas fuels or from improved supply of solid fuel sources and improved (efficient and clean) cook stoves
- 120 kWh electricity per capita per year for lighting, access to most basic services (drinking water, communication, improved health services, improved education services and others) plus some added value to local production.

An "improved energy source" for cooking must meet three conditions. First, it must require less than four hours per person, per week and per household to collect fuel. Second, it must meet the recommendations of the World Health Organization (WHO) for air quality (maximum CO concentration of 30 mg/m^3 for exposure periods of up to 24 hours and less than 10 mg/m^3 for exposure periods of up to 8 hours). Third, it must demonstrate an overall conversion efficiency greater than 25%.

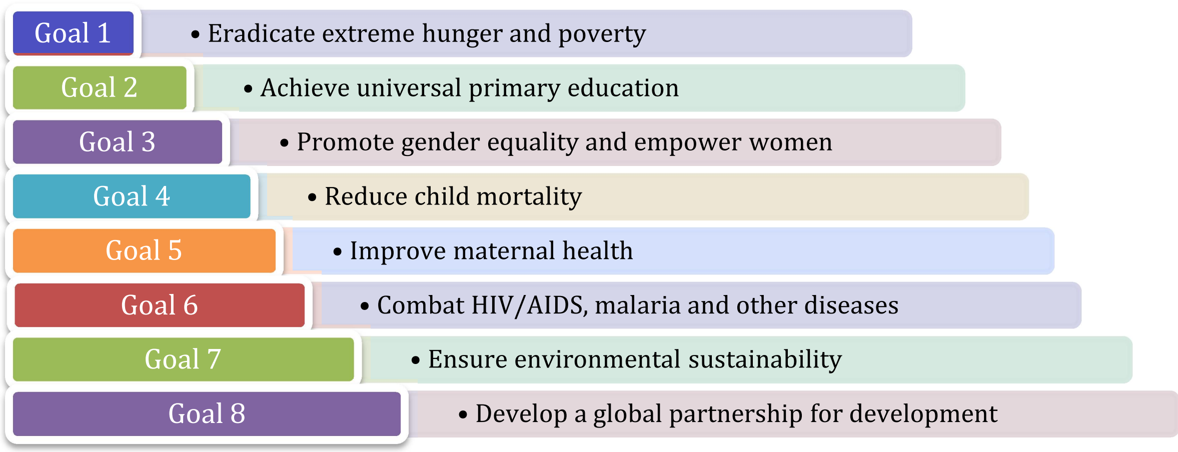
THE MILLENNIUM DEVELOPMENT GOALS (MDGS)

» *Overview*

The Millennium Development Goals (MDGs) were commonly described as a roadmap for world development by 2015. They symbolised the core content of the development agenda of "global governance" and international development cooperation.

In recognition of the central role of energy for the MDGs, the United Nations Development Programme (UNDP) concluded that energy is the fundamental prerequisite for achieving the MDGs and that access to energy, especially in the form of clean and affordable electricity, can help achieve substantial social and economic development.

With the yearly issue of the Millennium Development Goals Report tracked by the UNDP, the process of planning, implementing and monitoring the MDGs in a holistic manner has brought together a host of international organisations, financial institutions, bilateral agencies, non-governmental organisations (NGOs), civil leaders, pressure groups, private individuals and sovereign national governments. The MDGs seek to attain the following objectives:



There are several challenges to realising the benefits of the MDGs:

- Lack of reliable and consistent baseline data, inadequate data collection systems and improper analysis
- Lack of strategic and sustainable planning (in part due to inadequate data)

- Poor access to private, safe and clean toilets, thus leading to more infections and illnesses
- Poor access to and high cost of health facilities, particularly primary health care
- Huge funding gaps, failure and inability of some states to contribute counterpart funds to the Universal Basic Education (UBE) programme
- Human capacity challenges, inadequate human capacity at all levels (federal and state ministries, departments, agencies and local governments), as well as a lack of discipline in implementing programmes, resulting in poor project execution
- Weak governance
- Security and human right challenges
- Prevalence of sexual and gender-based violence against women and girls
- Accountability environment and poor coordination between tiers of government
- Socio-cultural practices such as early marriage, which most often deters girls from completing their education

SUSTAINABLE DEVELOPMENT GOALS (SDGs)

The Millennium Development Goals (MDGs) lapsed in 2015 and were replaced by the Sustainable Development Goals (SDGs). The SDGs are essentially 17 goals with 169 targets ratified by 193 countries in an attempt to kindle action in areas of critical importance to humanity.

The agenda of the SDGs, though ambitious, is expected to shape development efforts for the next 15 years. Coming at a time in human history where we have never been as challenged by issues such as migration, conflict, famine, droughts and climate-related disasters, global support for the adoption of these new universal goals is high.

There is widespread agreement that the solution to these challenges and other urgent issues can only be found in a truly global endeavour, one in which all countries – developed and developing, rich and poor – are committed to fulfilling this vision.

The SDGs take into account the different national realities, their capacities and levels of development while respecting national policies and priorities. All 17 goals are integrated and indivisible. They have a global focus and are universally applicable.

SDG targets are defined as aspirational and global. Each government is expected to set its own national targets guided by the global consensus to act, while taking into account national circumstances. Each government will also decide how these aspirational and global targets should be incorporated into their national planning processes, policies and strategies.

Table 1.2: The 17 Sustainable Development Goals

	Goal
1	End poverty in all its forms everywhere
2	End hunger, achieve food security, improve nutrition and promote sustainable agriculture
3	Ensure healthy lives and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all

	Goal
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation
10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalise the global partnership for sustainable development

» *Challenges facing SDGs in Nigeria*

It is yet to be seen if the challenges faced by the MDGs will prove to be a hindrance to the successful implementation of the SDGs. Most factors cited can be assumed to pose a serious challenge to achieving the aims of the SDGs in Nigeria. On the other hand, previous challenges such as security, human rights issues and sustainable planning are currently being addressed and Nigeria is achieving small victories in this regard.

SUSTAINABLE ENERGY FOR ALL (SE4ALL)

The Sustainable Energy for All (SE4ALL) initiative brings together top-level leadership from all sectors of society – governments, businesses and civil society – with the goal of attaining a broad-based transformation of the world's energy systems for a more prosperous, healthier, cleaner and safer world for this and future generations. First envisioned in 2011 for implementation by 2030, the objectives of SE4ALL include the following:

- Providing universal access to modern energy services
- Doubling the global rate of improvement in energy efficiency
- Doubling the share of renewable energy in the global energy mix[1]

By 2015, the initiative aimed to accelerate the provision of electricity to 200 million people, and clean and efficient cooking and heating solutions to 400 million individuals. In advancing its objectives, areas of intervention include renewable energy procurement, clean cooking solutions, gas flaring reduction, sustainable biofuels, off-grid lighting, and advanced lighting/appliance efficiency.[2] Through an emphasis on energy access which is crucial for socio-economic development, the initiative simultaneously draws attention to the need to invest in renewable energy, which not only creates local jobs and economic growth but can reduce greenhouse gas emissions and local pollution. Therefore, working to ensure universal energy access is a significant contribution to achieving the Millennium Development Goals (MDGs) and to promoting sustainable development.

[1] SE4ALL 2015.
[2] Ibid.

When considering the importance of energy to MDGs, it is important to note that energy is a critical enabler for primary health care services, especially maternal emergencies during childbirth. To support women's health, SE4ALL is focusing initially on providing clinics with electricity for lighting and other energy-dependent health services. Thus, access to energy spurs development on many levels – creating new markets to drive economic growth, improving social equity and protecting the environment for a healthier, more sustainable future.[1]

» *Challenges*

In Nigeria, one of the main problems facing rural electrification based on renewable energy sources is the inability of off-grid electrification projects to generate secured returns. This deters private investors and blocks the further development of these technologies. Considering further the general absence of public funding in this sector it is unsurprising that policy and the institutional framework alone have not succeeded in addressing this challenge.

REVIEW QUESTIONS

i. When is a society said to be in energy poverty? What indicators/factors in your environment do you think currently promote or decrease energy poverty?
ii. What are the expected outcomes of the Sustainable Energy for All initiative?
iii. What are the Millennium Development Goals?
iv. The MDGs face a number of challenges. List and discuss solutions to four of these challenges.
v. Assess the current status of 10 of the 17 SDGs for Nigeria.
vi. Describe the different impacts of global warming.
vii. Discuss the effects of energy extraction processes on the environment.
viii. Differentiate between the different classes of energy with examples.
ix. Considering the National Renewable Energy and Energy Efficiency Policy (NREEEP) 2015, discuss the opportunities for renewable energy in Nigeria.
x. How does energy efficiency affect human activities?
xi. To what extent have the renewable energy sources in your environment been utilised?

FURTHER READING

1. *Statistical review of world energy* • BP Global, 2015
www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html - accessed Aug. 30, 2016
2. *The Nigerian energy sector. An Overview with a Special Emphasis on Renewable Energy, Energy Efficiency and Rural Electrification* • GIZ-NESP, 2015
www.giz.de/en/downloads/giz2015-en-nigerian-energy-sector.pdf – accessed Aug. 30, 2016
3. *Africa energy outlook 2014: A Focus on Energy prospects in Sub-Saharan Africa. Paris: World Energy Outlook Special Report* • IEA, 2014

[1] SE4ALL 2014.

www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf – accessed Aug. 30, 2016

4. *Renewable energy resources (2nd edition)* • J. Tidwell and T. Weir, New York: Taylor & Francis, 2006

5. *Financing renewable energy in developing countries: Drivers and barriers for private sector finance in Sub-Saharan Africa* • Paris, UNEP Finance Initiative (2012) www.unepfi.org/fileadmin/documents/Financing_Renewable_Energy_in_subSaharan_Africa.pdf – accessed Aug. 30, 2016

6. *Climate change: Impacts, vulnerabilities and adaptation in developing countries* • United Nations Framework Convention on Climate Change, Bonn, Germany - UNFCCC (2007) www.unfccc.int/resource/docs/publications/impacts.pdf – accessed Aug. 30, 2016

2. LOAD ASSESSMENT

About this module

The design of any electrification system depends mainly on the electricity consumers and their characteristics. In renewable energy power supply systems, the energy consumption of the consumers often has a more critical impact on the system design and performance than in conventional power supply systems. It is important for participant to understand the operating characteristics of electricity consumers as a source of guidance when designing a system.

Learning outcomes

- At the end of this module, the participant is able to
- Understand the operating characteristics of common electricity consumers
- Understand the importance of energy-efficient appliances

2.1. APPLIANCES

Almost all electrical consumers fall into one of these four categories:

- Lighting equipment
- Motors, including machines, fridges, air conditioners, pumps, etc.
- Heaters
- Electronic devices such as television sets, personal computers, laptops, mobile phones, entertainment equipment, etc.

LIGHTING

Visible light is just a small part of a broad spectrum of electromagnetic waves. These waves have both a frequency and a wavelength, the values of which distinguish light from other forms of energy on the electromagnetic spectrum. Visible light, as can be seen on the electromagnetic spectrum, as given in Figure 2.1, represents a narrow band between ultraviolet light (UV) and infrared energy (heat). These light waves are capable of exciting the eye's retina, which results in a visual sensation called sight. Therefore, seeing requires a functioning eye and visible light.

Three primary considerations help ensure energy efficiency in lighting systems:

- Selection of the most efficient light source available in order to minimise power consumption and costs
- Matching the proper lamp type to the intended work task or aesthetic application, consistent with colour, brightness control and other requirements
- Establishing adequate light levels to maintain productivity and security

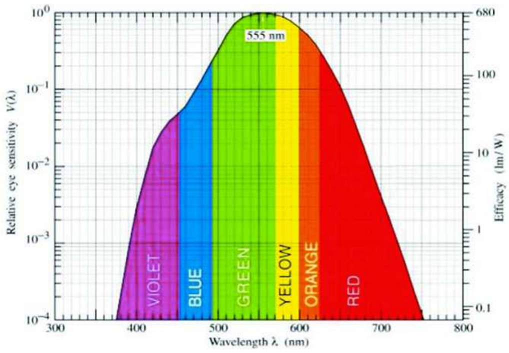


Figure 2.1: Electromagnetic spectrum

» *Basic parameters and terms*

- *Luminous flux:* Describes the quantity of light emitted in any direction by a light source. The lumen (lm) is the photometric equivalent of the watt. The lumen rating of a lamp is a measure of the total light output of the lamp. Unit: lumen (lm).

- *Illuminance (E):* Quantity of light which reaches a certain area, also described as the light intensity of a surface. This measure depends on the strength of the light source (lumen) as well as on the space between the light source and the surface. Illuminance decreases by the square of the distance. Unit: lux (lx) 1 lux = 1 lumen/m².
- *Circuit watts:* Total power drawn by lamps and ballasts in a lighting circuit under assessment.
- *Luminous efficacy*: Ratio of luminous flux emitted by a lamp to the electric power consumed by the lamp. It is a reflection of the efficiency of energy conversion from electricity to light. Unit: lumens per watt (lm/W).
- *Lamp circuit efficacy:* Quantity of light (lumens) emitted by a lamp for each watt of power consumed by the lamp circuit, i.e. including ballast or control gear losses. This is a more adequate measure for those lamps that require ballasts or control gears. Unit: lumens per circuit watt (lm/W).
- *Colour rendering index (CRI):* Measure of the effect of light on the perceived colour of objects. A low CRI indicates that some colours may appear differently when illuminated by the lamp. A CRI of 100 indicates that the colour appears exactly as under daylight.

» Lamp types

Based on their construction and operating characteristics, lamps can be categorised into four types:

Incandescent lamps: The principal parts of an incandescent lamp, also known as a GLS lamp (general lighting service lamp), include the filament, the bulb, the fill gas or vacuum and the cap. Incandescent lamps (Figure 2.2) produce light by means of a wire or filament heated to incandescence by the flow of electric current through it. The filament is enclosed in an evacuated glass bulb filled with a gas such as argon, krypton, or nitrogen. The presence of these types of gases serves to keep out oxygen to prevent the filament from burning out and to increase the brilliance of the lamp.

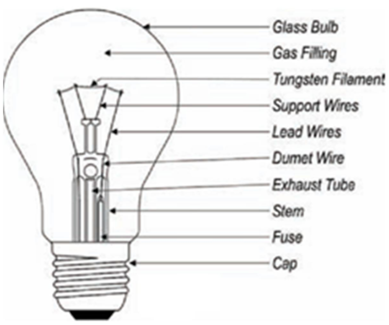


Figure 2.2: Cross-section of incandescent lamp

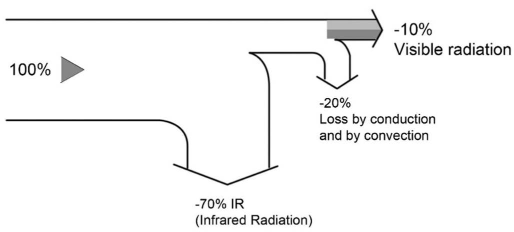


Figure 2.3: Energy flow diagram of an incandescent lamp

Halogen lamp: This type of lamp has a tungsten filament and a bulb filled with halogen gas. Current flows through the filament and heats it up, as in incandescent lamps. These lamps therefore generate a relatively large amount of heat. The halogen cycle increases the efficiency and extends the service life compared with traditional incandescent lamps. Low-voltage types are very small and are ideal for precisely directing light, but do require a transformer.

Fluorescent tube lamp (FTL): A fluorescent lamp is a glass tube containing a small trace of a gas such as mercury vapour (for a white colour), carbon dioxide (for green), neon (for red), etc., with a special fluorescent / phosphorescent coating on the interior surface of the tube. It contains two filaments, one at each end of the tube, and when the electrical supply is switched on, the contacts of the starter open and the filaments glow to heat up the gas contained inside the tube.

The luminous flux of fluorescent lamp is highly dependent on the ambient temperature. Fluorescent lamps are about three to five times as efficient as standard incandescent lamps and can last about 10 to 20 times longer. Fluorescent tubes are manufactured in different lengths, thicknesses and shapes.

Each fluorescent lamp needs a ballast for ignition and operation. Under operation the ballast consumes additional power which has to be added to the power consumption of the tube. Conventional ballasts are made of a copper wire coil. As this coil is an inductive load the lamp circuit needs a capacitor for power factor correction.

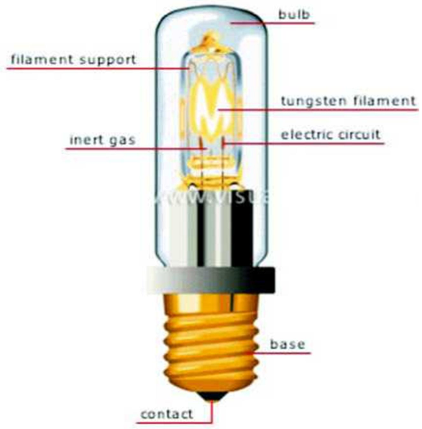


Figure 2.5: Halogen lamp

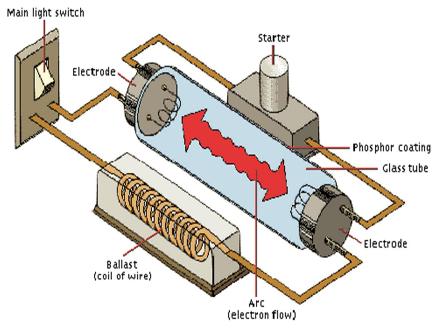


Figure 2.4: Fluorescent lamp

Table 2.1: Power consumed by different fluorescent tube lamps

Lamp wattage	*Ballast wattage*	*Total circuit wattage*
18	5	23
36	10	46
58	13	71

Modern FTLs use an electronic ballast for the same purpose. Compared to conventional ballasts, electronic ballasts consume less power while also extending the lifetime of the lamp and increasing lumen output. Another advantage is that the ballast operates with a very good power factor ($\cos \varphi = 0.95$) and therefore does not need a capacitor to function.

Compact fluorescent lamp (CFL): Compact fluorescent lamps are miniature versions of the linear or circular fluorescent lamps and operate in a very similar way. CFLs use less power and have a longer rated life compared to an incandescent lamp. They are designed to replace an incandescent lamp and can fit into most existing light fixtures formerly used for incandescent lighting.

CFLs are available with a screw or bayonet mount, which fits into standard sockets. The light they emit is similar to that of common fluorescent lamps.

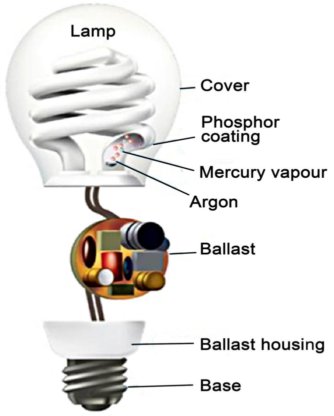


Figure 2.6: Cross-section of compact fluorescent lamp

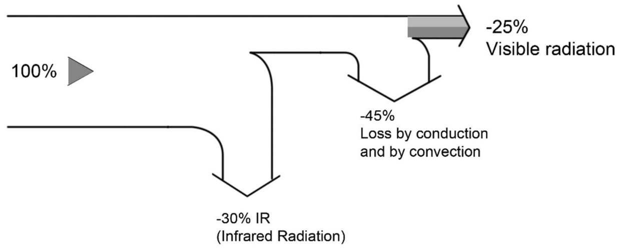


Figure 2.7: Energy flow diagram of a fluorescent lamp

A disadvantage of CFL is that many of them, especially cheap brands, have a poor power factor, which could be as low as 0.6. Thus, the savings to be gained from using these lamps may even be lost in such cases.

Mercury vapour lamp: In a mercury vapour lamp, electromagnetic radiation is created from discharge within mercury vapour, but the basic operating principle is different than a normal fluorescent lamp. During operation, the pressure within the lamp is in the range of 200 to 400 kPa. It is not possible to achieve the mercury vapour discharge in a cold lamp. For this reason, the lamp also includes argon, and the initial arc is struck as an argon arc. The energy from this discharge vaporises the mercury to get the main discharge going. The mercury vapour lamp produces a much greater proportion of visible light than a fluorescent lamp and gives off a bluish white light. Phosphor coating can be added to improve the colour rendering index.

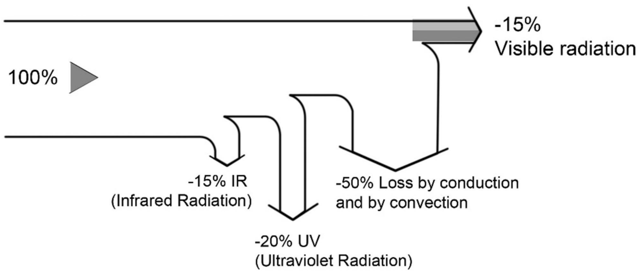


Figure 2.8: Energy flow diagram of a mercury vapour lamp

Sodium vapour lamp: Although low-pressure sodium vapour (LPSV) lamps are similar to fluorescent systems (because they are low-pressure systems), they are commonly included in the HID family. LPSV lamps are the most efficacious light sources, but they produce the poorest quality light of all the lamp types. Under an LPSV source, all colours appear black, white, or shades of grey. LPSV lamps are available in wattages ranging from 18 to 180 W. LPSV lamp use has been generally limited to outdoor applications such as security or street lighting and low-watt indoor applications where colour quality is not important (e.g. stairwells). However, because the colour rendition is so poor, many municipalities do not permit the use of LPSV lamps for roadway lighting.

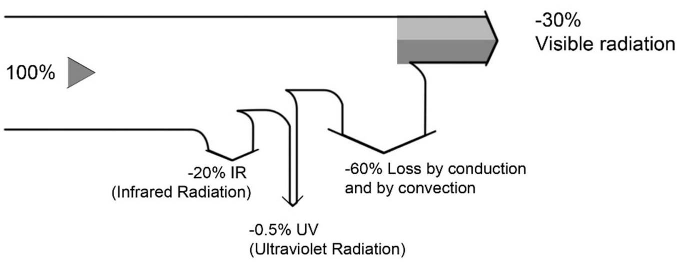


Figure 2.9: Energy flow diagram of a sodium vapour lamp

The high-pressure sodium vapour (HPSV) lamp is widely used for outdoor and industrial applications as it emits a yellowish light. Its higher efficacy makes it a better choice than metal halide for these applications, especially when good colour rendering is not a priority. HPSV lamps differ from mercury and metal-halide lamps in that they do not contain starting electrodes; the ballast circuit includes a high-voltage electronic starter. The arc tube is made of a ceramic material, which can withstand temperatures up to 1,300°C. It is filled with xenon to help start the arc, as well as a sodium-mercury gas mixture.

Metal halide lamp: The metal halide lamp can be considered as a variant of the high-pressure mercury vapour lamp (HPMV). In addition to mercury vapour and argon, this lamp contains various metal halides. The halides can be a mixture of rare earth halides, usually iodides or a mixture of sodium and scandium iodide. The mercury vapour radiation is augmented by that of the metals. Metal halide lamps have a significantly better colour rendering index than mercury vapour and can be tailored by the choice of halides.

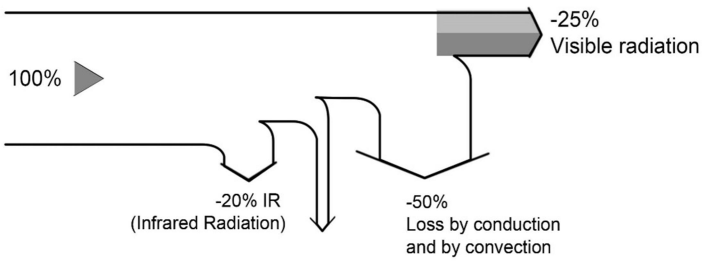


Figure 2.10: Energy flow diagram of metal halide lamp

Light-emitting diode (LED) lamp: An LED is a special variant of the p-n junction. Electron-hole recombination can result in the emission of photons, the wavelength of which depends on the energy gap between the conduction band and valence band. LEDs are potentially excellent sources of near-monochromatic light. When white or any intermediate colour is needed, it is possible to achieve this by mixing three colours. For white LED lamps the lumens output varies from 30 to 50 lumens per watt. Because of the low power requirement for LEDs, using solar panels becomes more practical and less expensive than running an electric line or using a generator. Hence, an LED with battery backup for remote application is very economical. However, unlike incandescent lamps, LEDs do not radiate light in 360 degrees. The light will be bright only where it is focused.

Figure 2.11: Energy efficient LED lamps

» *Other lamp types*

DC lamps: CFL, halogen and LED lamps are also available for extra-low voltage (ELV) and DC applications, mostly for 12 V as well as some very few products for 24 V systems on the market. These offer an advantage especially in small renewable energy power supply systems which use batteries for energy storage (solar PV, small wind). Because no inverter for AC conversion is necessary, costs can be saved and the reliability and efficiency of the system improved.

Table 2.2: Characteristics of different lamp types

Lamp type	Efficacy (lm/W)	Colour rendering	Typical application	Average lifetime (h)	Power factor (cos φ)
Incandescent	8–18	Excellent (100)	Domestic, commercial, public buildings	1,000	1
Halogen lamps	18–24	Excellent (100)	Domestic, commercial, public buildings flood Stadium exhibition grounds, construction areas	2,000–4,000	1
LED lamps	30–50	Good (70)	Domestic, commercial, public buildings, reading lights, desk lamps, spotlights, security lights, signage lighting	40,000–100,000	0.9–1
Compact fluorescent lamps (CEL)	40–70	Good to very good (65–85)	Domestic, commercial, public buildings	8,000–10,000	0.6–0.7
High-pressure mercury (HPMV)	44–57	Fair (45)	Factories, garages, car parking, streetlights, floodlighting	5,000	0.9 with power factor correction
Fluorescent lamps with magnetic ballast	46–60	Good (67–77)	Domestic, commercial, public buildings	5,000	0.9 with power factor correction, 0.5 without
Fluorescent lamps with electronic ballast	50–65	Good (67–77)	Domestic, commercial, public buildings	7,000	1
High-pressure sodium (HPSV) SON	67–121	Fair (22)	Factories, garages, car parking, streetlights, floodlighting	6,000–12,000	0.9 with power factor correction
Metal halide lamps	75–125	Good (70)	Industrial bays, spot lighting, flood lighting, retail stores	8,000	0.9 with power factor correction
Low-pressure sodium (LPSV) SOX	101–175	Poor (10)	Tunnels, canals, street lighting	6,000–12,000	0.9 with power factor correction

MOTORS

Motors convert electrical energy into mechanical energy by the interaction between the magnetic fields in the stator and rotor windings. Electric motors can be broadly classified as AC motors and DC motors. AC motors can be single-phase or three-phase.

- AC motors: Include induction motors (asynchronous motor), synchronous motors and linear motors, all with several sub-types such as squirrel cage, wound rotor, slip ring, permanent magnet synchronous, etc.
- DC motors: Include brush DC and brushless DC (again with sub-types such as servo, permanent magnet, universal, etc.)
- All motor types have the same four operating components: Stator (stationary windings), rotor (rotating windings), bearings, frame (enclosure).

» *Motor types and function*

INDUCTION MOTORS (ASYNCHRONOUS MOTORS)

An AC induction motor, like most motors, has a series of fixed outer windings called the stator. A spinning rotor inside the stator creates a magnetic field that induces a voltage in the rotor windings. As the rotor windings are short-circuited, a current flows which generates a magnetic field around the windings. As a result of the rotating magnetic field of the stator and the magnetic field around the rotor windings, the rotor starts moving in line with the stator field rotation and eventually begins to spin. If only a single-phase supply is available, a capacitor is used to create a shifted phase from the original phase. In this way the original phase, shifted phase and neutral work as the three phases in generating the rotating rotor field. Induction motors are commonly used in domestic applications such as water pumps.

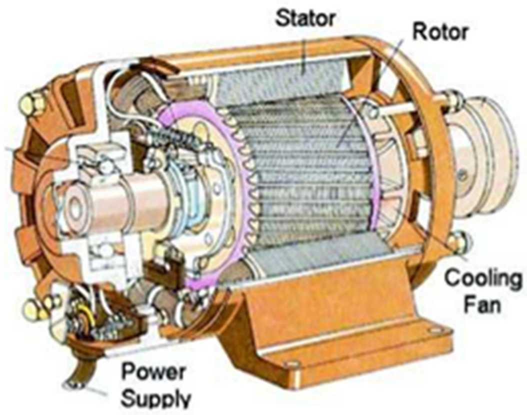


Figure 2.12: Induction motor

SYNCHRONOUS MOTORS

Like an asynchronous motor, the synchronous motor generates a rotating magnetic field in the stator windings. The rotor of the synchronous motor has magnets, either electrically excited magnets (from DC voltage supplied by brushes) or permanent magnets. The rotor magnets follow the rotating magnetic field of the stator and the rotor spins.

DC MOTORS

Direct-current motors, as the name implies, use direct (unidirectional) current. The stator of a DC motor is made of DC-supplied electromagnets or permanent magnets. The rotor windings are also connected to the DC supply which they use to generate their own magnetic field. The rotor spins as a result of the attraction between the two magnetic fields. As the rotor spins, the next winding of the rotor will be supplied with voltage via the brushes and become attracted by the stator magnetic field. The previous winding, in turn, will be supplied with a DC voltage in the opposite direction, resulting in an attraction to the next magnetic field of the following stator winding. Direct current motors are used in special applications where high starting torque or smooth acceleration over a broad speed range is required.

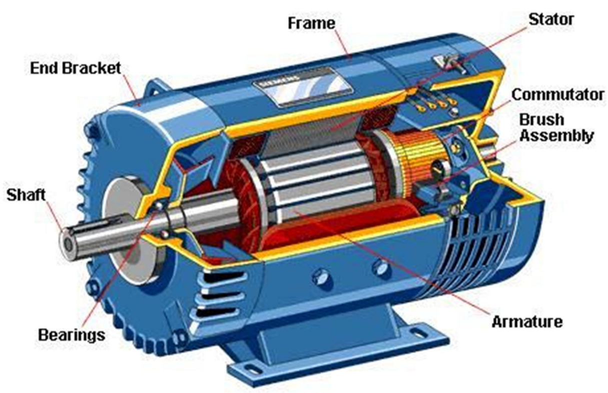


Figure 2.13: DC motor

UNIVERSAL MOTORS

A universal motor is basically a DC motor which can also run on AC. Both the stator and rotor windings are supplied with AC voltage and the rotor windings change their polarity due to the supply with AC voltage.

» *Motor characteristics*

MOTOR SPEED

The speed of a motor is the number of revolutions in a given time frame, typically counted in revolutions per minute (RPM). The speed of an AC motor depends on the frequency of the input power and the number of poles for which the motor is wound. The speed of a DC or a universal motor depends on the voltage supplied. This voltage is controlled via resistors.

POWER FACTOR

The apparent power (VA) is the product of the supplied voltage and current. It is the power which has to be supplied by the power source (e.g. generator, inverter). The efficient power (W) is the part of the apparent power which is used in electric power conversion processes. In an electric motor this is mainly for magnetic fields and conversion to heat. The power factor of an AC motor is given as:

$$\text{Power Factor} = \text{Cos}\ \phi\ = \frac{\text{kW}}{\text{kVA}}$$

DC motors do not have a power factor and are rated by efficient power alone. It would be equally correct to say that their apparent power is identical to their effective power and their power factor therefore is 1.

MOTOR EFFICIENCY

Efficiency is defined as the ratio of the mechanical power delivered at the rotating shaft to the electrical efficient power input at its terminals. Some possible losses which reduce the efficiency in an electric motor:

- Electric losses due to resistance in the windings (conversion to heat)
- Iron losses due to dissipation of the magnetic field in the rotor and stator
- Mechanical losses due to friction in bearings and by airstream

STARTING CURRENT OF MOTORS

For a short moment when switching on, all types of electric motors draw a very high current. This starting or inrush current is 5 to 10 times higher than the nominal operating current. For induction motors, the inrush current lasts for about 0.5 seconds, while for DC motors, the starting current lasts no more than 0.2 seconds. This current surge must be considered when designing the power supply and protective devices.

MOTOR NAME PLATE

The motor name plate gives all relevant specifications of an electric motor such as:

- Supply voltage and frequency
- Current under full load
- Efficient power
- Apparent power, if not given, can be determined as voltage × current
- Power factor, if not given, can be determined as efficient power / apparent power

Figure 2.14: Name plate of single-phase induction motor

REFRIGERATION EQUIPMENT

Refrigerators are categorised into two types: compression fridges and absorption fridges.

» Compression systems

As far as power consumption is concerned, compression fridges can be seen as electric motors. Most compression fridges are equipped with a single-phase induction motor (capacitor motor) to drive the compressor. This type of motor has a low efficiency and poor power factor unless it has an added capacitor for power factor correction. Like all electric motors, induction motors have a very high starting current and power, approximately 5 to 10 times the nominal power for no longer than 0.5 seconds. That means a refrigerator with a 100 W compressor motor acts as a 0.5 to 1 kW load for approximately 0.5 seconds.

Compression fridges are the most common fridges for domestic use. With regards to energy consumption there can be huge differences between fridges of the same size. A modern 200-litre fridge-freezer combination might consume less than 1 kWh per day while a 20-year-old fridge of the same type might consume 3 to 4 kWh per day.

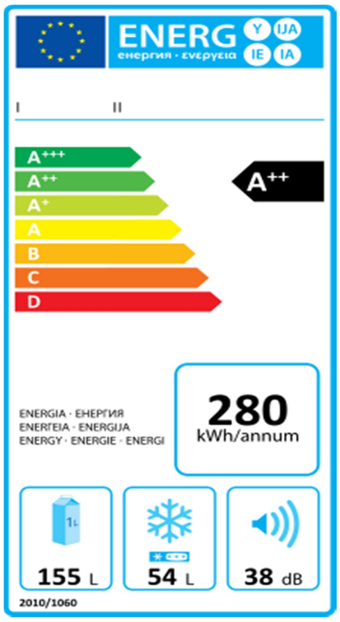


Figure 2.15: Energy label for refrigerator

Fridges today often come with an energy class label that indicates their energy efficiency. Super-efficient fridges receive an A+++ rating while inefficient fridges with high energy consumption receive a class D label. The motors of modern "A" class fridges often have an improved power factor simply due to an added capacitor for power factor correction.

The energy consumption of a fridge depends on:

- Size (volume)
- Quality and strength of insulation
- Type, quality and efficiency of motor and compressor
- Ambient temperature
- Temperature set point
- Installation site and orientation (ventilation)
- Usage (door openings, contents)

» Absorption systems

As far as its electrical behaviour is concerned, an absorption fridge can be regarded as an electric heater in combination with an induction motor (pump).

Absorption refrigerators cannot reach the same low temperatures that can be achieved by compressor fridges. They are simpler in construction, as no compressor is needed, and therefore cheaper. The process heat can also be generated by alternate energy sources as gas or excess heat from other processes. They have a wide range of applications from domestic to industrial and outdoor use.

» ***Air-conditioning equipment***

Most air-conditioning units work basically the same way as a compression fridge. However, their power consumption is much higher. For domestic use it is usually from at least 1 kW to several kilowatts, depending on the size of the room to be cooled. Therefore, running an air-conditioning unit during the day can consume several kilowatts of electrical energy and its necessity should be considered carefully.

OTHER LOAD TYPES

» ***Electric heating equipment***

Electric heaters are the simplest of all electric devices. They are used for hot water kettles, water heaters in bathrooms, for heating rooms and for process heat. An electric heater is basically a heat-resistant conductor with a certain resistance. Depending on voltage and resistance, a current flows and heats up that heating element. Electric power is directly converted to heat. As heat is the desired outcome the efficiency is 100%. The power factor is 1 as there are little or no magnetic fields.

However, from the perspective of power generation, the overall efficiency of the heating process is very low. If a diesel generator is used to generate electric power, for example, then 50% of the thermal energy of the diesel would be converted to mechanical energy. From this mechanical energy, depending on the actual operation, 50 to 80% would be converted to electrical energy. In total, then, only 25 to 40% of the diesel’s thermal energy is converted to electrical energy, which would again be converted to thermal energy by the heater. In this case, it would be much more economical to directly use the diesel fuel for heating instead of generating electricity for a heater.

» ***Electronics***

Today, electronic devices are part of every household, office or other commercial building. The most common electronic devices are:

- Mobile phones
- Laptops and PCs
- TV sets, music systems and gaming devices
- Electronic security equipment
- Controlling equipment for devices and machines

As electronic devices in most parts of the circuit use extra-low voltage (5 V, 12 V), the primary power-consuming device is the power supply. Because most electronics are built for connection to an AC power supply, they need an AC - DC converter.

Modern electronics mostly use switched-mode power supplies (SMPS) as they are cheaper and can be built smaller and lighter compared to the step-down transformer power supplies of earlier electronics generations. The disadvantage of SMPS is that they often have a poor power factor and additionally are a source of harmonic waves on the power line. These two problems, poor power factor and harmonic distortion, are an additional stress on the electric power generator, especially for electronic voltage conversion devices like inverters. However, some manufacturers have started to offer energy-efficient electronics with a power factor of 1 which are preferable with regard to saving energy.

» *Power consumption of electronics*

The power consumption of electronic devices can vary from very few watts for mobile phone chargers up to several hundred watts for a large plasma TV. Another concern when estimating the energy consumption of electronic devices is that almost all devices consume power even when they are switched off (standby consumption). This can only be avoided by unplugging the device from the power source.

Table 2.3: Power and standby consumption of typical electronic devices

Device	*Operation power (W)*	*Standby power (W)*
Ordinary phone (charging)	3	1
Smartphone (charging)	7	1
Laptop running or charging	20–70	5–15
Laptop running + charging	40–120	5–15
Desktop PC + monitor	60–180	10–30
Inkjet printer	10–30	2–5
Laser printer	100–500	2–5
Mid-size TV	50–100	5–15
Large CRT TV (32 to 51 inch)	100–400	5–15

2.2. LOAD ANALYSIS

BASIC CONCEPTS

When designing a power supply of any kind, it is necessary to investigate the loads which have to be supplied. The power supply must be able to provide enough power for the peak load under any conditions. It also must provide the required power for the required period of time.

» *Peak power*

The peak power is the sum of the power consumption of all devices which are able to operate simultaneously. High surges like the start-up power of an induction motor on a refrigerator must be considered, as well as the power factor of certain devices. A poor power factor results in higher power demands than the efficient power in watts which is usually indicated on the device label.

» *Total energy demand*

This is the cumulative sum of energy required by a load over a given period, usually a day. It is calculated by multiplying the continuous power requirement of each load with the number of hours in operation. Power supply designers also need to include the standby power consumption of devices. Standby consumption is measured in watt hours (Wh) from the point of view of the consumer or in VAh from the point of view of the generator.

Example: Total energy demand calculation

Example: A family's home has the following electric devices in operation: CFL light bulbs, a TV, one old large fridge and two laptops. The power consumption and running time for the devices are given in the table below:

Equipment	*Quantity*	*Power (W)*	*Power factor*	*Apparent power (VA)*	*Running time (h)*	*Daily energy (VAh)*
Lights	12	14	0.6	280	5	1,400
TV	1	360	0.9	400	8	3,200
Fridge	1	240	0.6	400	6	2,400
Security lights	8	15	0.6	200	12	2,400
Laptop	2	90	0.9	200	7	1,400
Total				**1,480**		**10,800**

⇒ *The total apparent power which has to be generated is 1,480 VA.*

⇒ *The surge power of the fridge is 400 VA × 7 =2,800 VA for 0.5 seconds.*

⇒ *The power supply must also be able to provide a continuous power of 1,480 VA and a short-term power of 1,480 VA + 2,800 VA = 4,280 VA for 0.5 seconds.*

⇒ *The daily energy to be provided by the grid or generator is 10,800 VAh.*

» Power supplied by inverters

If the electric power is supplied by an inverter, then the power conversion from DC to AC is subject to conversion losses. Good quality inverters have an efficiency of more than 90% depending on their mode (charging, discharging or standby) of operation.

Example: The daily apparent energy of 10,800 VAh has to be supplied by an inverter with an efficiency of 90%. The total daily energy demand including the energy losses from the inverter is 10,800 VAh/0.9 = 12,000 VAh.

» The load profile

The load profile is basically a timeline showing the hours at which various loads are running. The load profile requires particular attention from a power generation perspective, especially when power is generated by a renewable energy power supply which has a limited daily generation capacity and a daily power generation profile, as for example a solar electric system.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	Solar power generation in KW																								Daily energy generation	
Peak power	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	1.3	2.0	2.8	2.9	2.7	2.2	1.8	1.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	18.5	**KWh**

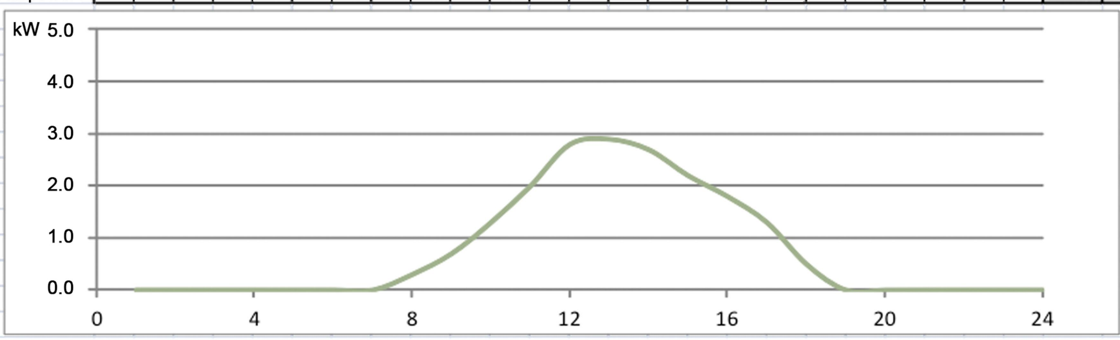


Figure 2.16: Power generation profile of a 5 kWP solar PV system

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	Power consumption in KVA																								daily energy	
Lights																		0.3	0.3	0.3	0.3	0.3	0.3		1.8	KVAh
TV														0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4			3.6	KVAh
Fridge	0.4				0.4				0.4				0.4				0.4				0.4				2.4	KVAh
Sec. lights	0.2	0.2	0.2	0.2	0.2	0.2	0.2												0.2	0.2	0.2	0.2	0.2	0.2	2.6	KVAh
Laptops									0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2									1.6	KVAh
Peak power	0.6	0.2	0.2	0.2	0.6	0.2	0.2	0.0	0.6	0.2	0.2	0.2	0.6	0.6	0.6	0.6	0.8	0.7	0.9	0.9	1.3	0.9	0.5	0.2	12	**KVAh**

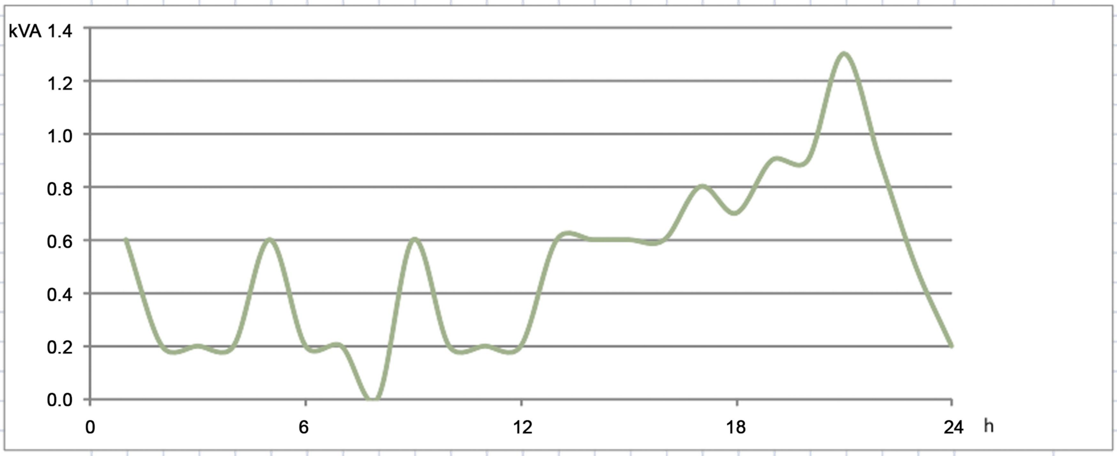


Figure 2.19: Load profile of a family home

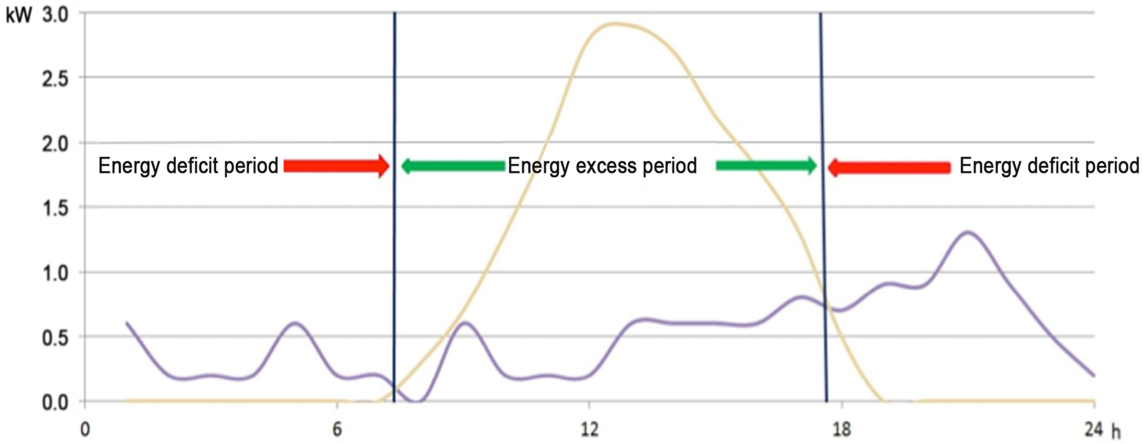


Figure 2.17: Comparison of load and generation profile of family home and solar generator

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	Hydro power generation in KW																								Daily energy generation	
Peak power	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	120.0	**KWh**

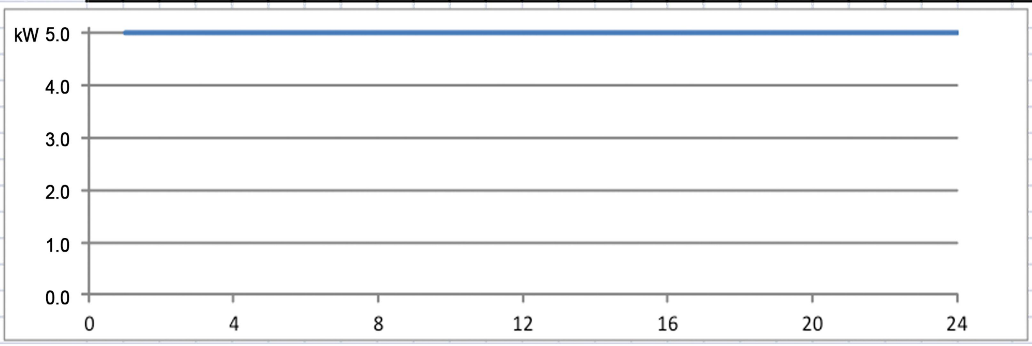


Figure 2.18: Typical generation profile of a hydropower plant

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Daily energy generation	
	Wind power generation in KW																									
Peak power	5.0	3.0	1.0	1.0	0.0	1.0	3.0	4.0	3.0	1.0	0.0	0.0	1.0	2.0	1.0	0.0	1.0	2.0	3.0	3.0	2.0	4.0	4.0	5.0	50.0	KWh

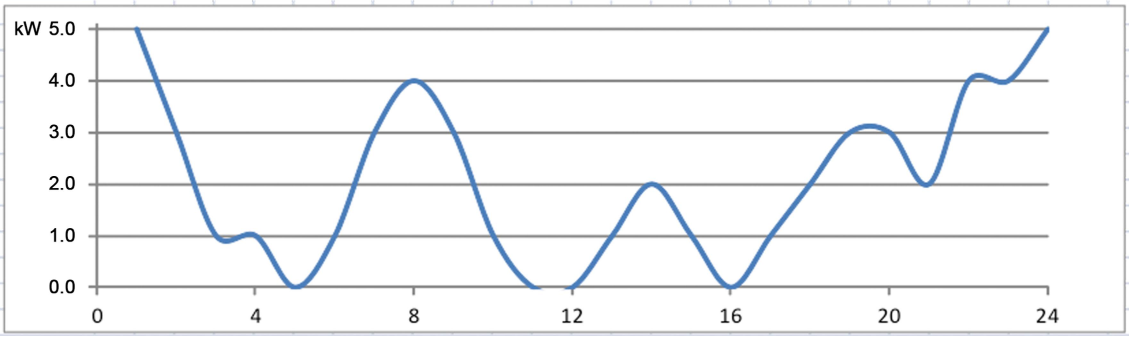


Figure 2.20: Generation profile of a wind generator

» *Load optimisation*

Load optimisation means using the provided power source in the most efficient way. This can be accomplished through either of the following:

- Reducing electric consumption by eliminating unnecessary loads or replacing electric consumers with more efficient ones, e.g. replacing an old fridge with a modern A+++ rated appliance or disconnecting electronic devices from the socket to avoid standby consumption.

Timing electric consumption to avoid peak loads which might overload the generator or switching on loads during top electricity-producing hours. For a solar system, this could include switching on a water pump to refill a storage tank at noon when the Sun is strongest.

3. GENERATION TECHNOLOGIES

About this module

Solar power provides viable options for solving Nigeria's energy problems. This module introduces participants to the fundamentals of solar power and the technologies used to harness solar energy.

Learning outcomes

At the end of this module, the participant is able to

- Explain the photovoltaic (PV) principle
- Measure characteristics of PV cells
- Carry out solar resource assessments
- Identify and describe solar technologies for generating electricity

3.1. SOLAR POWER (FOCUS TOPIC)

THE SUN, SUNLIGHT AND ITS PROPERTIES

"The largest and most impressive source of energy in our world and the source of life for every plant and animal, yet a source so little used by mankind today is the Sun... Solar energy will continue to flow toward us almost indefinitely." – Ben Gurion (1956).

» Describing the solar resource

The Sun supplies energy in the form of radiation, without which life on Earth would not exist. This energy is generated in the Sun's core through the fusion of hydrogen atoms into helium. Part of the hydrogen mass is converted into energy. In other words, the Sun is an enormous nuclear fusion reactor. Because the Sun is such a long way from Earth, only a tiny proportion (around two-millionths) of the Sun's radiation ever reaches the Earth's surface. But this tiny portion contains enough energy to cover the energy demand of the planet many thousands of times over and even sustain it for the next 5 billion years. If just half of Nigeria's surface were covered by solar panels, the output would be enough to supply the whole planet with electricity.

We mostly perceive solar energy on Earth in the form of visible light. To understand light, there are two broad approaches used by scientists:

- Geometric optics, a more classic approach which is important to investigate the light falling on a solar collector, as well as the shading and design of passive solar systems.
- Quantum mechanics, an approach which is important to understand the interaction between a solar collector and the incident light impinging on it.

The electromagnetic spectrum presents light as a wave at a particular wavelength. For solar energy, however, it is difficult to describe light as just waves, since this perspective does not explain the interaction of light with solid matter, which is the basis of the photoelectric effect. Albert Einstein explained this relationship in 1905 by describing light as quantum particles or packets of energy with no mass called photons.

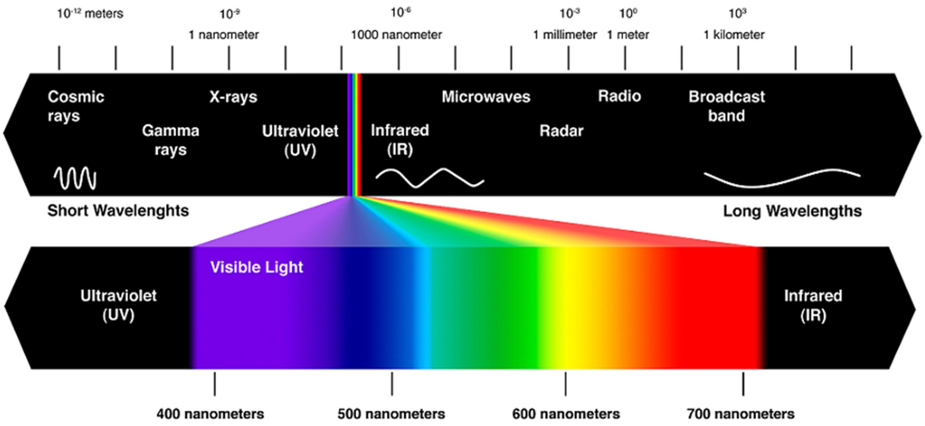


Figure 3.1: Electromagnetic spectrum

» *Terminology and units*

RADIATION

- Direct radiation: Radiation that reaches the Earth's surface directly instead of being reflected or scattered. This is called direct radiation (G_B) and is the radiation from the visible Sun which is not covered by clouds.
- Diffuse radiation: Radiation that is scattered before reaching the Earth's surface is called diffuse radiation (G_D). Natural occurrences in the atmosphere such as clouds, dust and smoke particles, water molecules, etc. increase the occurrence of diffuse radiation. This type of radiation is why the blue of the sky appears blue or the white of the clouds white.

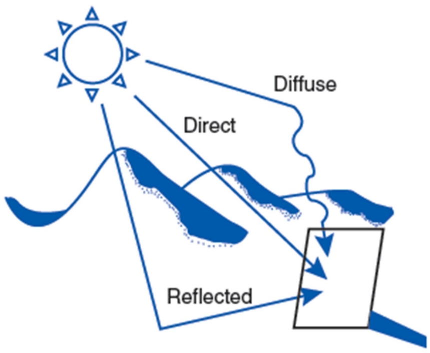


Figure 3.2: Direct, diffuse and reflected radiation reaching an object

- Reflected radiation (G_R) is the radiation reaching Earth's surface after reflection from objects not in the atmosphere like clouds, snow or mountains.
- Total global radiation (G) is the sum of three above: $G = G_B + G_D + G_R$.

For example, on a clear afternoon, direct radiation could comprise up to 85% of total irradiance reaching Earth's surface, with diffuse and reflected radiation making up the remaining 15%.

SOLAR POWER – IRRADIANCE

Solar radiation is power and the unit for measuring power is watt (W). The term irradiance is used to describe solar radiation as a source of power. The unit for irradiance is E. However, irradiance must be defined as power per unit of area, so its unit of measure is often W/m^2 or kW/m^2.

On a cloud-free day in northern Nigeria, the solar irradiance can reach an intensity of 1 kW/m^2. In some regions, such as deserts, it can reach up to 1.3 kW/m^2.

SOLAR CONSTANT

The solar constant is the measure of the flux density of solar energy, including all wavelengths and not only visible light. It is the mean solar irradiance per unit area that would be incident on a plane perpendicular to the Sun's rays received per unit area at the top level of Earth's atmosphere. The solar constant varies by about 0.3% over the 11-year solar cycle but averages about 1,368 W/m[2].

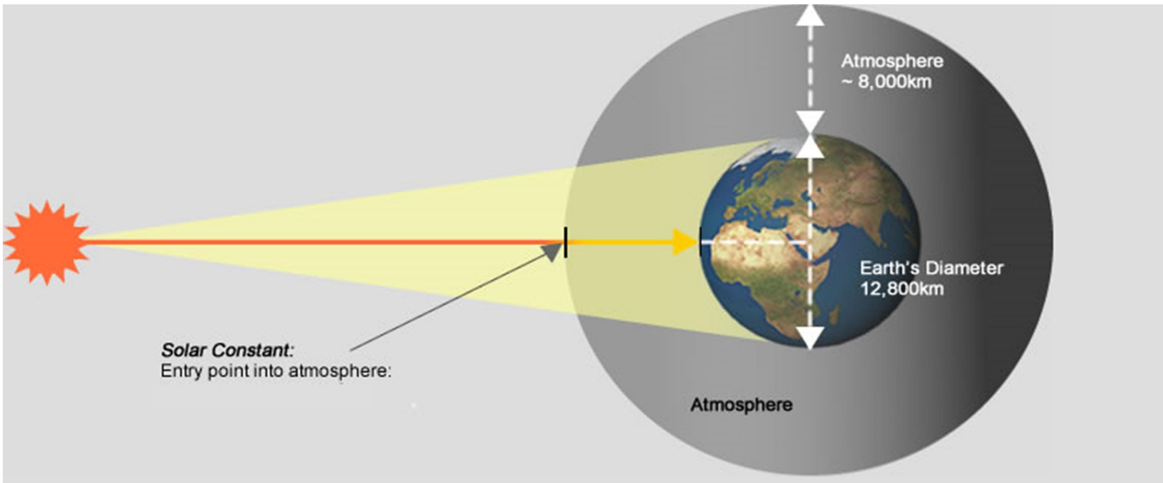


Figure 3.3: Solar constant – *Courtesy: Green Rhino Energy Ltd., Green Rhino Energy Ltd., www.greenrhinoenergy.com*

AIR MASS

This refers to the length of the path through the atmosphere to sea level that is traversed by solar radiation. The entry point into the atmosphere is called "air mass 0" or "AM0", where "0" indicates that there is no air for the light to pass.

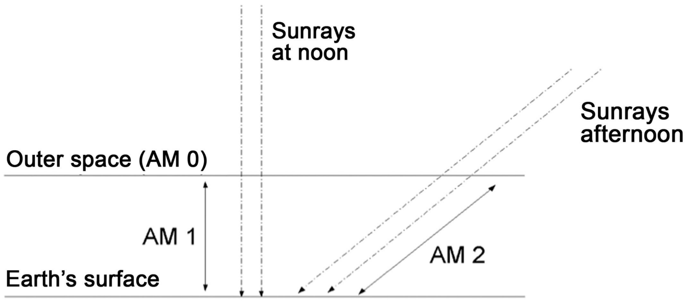


Figure 3.4: Effect of angle of incident on AM

At sea level the radiation from the Sun at its zenith (θz) corresponds to an air mass of 1 (AM1). AM1.5 is used to calibrate and gauge the efficiency of solar cells. Air mass is an indicator for the spectrum of radiation reaching the Earth's surface. At AM0 the full spectrum of radiation as emitted by the Sun is present; after travelling through the atmosphere to sea level (AM1), a part of the original spectrum of radiation is filtered out, e.g. a large share of ultra-violet (UV) radiation.

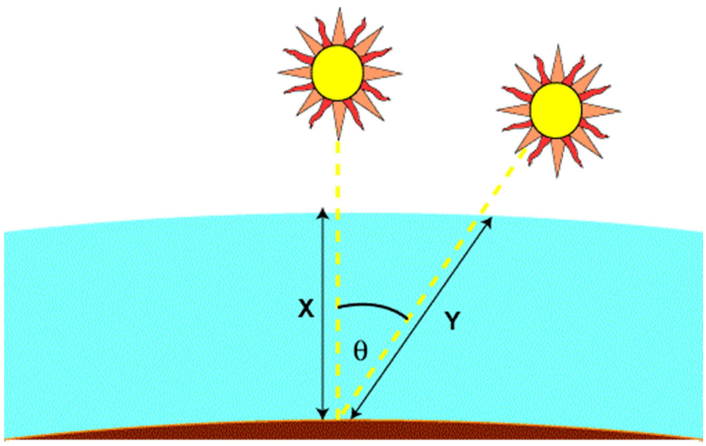


Figure 3.5: Determination of AM according to angle of incident – *Courtesy: C. Honsberg and S. Bowden, www.pveducation.org*

When radiation hits the surface at an angle other than vertical this also changes the space of air the radiation has to travel through, meaning that the air mass increases.

$$AM = \frac{1}{\cos\theta}$$

Where θ = angle of deviation from vertical zenith

SOLAR ENERGY – IRRADIATION

Irradiation refers to the total amount of solar energy received on a given surface during a particular time period. It is represented by the symbol H and measured in watt-hour per square metre (Wh/m^2). In solar system design it is necessary to know how much solar energy can be harvested during one day, one month or one year. Therefore solar energy is measured in kilowatt-hours per square metre per day ($kWh/m^2/day$) or per month or per year.

PEAK SUN HOURS (PSH)

The average daily solar irradiation ($kWh/m^2/day$) incident on the Earth's surface at a particular location is sometimes also referred to as peak sun hours. Peak sun hours denote the cumulative number of hours that a solar radiation of 1 kW/m^2 can be harnessed. At morning the sun does not have its full power of 1 kW/m^2 and the same applies in the evening. However, over the course of the day, the solar radiation power at different hours sums up to a certain amount of energy. The peak sun hours are found by integration of the irradiance over a one-day period.

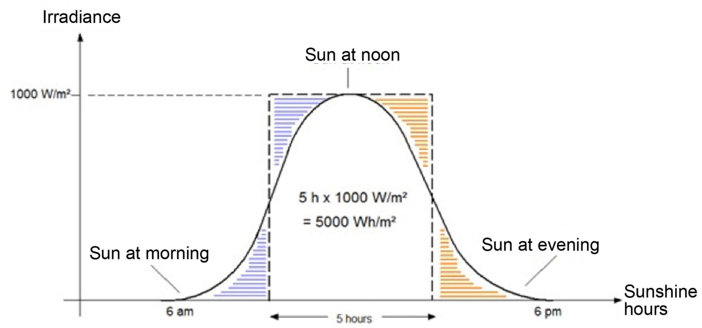


Figure 3.6: PSH as integration of irradiance over time

On a sunny day in northern Nigeria, it is common to experience approximately five hours with a solar radiation of 1 kW/m^2, meaning we have five peak sun hours which is the same as 5 $kWh/m^2/d$.

» ***Weather and meteorology***

MEASURING THE SOLAR RESOURCE

Solar photovoltaic system design requires that the amount of solar energy available at a particular site at a given time is known. There are two commonly applied methods for measuring insolation (the amount of solar radiation that reaches the earth's surface). .

The most common instruments used to measure solar radiation are presented below:

Pyranometer

The pyranometer is designed to measure global radiation. It is normally mounted on a horizontal surface to collect general data for global radiation. However, it is also often mounted in the plane of a photovoltaic generator in order to measure the global radiation incident on the PV generator.

Main pyranometer components:

- Thermopile sensor with black coating: Absorbs all solar radiation and has a flat spectrum covering the 300 to 50,000 nanometre range.

- Glass dome: Limits the spectral response from 300 to 2,800 nanometres (cutting off the part above 2,800 nm), while preserving a 180-degree field of view. Another function of the dome is that it shields the thermopile sensor from heat loss through convection.

The black coating on the thermopile sensor absorbs solar radiation. This radiation is converted to heat. The heat flows through the sensor which generates a voltage output signal proportional to the solar radiation. This signal is recorded for long-term solar energy measurements.

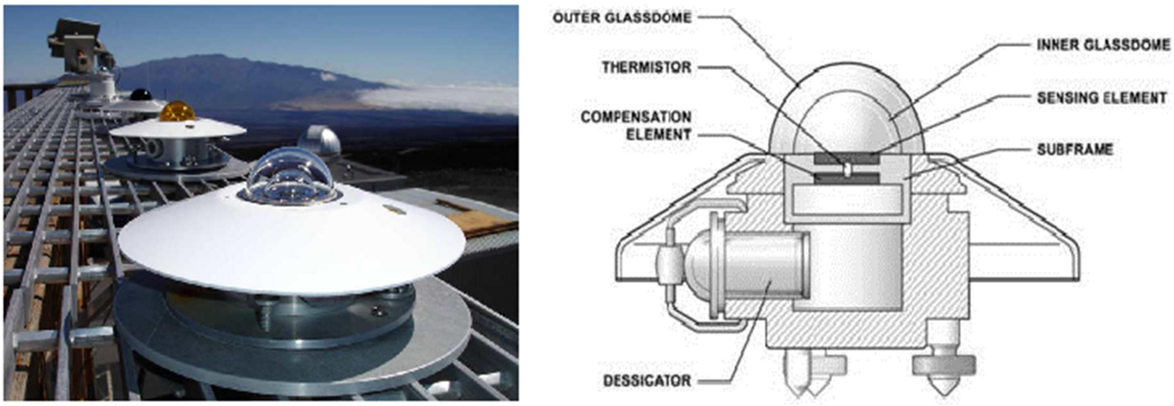


Figure 3.7: Pyranometer in action (left), schematic of pyranometer (right)

Pyrheliometer

A pyrheliometer is an instrument used for the direct measurement of solar irradiance; it cannot measure diffuse radiation. In terms of its major components and principle of converting irradiance to an electric signal, the pyrheliometer is similar to the pyranometer. Sunlight enters the tube of the instrument through a window and is directed onto a thermopile sensor, which then converts heat to an electrical signal that is directly proportional to irradiance. It is used with a solar tracking system to keep the instrument aimed at the sun. A pyrheliometer is often used in the same setup with a pyranometer. Pyranometers and pyrheliometers are very expensive high-precision instruments.

Figure 3.8: Pyrheliometer

Campbell-Stokes recorder

Alternatively, the Campbell-Stokes recorder measures solar radiation by focusing the Sun's rays and burning them into a card of heat-sensitive material. The intensity of the traces of heat gives information about solar radiation intensity. This method is less precise but also cheaper in comparison to the use of a pyranometer or a pyrheliometer. The technology for Campbell-Stokes recorders was invented almost 150 years ago and is rarely used today.

Photovoltaic sensor

A photovoltaic sensor is a calibrated PV cell which is used to measure irradiance via the output of generated current. These sensors cost much less than pyranometers but are less accurate and cannot capture the full spectrum of irradiance. They are often used in handheld instruments for a fast and rough estimate of solar irradiance at an installation site.

Figure 3.9: Photovoltaic sensor

METEOROLOGICAL DATA

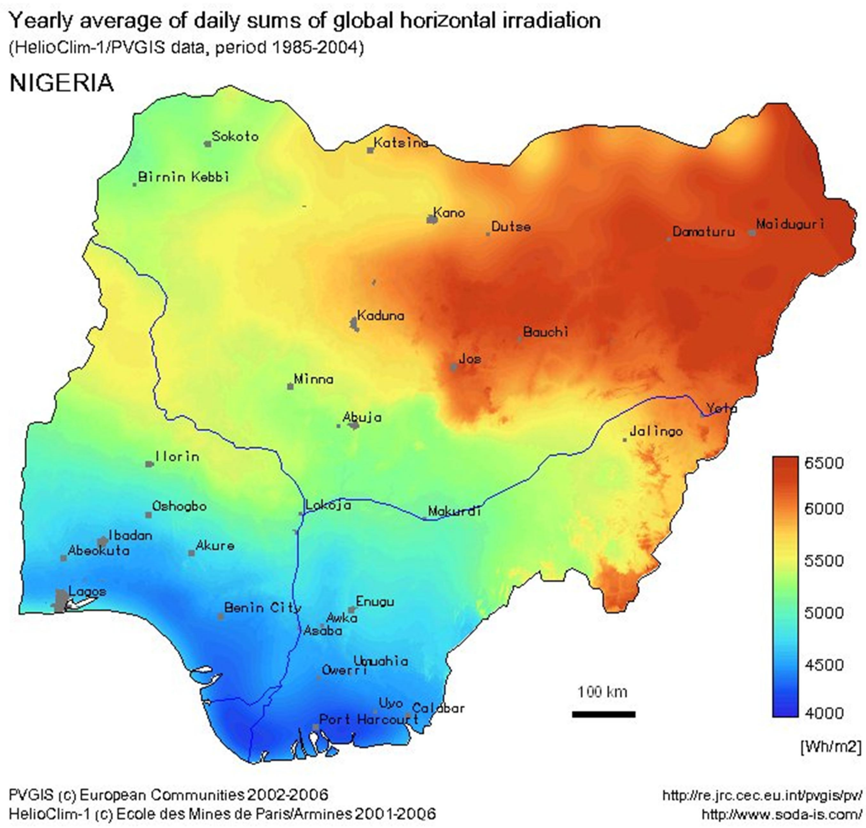


Figure 3.10: Average global horizontal irradiation for Nigeria

The amount of solar radiation on the Earth's surface depends mainly on four factors:

- Location (latitude)
- Time of year
- Time of day
- Local weather
- Latitude and time of the year

The latitude of a location determines the solar radiation received at that location. Throughout the year the Sun travels between the Tropic of Cancer (latitude 23.45° N) and the Tropic of Capricorn (latitude 23.45° S). On 20th or 21st June the Sun appears vertically above the Tropic of Cancer and on 21st or 22nd December it appears vertically above the Tropic of Capricorn. The angle between the line joining the centres of the Sun and the Earth and the equatorial

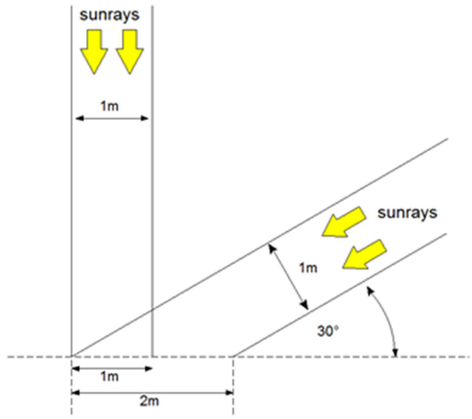


Figure 3.11: Intensity of sunlight as it impinges the Earth's surface

plane is called the solar declination and is denoted by δ. This angle is zero at the equinoxes on 20th March and 22nd or 23rd September. Seasonal variations increase with an increase in latitude from the Equator. This is why Nigeria, which is located between latitudes 3° N and 10° N, experiences only two main seasons and Germany, which is located between latitudes 47° N and 55° N, experiences four seasons.

Time of day - the Earth rotates around its axis every 24 hours. Relative to Earth, the Sun stays in its position. On the Earth we perceive the Sun as "rising" in the morning and "setting" in the evening. At noon the Sun is at its "highest" point, meaning the angle of incidence is closest to 90°. At an angle less than 90°, as in the morning and afternoon, the Sun's rays have to travel through more air (higher air mass value) until they reach the Earth's surface, which results in less irradiance as the atmosphere absorbs some of the radiation spectrum. Also, the radiation power is spread over a bigger surface of incident when the sunrays come from the side.

Local weather - the local weather is different in every part of the world and is constantly changing. However, some regions have a "typical" weather, e.g. the Sahara with its constantly high irradiation or mountainous regions that are constantly cloudy with low irradiation.

Collecting meteorological data - meteorological data can be obtained from many sources. National meteorological institutes can provide data as solar radiation tables for certain sites. These institutes often publish relevant data on their websites. For example, NASA provides a free and comprehensive set of meteorological data for every location on Earth that is also highly relevant to renewable energy systems.[1]

The most important data for the design of solar electric power supply systems are tables which indicate the daily irradiation or peak sun hours (PSH) for the desired site throughout the year. These tables are sometimes called insolation tables.

Table 3.1: Average monthly insolation on a horizontal surface in kWh/m²/d for Kainji, New Bussa (latitude 9.86° N) – *Source: NASA*

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual average
22-yr avg.	5.73	6.02	6.27	6.13	5.75	5.17	4.65	4.38	4.83	5.39	5.73	5.74	5.47

Table 3.2: Minimum PSH for the same site as a percentage of monthly average values for Kainji, New Bussa (latitude 9.86° N) – *Source: NASA*

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1-day minimum	52.3	45.6	17.2	20.0	12.6	12.5	7.31	17.1	4.76	27.8	40.3	61.8
3-day minimum	81.8	76.9	63.7	59.4	63.6	58.9	58.9	53.3	48.5	52.9	72.3	77.9

[1] Meteorological data by NASA:https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
7-day minimum	84.3	82.8	82.9	74.2	69.4	68.7	71.8	72.5	73.9	67.5	83.6	83.8
14-day minimum	87.5	86.1	90.9	83.6	78.1	82.3	79.0	82.8	76.7	79.2	90.8	88.5
21-day minimum	91.3	88.3	93.0	88.9	86.2	86.5	85.3	84.3	80.6	82.0	92.8	92.5
30-day minimum	94.2	91.8	93.6	99.3	88.3	93.2	93.5	89.4	85.0	90.1	93.5	95.2

Table 3.3: Average monthly midday irradiance on a horizontal surface for Kainji, New Bussa (latitude 9.86° N) – *Source: NASA*

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
22-yr avg.	0.82	0.86	0.88	0.81	0.75	0.69	0.60	0.56	0.65	0.74	0.81	0.82

PHYSICS OF PHOTOVOLTAICS

A photovoltaic cell converts sunlight directly into electricity. Photovoltaic stands for photo (light) and voltaic (electricity), whereby sunlight photons move electrons inside the photovoltaic cell. The photovoltaic effect was first observed by Alexandre-Edmond Becquerel in 1839. The first photovoltaic cells for commercial use were developed in 1950 at Bell Laboratories, USA, and were initially intended above all for space applications.

» Semiconductors

Semiconductors are the foundation of modern electronics. A semiconductor is a material which possesses electrical characteristics that are midway between metals and non-metals. A semiconductor is an element or a compound of two or more elements. Semiconductor elements are sometimes called metalloids. In the periodic system of elements they are placed between the metals and non-metals. However, the definition of a semiconductor in the periodic system of elements has changed as the newer definition relates more to the physical structure of the element than the chemical and electrical characteristics emphasised in previous definitions.

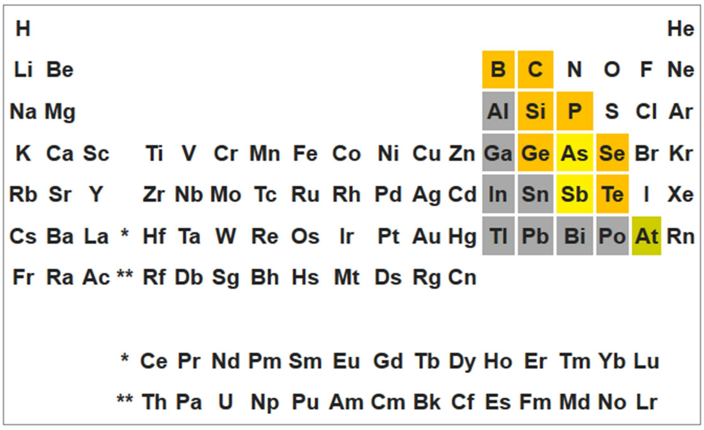


Figure 3.12: Periodic system of elements. Metalloids after the old definition are highlighted in orange, yellow and green, metalloids after the new definition in grey

Semiconductor materials are characterised as perfect insulators at a temperature of absolute zero, with charge carriers being made available for conduction as the temperature of the material is increased. It is imperative to note that different semiconductor materials have different electrical and physical properties. Silicon (Si) is the most commonly used semiconductor material which forms the basis for electronics and solar photovoltaics.

PHYSICAL STRUCTURE OF SEMICONDUCTORS

Silicon is the most commonly used semiconductor material in the world today. Pure silicon is rarely found in nature and as such, it often occurs in the form of silicate compounds like those in common sand. Silicon is a tetravalent element (it has four electrons on its outer shell). An individual silicon atom is electrically neutral, possesses an equal number of electrons (negatively charged particles) and protons (positively charged particles) and forms covalent bonds with other silicon atoms. When two atoms share electrons to complete the structure of their outermost shells, this bond is termed a covalent bond. Each silicon atom forms four covalent bonds with its four surrounding atoms as shown in the figure below:

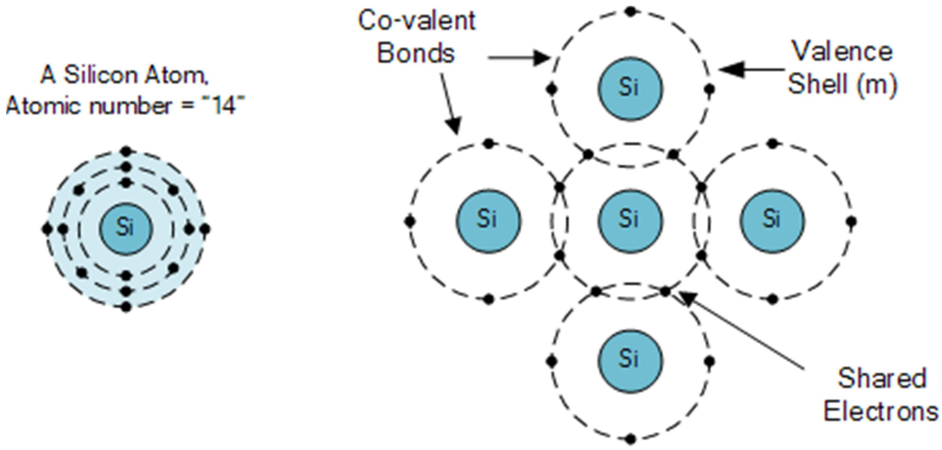


Figure 3.13: Silicon atom showing four electrons in outer shell (left), silicon crystal lattice (right) – *Courtesy: Electronics Tutorials, www.electronics-tutorials.ws/diode/diode_1.html*

ELECTRICAL CHARACTERISTICS OF SEMICONDUCTORS

Semiconductors change their properties relative to the temperature. At low temperatures, semiconductors act as insulators whereas at high temperatures, they act as conductors. At higher temperatures, the electrons in the outermost shell of the atom gain enough energy to break away from the bonds holding them in place, thus enabling them to move freely about the lattice structure, as is the case in metals. In reality, electrons are never stuck in the covalent bond, except at an absolute zero temperature (0 °C or -273 K). The minimum energy required to excite an electron, i.e. to enable it to break free of its covalent bond and participate in conduction, is called the band gap. The space left behind by these "excited" electrons allows the covalent bond to move from one electron to another, thus appearing to be a positive charge moving through a crystal lattice. The band gap is important because it enables excited electrons to remain in higher energy levels for long enough to be exploited to form electric current.

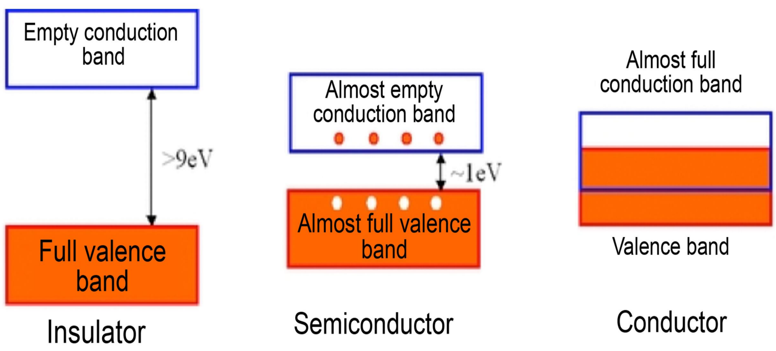


Figure 3.14: Band gaps of various materials

An excited electron leaves behind a hole which can be filled by an electron from a neighbouring atom. This second electron, on moving to fill the hole created, leaves behind another hole which is filled by yet another electron. This constant movement of electrons and the creation and filling of holes can be illustrated as the movement of positively charged particles through the crystal structure of a semiconductor. Thus, holes and electrons are commonly called carriers.

INTRINSIC SEMICONDUCTOR

A semiconductor material without a significant amount of dopant (impurities) is referred to as an intrinsic semiconductor. In intrinsic semiconductors, the number of free electrons and holes is equal, since the creation of an electron in the conduction band creates a matching hole in the valence band.

Doping **-** *d*oping refers to a method used to increase the population of holes and electrons by introducing impurities into the lattice structure of an intrinsic semiconductor. These impurities contribute more (N-type, negative) or fewer (P-type, positive) electrons to the silicon crystal than native elements. A doped semiconductor is an extrinsic semiconductor.

N-type semiconductors are created when atoms with one more valence electron (e.g. group V) are introduced as impurities into an intrinsic semiconductor. The spare electron roams freely about the lattice structure of silicon thereby increasing its conductivity due to the increased number of available electrons.

P-type semiconductors are created when the dopant carries one less valence electron (e.g. group III). The result is a material with a spare hole as four electrons are required to complete the bonding for an intrinsic semiconductor. P-type materials increase conductivity due to the increased number of holes in their structure. For use in photovoltaic cells both types of doped silicon are necessary.

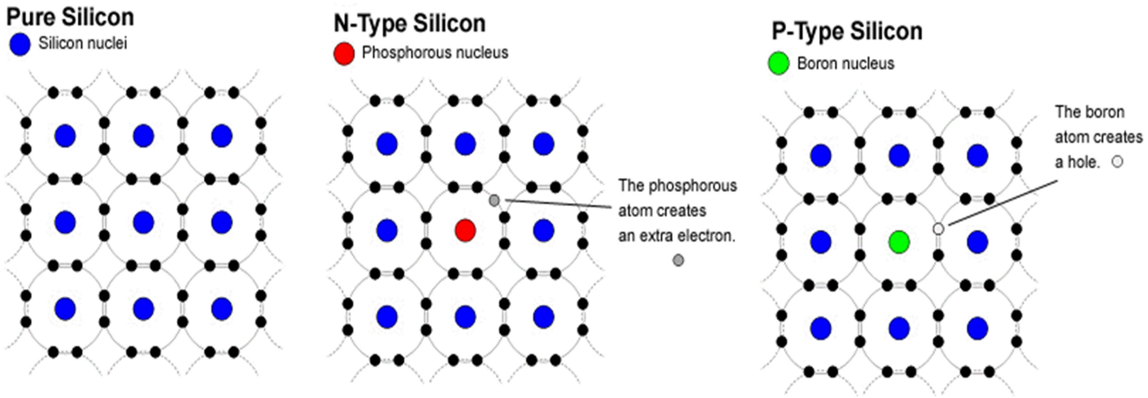


Figure 3.15: Arrangement of electrons in intrinsic silicon (left), N-type silicon (centre) and P-type silicon (right)

Table 3.4: Summary of doping in silicon

	N-type (negative)	*P-type (positive)*
Dopant	Group V (e.g. phosphorous)	Group III (e.g. boron)
Bonds	Excess electrons	Missing electrons (holes)
Majority carriers	Electrons	Hole
Minority carriers	Holes	Electrons

P-N JUNCTION

A P-N junction is formed by joining P-type and N-type semiconductor material. On one side of the junction, there is an excess of electrons (N-type region) and on the other side, there is an excess of holes (P-type region), an arrangement which creates a concentration gradient across the junction. This concentration gradient causes the free carriers to diffuse across the junction in a process called recombination. During recombination, excess electrons from the

N-type material diffuse to the P-type side and excess holes from the P-type material diffuse to the N-type side. The result on the P-side is boron atoms with 6 electrons instead of 5, which creates a negative charge. On the N-side the recombination process leaves phosphorus atoms with 14 electrons instead of 15, thus leaving these atoms positively charged.

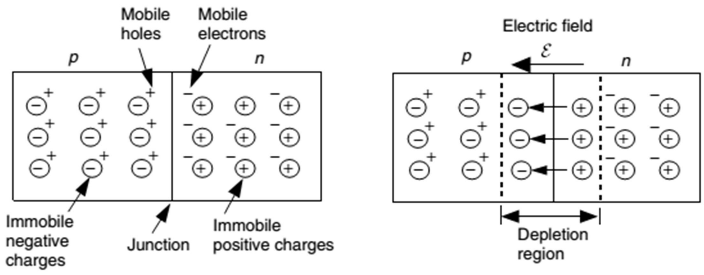


Figure 3.16: P-N junction when first assembled (left) and after recombination (right)

The movement of free carriers across the junction creates a layer of fixed charge due to the positively and negatively ionised (i.e. impure) atoms on either side of the junction. This space charge sets up an electric field that opposes further migration across the junction and stops the diffusion process. Devoid of free carriers, this region is called the depletion region. As a result of the electric field, a voltage is induced over the junction.

PHOTOVOLTAIC EFFECT

The photovoltaic effect refers to the conversion of light to voltage and electrical current. This is possible when a photovoltaic material is exposed to light.

When light (photons) with more energy than the band gap hits an electron in the valence band of a silicon atom, it lifts that electron into the conduction band. If this happens close enough to the P-N junction, then the electric field prevents the electron from falling back to its original position (recombination) and directs that electron from the P-side over the P-N junction to the N-side, accumulating a negative charge on the N-side. The second result of the movement of electrons to the N-side is movement of holes to the P-side, where a positive charge is accumulated. This accumulation of negative and positive charge creates a voltage, typically 0.6 V, across the solar cell.

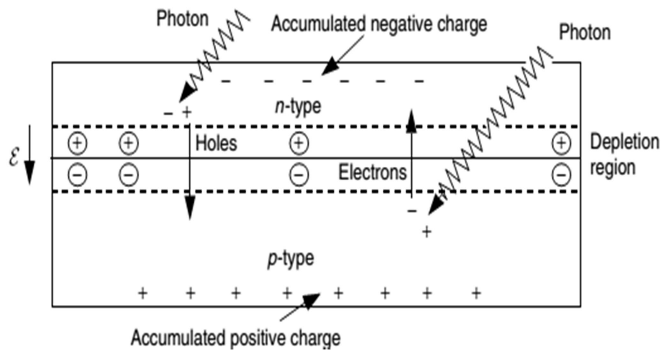


Figure 3.18: Photovoltaic effect

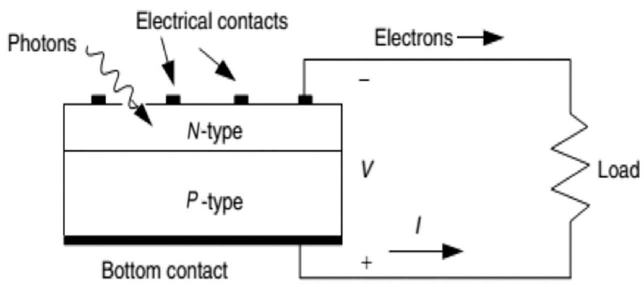


Figure 3.17: Basic circuit showing electron flow from an N-type semiconductor material

When a conductor connects to the P-layer and to the N-layer to create a circuit, the electrons which have accumulated in the N-layer travel back to the P-layer and fill the holes there. As light (photons) continues to strike into the PV cell, the process of movement of electrons continues.

This conversion of light mostly happens in the P-layer since it is much thicker compared to the N-layer. Most photons simply pass through the N-layer, making it a fleeting stop. The P-layer is the bottom layer of a solar cell.

LOSSES IN SOLAR PHOTOVOLTAIC CELLS

Efficiency and electric conversion losses - efficiency refers to the percentage of solar radiation that is converted to usable electric energy. Not only the visible light is converted to electric energy but also invisible radiation as UV and infra-red (IR) radiation. Short-wave UV radiation is more powerful than long-wave IR radiation.

Losses due to the non-usable radiation spectrum - photons must have enough energy to lift an electron from the valence band to the conduction band. That band gap differs with the type of material which is used for the solar cell. Depending on the PV cell material, a major portion of the solar spectrum cannot be used for lifting electrons into the conduction band and thus remains ineffective. Either the photons do not have enough energy or they have too much energy which cannot be fully used.

Losses due to recombination - after the electron is lifted into the conduction band, it might simply fall back into its original position or into another empty space in a different valence band. Should this occur, the electron is then lost as part of usable electric current. This process is called recombination and depends mainly on the quality of the material. Impurities in the material and multi-crystalline structures increase the recombination rate of electrons.

Losses due to reflection - a small part of solar radiation never penetrates the semiconductor material because it is reflected on the material surface or already on the cover glass. Fine electrical contacts on the upper layer also reflect some of the radiation. Reflection can be reduced by using an anti-reflective (AR) coating and by keeping the electrical contacts as thin as possible.

Electrical losses - electrical losses occur due to the ohmic resistance which the electrons face on their journey through the semiconductor. This series resistance is mainly influenced by the electron-emitting N-layer and the surface contacts; it is dependent on the design and quality of the cell. Internal short-circuits can also occur, mainly due to manufacturing defects or cell damage, an effect which is referred to as shunt resistance.

In a typical commercial silicon solar cell with an efficiency of 18%, the losses are approximately distributed as follows:

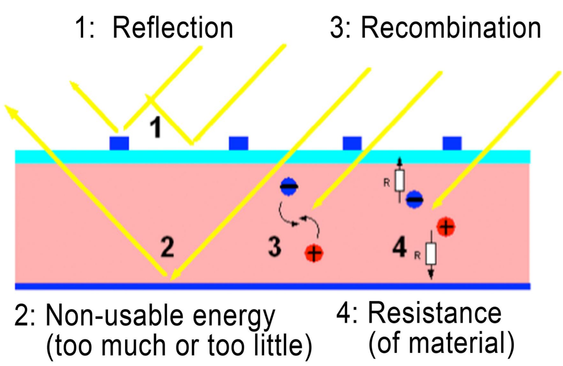


Figure 3.20: Losses in a silicon photovoltaic solar cell

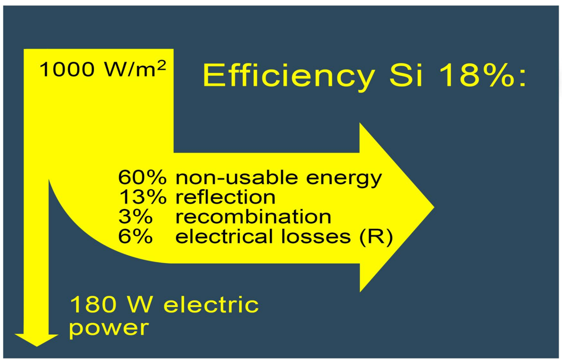


Figure 3.19: Losses in a PV cell due to reflection and recombination

» *Photovoltaic cell design and material*

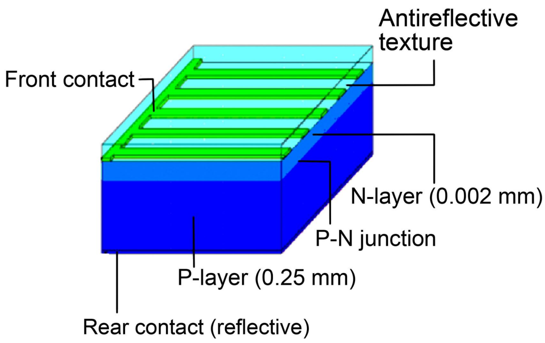


Figure 3.21: Typical structure of a solar cell

PHOTOVOLTAIC CELL DESIGN AND STRUCTURE

The basic solar cell is a semiconductor wafer grown or deposited on a conducting substrate. The area of a solar cell is usually in the range of 10 to 100 cm^2. The front surface is usually coated with an anti-reflection (AR) material and contacted with a fine metal grid which serves as a conductor for the electrons. The upper layer where the sunlight first strike is the N-layer, which is very thin compared to the lower P-layer. Under the P-layer is the rear electrical contact. This contact simultaneously serves as a reflector to reflect unused light particles (photons) back into the solar cell. Cells are usually connected in series to deliver a useful voltage (17 V to 34 V as standard) before being encapsulated into modules. A typical device structure is shown above

PHOTOVOLTAIC CELL MATERIALS

There are many semiconductor materials which can be used for solar cells. However, few are suitable for large-scale manufacturing and commercial use from an economical and environmental standpoint. Some are used only in special applications where material costs and environmental sustainability are not important factors (e.g. space applications). Furthermore, these various semiconductor materials can be combined in the form of thin layers to create solar cells that are capable of absorbing a broader spectrum of light, thereby increasing their efficiency.

The most common material by far is monocrystalline or polycrystalline (multi-crystalline) silicon. Silicon is relatively cheap, abundant and non-toxic, and benefits from the extensive development of silicon technology for the microelectronics industry.

The best lab efficiency obtained with a simple silicon solar cell is 24.7%. In mass production, 16 to 20% can be achieved depending on the device technology used. Polycrystalline silicon is cheaper to produce but delivers a lower efficiency (around 15 to 18% in the best cells).

Thin-film solar cell materials include amorphous silicon, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). Amorphous silicon has been used as the base material for inexpensive consumer PV products such as solar-powered calculators, but suffers from material degradation (Staebler-Wronski effect), which may inhibit its use in higher power applications.

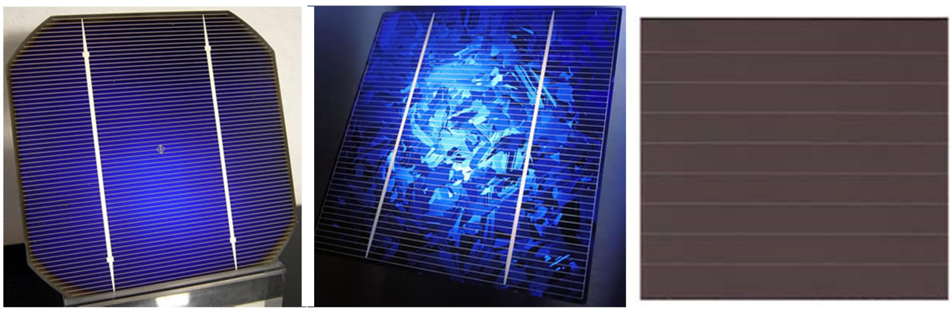


Figure 3.22: Types of cells: Monocrystalline silicon (left), poly-crystalline silicon (centre) and amorphous silicon (right)

Table 3.5: Comparison of different PV cells

Cell type	*Efficiency*	*Advantages*	*Disadvantages*
Mono-crystalline silicon	16–20%	Higher efficiency Good low-light performance Good power-to-size ratio Outstanding performance in cool conditions Excellent lifespan Well understood technology Non-poisonous material	High amount of waste during manufacturing High retail cost Poor performance in high-temperature environments
Poly-crystalline silicon	15–18%	Less expensive to produce than monocrystalline Slightly better performance in hotter conditions Excellent lifespan Non-poisonous material	High amount of waste during manufacturing Low performance in high temperature Less aesthetically pleasing appearance
Amorphous silicon	6–9%	Optimal performance in hotter climate Cheaper to manufacture than mono- and poly-crystalline Non-poisonous material	Expected lifespan is less than crystalline panels Requires 2 to 3 times more panels and surface area for same output as crystalline
Cadmium telluride	7–10%	Low cost of manufacturing Aesthetic appearance Can be manufactured to be flexible Excellent performance in high temperatures	Cadmium is very poisonous Requires a lot of space Faster degradation than crystalline silicon
Gallium arsenide	20–30%	Temperature resistant Suitable for use in space exploration	Very expensive to manufacture Arsenide is very poisonous

ELECTRICAL CHARACTERISTICS OF PHOTOVOLTAIC CELLS

Equivalent circuit - the complex physics of the photovoltaic cell can be represented by the equivalent electrical circuit shown Figure 3.23. The circuit parameters are as follows: The current I at the output terminals is equal to the light-generated current I_L, less the diode current ID and the shunt-leakage current I_{sh}. The series resistance R_s represents the internal resistance to the current flow.

The shunt resistance R_{sh} is inversely related to the leakage current to ground. In an ideal photovoltaic cell, R_s =0 (no series loss) and $R_{sh} = \infty$ (no leakage to ground).

In a typical silicon cell, R_s varies from 0.05 to 0.10 Ω and R_{sh} from 200 to 300 Ω. The conversion efficiency of a photovoltaic cell is sensitive to small variations in R_s, but is insensitive to variations in R_{sh}. A small increase in R_s can decrease the output significantly. In the equivalent circuit, the current delivered to the external load equals the current I_L generated by the illumination, less the diode current ID and the shunt leakage current I_{sh}.

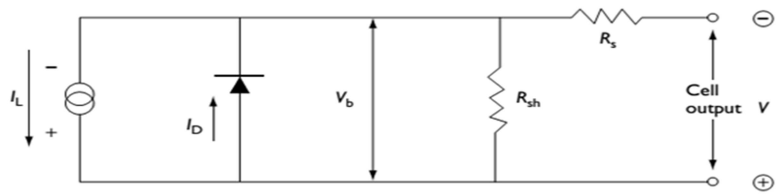


Figure 3.23: Simplest equivalent circuit of a solar cell

The open-circuit voltage V_{OC} of the cell is obtained when the load current is zero, i.e., when I_L = 0.

Voltage output **-** the voltage generated by a solar cell depends mainly on three factors:

- Cell technology (semiconductor type, structure and junctions): A silicon cell usually has an open-circuit voltage of approximately 0.6 V; other cell technologies can be slightly higher or lower.
- Temperature: With increasing temperature the open-circuit voltage decreases slightly, approximately 0.5% per Kelvin.
- Irradiance: A solar cell generates its full voltage already at a very low irradiance. This voltage remains almost constant at any level of irradiance.

Open-circuit voltage (Voc) **-** this is the voltage across a solar cell when the resistance between the positive and negative terminals is infinite. It is the voltage across the cell under no-load conditions.

Current output **-** the current generated by a solar cell depends mainly on three factors:

- Cell technology (semiconductor type, structure and junctions): Certain cell designs can convert a broader spectrum of solar radiation to electrical current than others.
- Cell size: A solar cell with a larger area can absorb and convert more radiation than a smaller cell.
- Irradiance: The output current of a solar cell is directly proportional to the irradiance which it receives.

Short-circuit current (Isc) **-** this is the current flowing through a solar cell when it is not connected to any load and the voltage across it is zero.

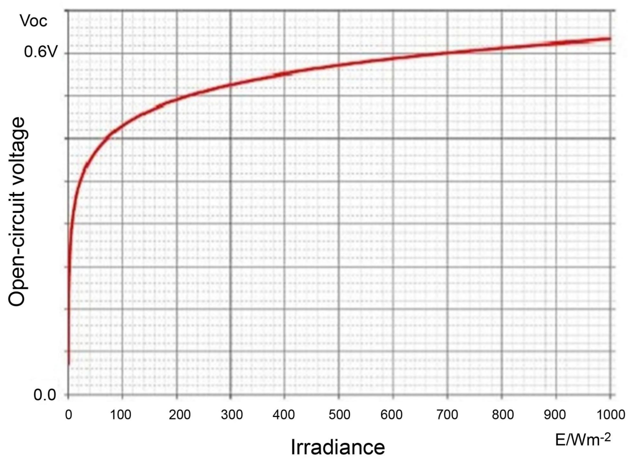


Figure 3.24: Relationship between irradiance and open-circuit voltage of a solar cell

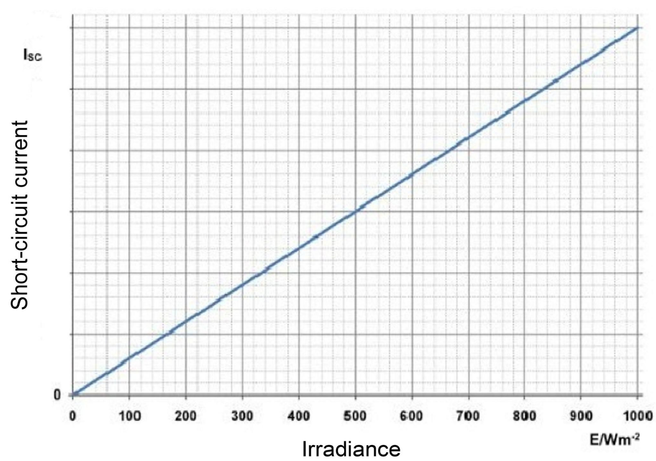


Figure 3.25: Relationship between irradiance and short-circuit current of a solar cell

I-V curve - the IV curve is often used to illustrate cell performance. It shows the relationship of current and voltage at open-circuit, load and short-circuit conditions. I-V curves at different irradiance levels illustrate that an increase in light intensity causes a clear increase in short-circuit current and load current and only a minimal increase in the open-circuit voltage.

Effect of temperature - higher temperatures increase the conductivity of the semiconductor, therefore decreasing the efficiency of the solar cell. This occurs because increased conductivity balances out the charge within the material, which reduces the magnitude of the electric field at the junction. Charge separation is inhibited and the voltage across the cell lowered. It should be noted though that a higher temperature increases the mobility of electrons, which causes the flow of current to increase slightly. This increase in movement is, however, minor and insignificant compared to the decrease in voltage. In essence, I-V curves at different temperature levels show that the open-circuit voltage is rapidly decreasing with rising temperature while the short-circuit current decreases slightly.

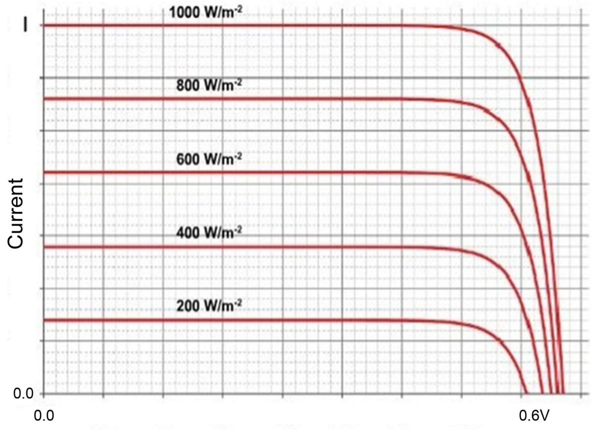


Figure 3.26: Effect of changing irradiation on a solar cell

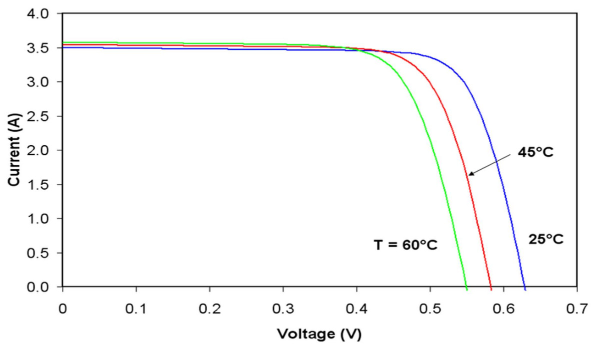


Figure 3.27: Effect of temperature on the I-V curve of a solar cell

Power output - when recording the I-V curve of a PV cell under changing load conditions at a constant irradiance and calculating the resulting power, it can be observed that each solar cell has a certain point where maximum performance with regards to power output is achieved. This point is called the maximum power point (MPP). The voltage level at this point is approximately 80% of the open-circuit voltage (V_{OC}). The voltage at this MPP is called the maximum power voltage (V_{MPP}). The current at this MPP is called the maximum power current (I_{MPP}).

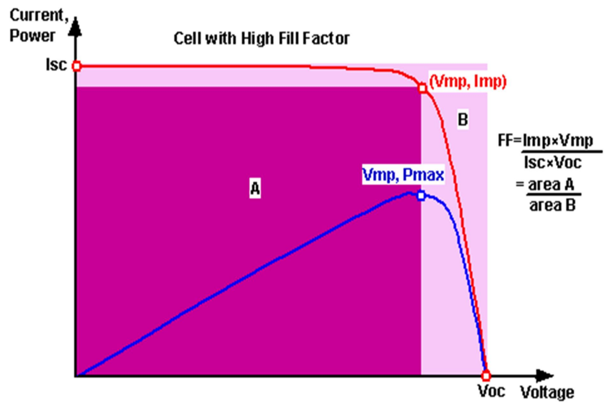


Figure 3.28: I-V (red) and power (blue) curves of a solar cell – *Courtesy: C. Honsberg and S. Bowden, www.pveducation.org*

Fill factor (FF) - a solar cell does not generate any power at V_{OC} or at I_{SC}. However, this theoretical power which is the product of V_{OC} and I_{SC} is used to determine the fill factor of a solar cell. The fill factor is indicated as a percentage and used as a measure of the quality of a solar cell. The fill factor of a good quality solar cell should be greater than 80%.

COMPONENTS OF PV SYSTEMS

» PV modules

PV cells are connected electrically in series to PV modules in order to produce higher voltages and power levels. Most PV modules consist of 30, 36, 60 or 72 cells connected in series. These cells generate an open-circuit voltage (V_{OC}) of 18.5 V to 22.5 V or 37 V to 45 V.

Figure 3.29: Field of solar panel arrays

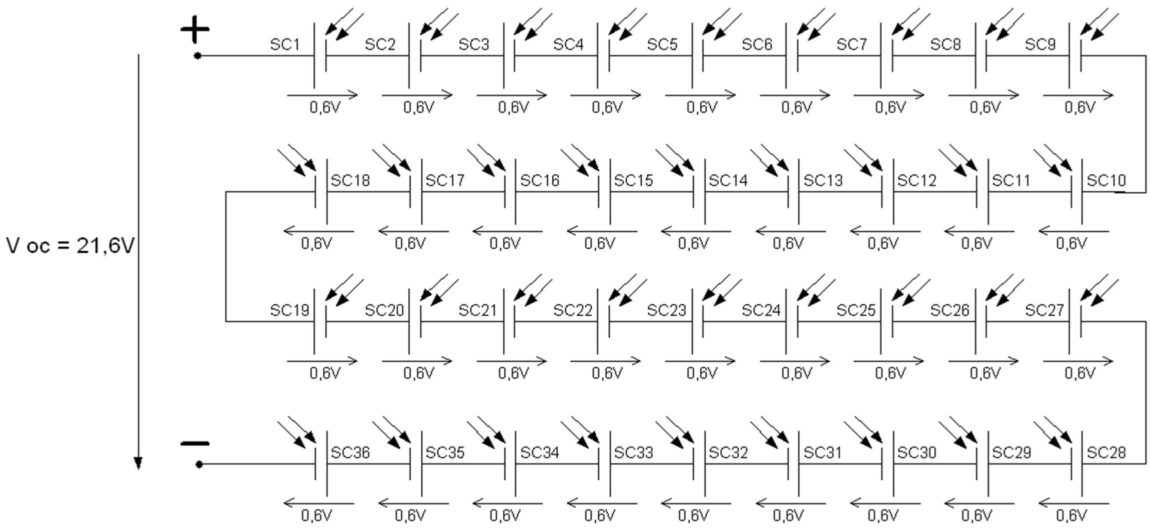


Figure 3.30: Circuit diagram of 36-cell PV module

Primary PV module components:

- Tempered glass cover with antireflective texture
- Laminate for additional sealing of solar cells from environmental impacts such as moisture
- Solar cell circuit with electrical contacts
- Second layer of laminate
- Back sheet
- Aluminium frame
- Junction box for wiring connections
- Bypass diode(s) inside the junction box

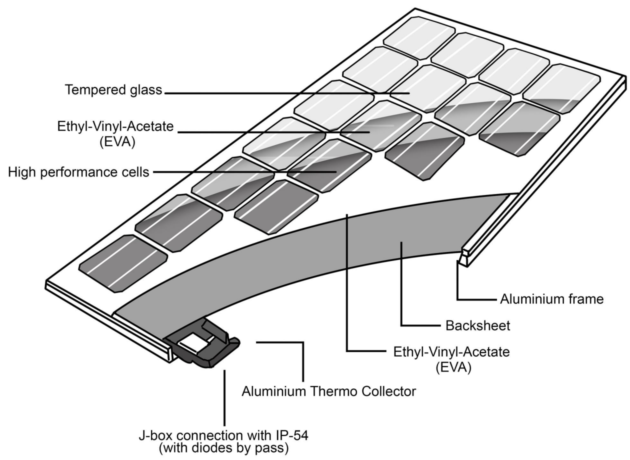


Figure 3.31: Cross-section of PV module

» *Performance of PV modules and STC*

Manufacturers of photovoltaic modules provide the technical specifications for their products on a data sheet and on the label on the rear facing of the solar module. However, most of the stated performance specifications are not real-life values, i.e. values that refer to operation in a realistic environment, but are based instead on certain laboratory conditions. This somewhat artificial environment is also known as STC or standard test conditions.

Standard test conditions are used globally by photovoltaic module manufacturers to specify performance and to compare different modules. STC are based on the following values:

- Temperature = 25°C
- Irradiance = 1,000 W/m^2
- Air mass = AM 1.5

A data sheet section for a "Lorentz LC80-12M"photovoltaic module is shown below. The tolerance of ±3% refers to the power output. The high open-circuit voltage of 22.4 V is typical for a 36-cell photovoltaic module. The negative temperature coefficient for P_{max} and V_{OC} indicates the power and voltage loss with increasing temperature. The positive temperature coefficient for I_{SC} indicates the current gain with increasing temperature.

Electrical Data

Peak power	Pmax	[Wp]	80
Tolerance		[%]	+3/−3
Max. power current	Imp	[A]	4.6
Max. power voltage	Vmp	[V]	17.2
Short circuit current	Isc	[A]	5.0
Open circuit voltage	Voc	[V]	22.4
Temperature co-efficient for Pmax		[%/°C]	-0.50
Temperature co-efficient for Voc		[%/°C]	-0.35
Temperature co-efficient for Isc		[%/°C]	0.09
Max. system voltage		[V]	600

All technical data at standard test condition:
AM = 1.5, E = 1,000W/m², cell temperature: 25 °C

Figure 3.32: Data sheet section of Lorentz LC80-12M photovoltaic module

Example: At noon and under intense sunlight, the Lorentz LC80-12M PV module reaches a cell temperature of 65°C.

- ⇒ *This temperature is 40°C higher than STC.*
- ⇒ *The power loss would be 40 × 0.5% = 20%.*
- ⇒ *The power output at 1,000 W/m² and 65°C would be 80 W – 20% (80 W) = 64 W.*
- ⇒ *The reduction of open-circuit voltage would be: 40 × 0.35% = 14%*
- ⇒ *V_{OC} would be 19.3 V.*
- ⇒ *The power output at 600 W/m² and 65°C would be 80 W × 0.6 – 20% = 47.8 W.*

At very low operating temperatures, the voltage and power output of a photovoltaic module increase. This increase has to be considered when sizing charge controllers. Modules with a higher number of cells and higher voltages are preferable in off-grid installations at sites with high temperatures as the output voltage decreases with rising temperature.

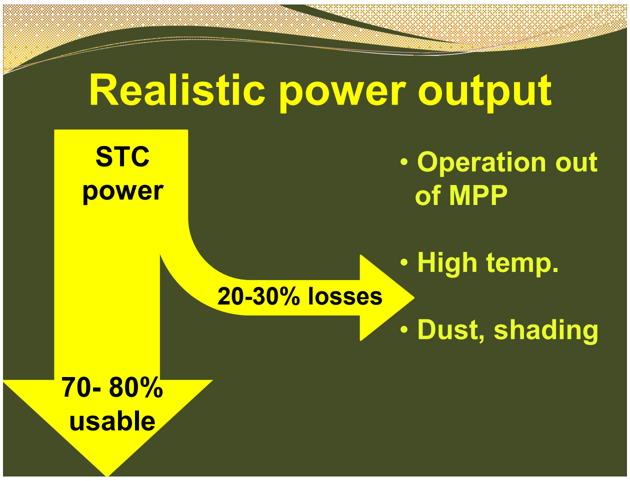


Figure 3.33: Losses in a PV module

SHADING

Shade on a solar module, whether full or partial, has a highly adverse effect and causes a massive reduction in power output. A shaded cell is not only lost as a generator of electric power, it also reverses its behaviour from generating current to resisting its flow. As the other cells still work and generate electricity, they are forced to "push" their current through the shaded "resistor cell", which consumes power generated from the other cells. Therefore, a shaded cell becomes an electrical power *consumer*.

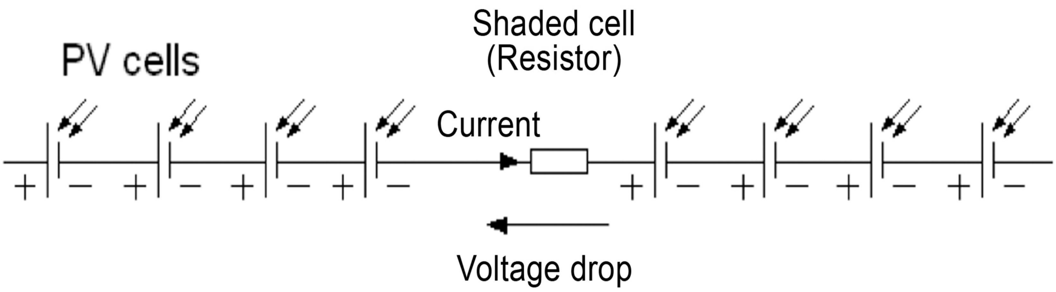


Figure 3.34: Current pattern in shaded cell

Important **-** even small amounts of shading – as little as 2% – on a photovoltaic module can reduce the power output of the module by up to 100%

HOT SPOT EFFECT

When a photovoltaic module is shaded, the shaded cell behaves like a resistor, thereby causing a voltage drop in the cell. Electrical power is consumed as the shaded cell heats up.

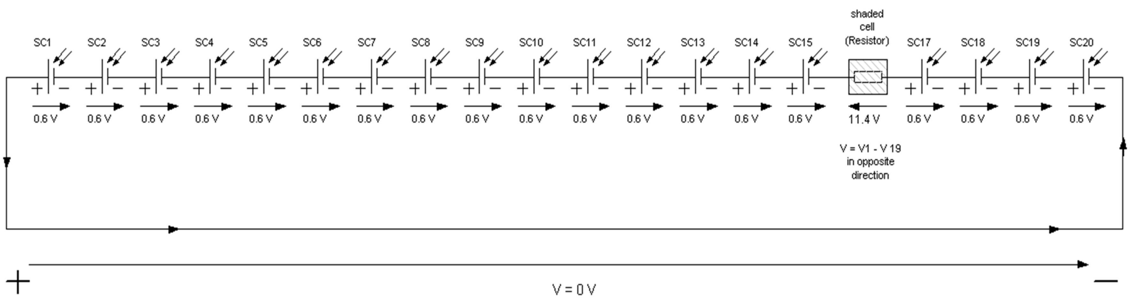


Figure 3.35: Hotspot in a PV module

Under certain conditions [see later section on shunt (parallel) controllers], this one cell can consume the power generated by one whole PV module or even by all PV modules connected in series and therefore become so hot that the cell and the complete PV module will be destroyed. To avoid this scenario, powerful modules connected in series must be equipped with so-called bypass diodes. As Figure 3.36 shows, with a bypass diode, current is now able to bypass a shaded cell. Power generated by other cells is not consumed and the other modules are protected from damage caused by a hotspot.

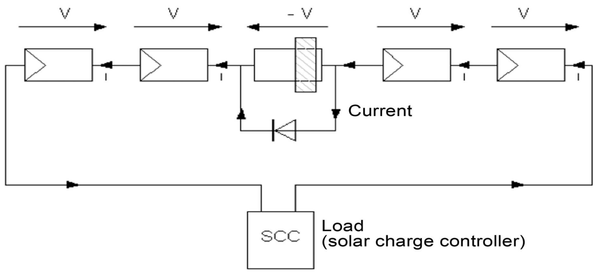


Figure 3.36: Bypass of current over diode

SHADING CAUSED BY DUST

Dust is a source of shade and a very common factor that significantly reduces the output of a PV system, especially when the system is mounted on a hard-to-reach site like a tilted roof on a high building. Dust causes even shading of all cells and modules and therefore does not result in hotspots, but it can easily and quickly lower the system's performance.

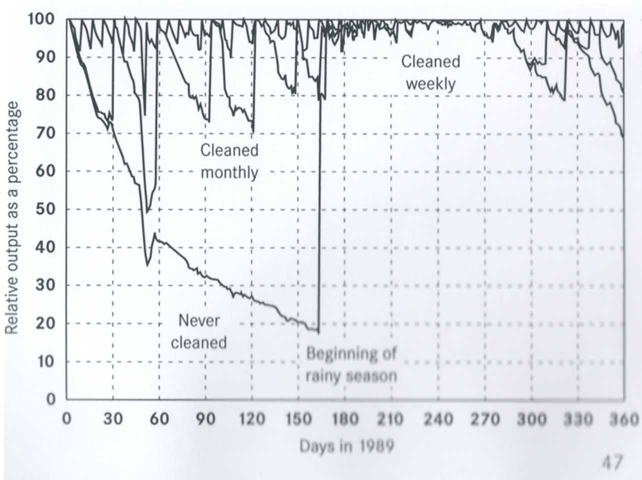


Figure 3.37: Solar array output at different cleaning intervals in % for an installation in Senegal

Table 3.6: Some maintenance activities for solar panel arrays

Frequency of cleaning	*Effect*
Weekly	Approximately 10% loss towards the end of the week during dry season, output returns to 100% after cleaning
Monthly	Approximately 30% loss towards the end of the week during dry season, output returns to 100% after cleaning
Never	Approximately 80% loss towards the end of the dry season, output returns to 100% with beginning of rainy season

» *Lifetime*

Today's photovoltaic modules are extremely safe and reliable products, with minimal failure rates and projected service lifetimes of 20 to 30 years (crystalline silicon) and 7 to 10 years (amorphous silicon). Most major manufacturers offer warranties of twenty or more years as the modules maintain high percentage of the initial rated power output.

» *Solar array*

The connection of several photovoltaic modules to achieve a higher power output is called a solar array. Depending on how the photovoltaic modules are connected, whether in series or parallel, it is possible to increase either the voltage or current.

- Series connection to achieve higher voltages:

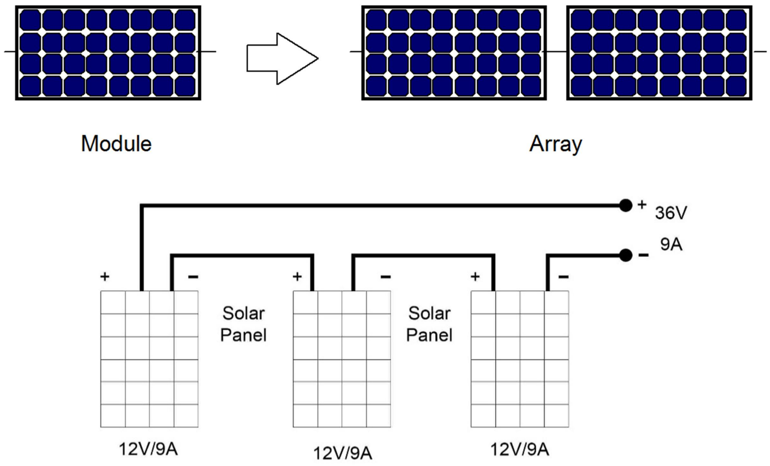


Figure 3.38: Connecting identical PV modules in series

The array voltage is the sum of the individual voltages of each solar panel. The array current is determined by the solar module with the least current.

- Parallel connection to achieve higher currents:

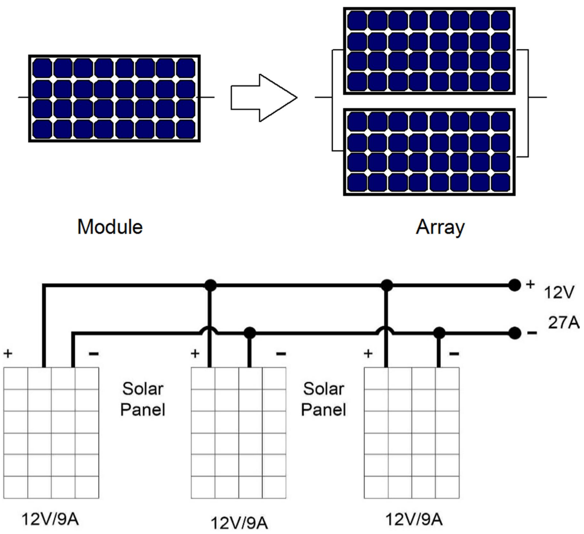


Figure 3.39: Connecting identical PV modules in parallel

The array current is the sum of the individual currents of each solar panel. The array voltage is determined by the solar module with the lowest voltage.

- Series-parallel connection to achieve higher voltages and currents:

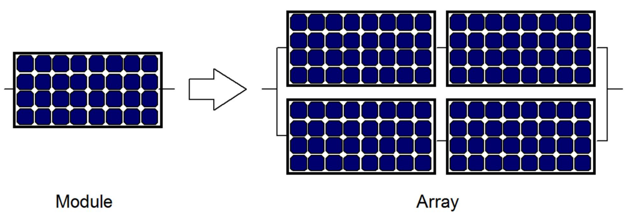


Figure 3.40: Series-parallel configuration of solar panels

When connecting photovoltaic modules, it is important to remember the following important points:

- The array voltage is the sum of the individual voltages of each solar panel in a string.

- The string with the least voltage determines the array voltage.
- The array current is the sum of the individual currents of each string.
- The string current is determined by the current of the photovoltaic module with the least current.

It is very important that all of the panels in your array are as identical as possible. In an array, you should use panels of the same brand and the same characteristics, because any difference in their performance will have a large impact on the health and overall performance of your system. Even panels that have identical performance ratings will usually display some variance in their characteristics due to manufacturing processes. The operating characteristics of two identical panels from the same manufacturer can vary by as much as ±10%. Whenever possible, it is a good idea to test the real-world performance of individual panels to verify their operating characteristics before assembling them into an array.

Figure 3.41: Rooftop-mounted

Figure 3.42: Pole-mounted PV array – *Courtesy: Accutrack Solar Systems, www.accutrack.com*

» Mounting

Solar modules and arrays can be mounted in many ways; however, most systems are installed on poles, rooftops, or on the ground, either as fixed-tilt or tracking systems.

Figure 3.43: Ground-mounted solar PV array – *Courtesy: Melissa Van Hoorne, http://blog.solarmicronics.co (accessed Jan. 28, 2016.)*

Figure 3.44: Tracking systems mounted on poles

When choosing a location and structure for mounting, achieving the maximum energy yield is the number one concern. That means aiming to install the system with the best possible angle and orientation and to avoid shading as much as possible. When mounting on poles or on the ground, the space between the arrays must be considered to minimise shading in the early morning or late afternoon. Anti-theft measures should also be taken to protect the photovoltaic modules. This can be done in several ways:

- Mounting out of reach (pole, rooftop, perimeter fencing)
- Anti-theft mounting techniques (anti-theft screws, locks)
- Electronic alarm
- Surveillance measures (guards)

Table 3.7: Advantages and disadvantages of mounting sites and techniques

	Advantages	*Disadvantages*	*Application*
Pole mounting	Simple construction Possible on almost any terrain Can be adjusted to optimise tilt and direction Good protection against theft	Difficult to clean	Inner-city installations Signposts and parking lots
Rooftop mounting	Installation is close to the consumer resulting in less energy loss Less mounting infrastructure required compared to other mounting types Less land required Good protection against theft	Feasibility depends on roof Not usually possible to optimise direction/orientation Difficult to clean	Privately owned systems All buildings with suitable roof Domestic and commercial
Ground mounting	Easy to clean Can be adjusted to optimise tilt and direction	Poor anti-theft protection	Suitable for applications that require large arrays
Tracking systems	Higher energy yield per unit area Higher output power in the early morning and late afternoon	Extra cost Extra maintenance	Suitable for applications that require maximum output on limited space Applications that require increased output in morning and afternoon, e.g. pumping systems

A tracking system can achieve an energy yield that is up to 30% higher than that of fixed-tilt systems. However, tracking systems also involve extra investment and maintenance costs. In some cases, that extra money might be better spent on extra fixed-tilt solar modules, especially since the prices for solar modules have greatly decreased in recent years.

» *Batteries*

A battery is a device that produces electrical energy from chemical reactions. Batteries are an integral component of every solar-powered off-grid system and account for up to 40% of capital costs. They also require maintenance and replacement as they have a finite lifespan which is less than that of the photovoltaic modules.

CLASSIFICATION OF BATTERIES

Batteries can be broadly classified into primary and secondary batteries, with a number of subtypes.

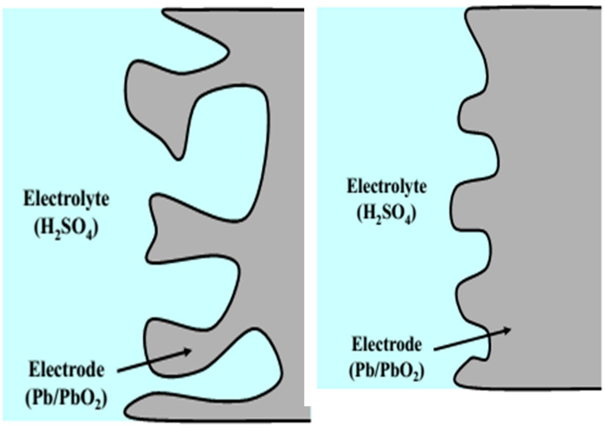


Figure 3.46: Electrode structure of starter battery (left) and deep cycle battery (right) – *Courtesy: Professor Ingo Stadler*

Figure 3.45: 1.5 V alkaline batteries

Primary batteries **-** primary batteries cannot be recharged after use and are discarded following discharge. Most primary batteries are contained within absorbent (semi-solid) material and are thus termed dry cells. Examples include 1.5 V alkaline batteries.

Secondary batteries **-** a battery that can be electrically recharged after use to its original precharge state by passing current through it is called a secondary battery. Examples include car and laptop batteries.

TYPES OF SECONDARY BATTERIES

Lithium-ion batteries **-** these batteries are often found in electronic devices such as laptops and mobile phones. They are currently one of the most common types of secondary batteries in the market. In this battery, a lithium ion moves from the anode to the cathode during operation, whilst the reverse is the case during the charge process.

Advantages	***Disadvantages***
• High energy density.	• Moderate discharge current.
• 1,000 charge cycles.	• High manufacturing costs.
• Low self-discharge.	• Susceptible to explosion due to mechanical, thermal or chemical stress.
• High efficiency.	• Requires built-in protective circuit to keep current and voltage within safe limits.
• High open-circuit voltage.	• Subject to ageing even when unused.

Nickel-cadmium (NiCd) batteries **-** the anode of the NiCd battery is made of cadmium, a poisonous metal, whilst the cathode is made of nickel hydroxide. The anode and cathode are separated by a layer of nylon. The electrolyte is potassium hydroxide. A typical NiCd battery weighs about half the weight of a lead-acid battery of comparable capacity and is more tolerant of a wide range of temperatures. However, the NiCd battery is generally being replaced because of the adverse environmental effect of cadmium.

Advantages	***Disadvantages***
• Simple charger technology • Long cycle life • Very robust, allows deep discharge and storage in discharged state • Wide temperature range	• Memory effect, must be completely discharged regularly to prevent capacity loss • Poisonous material

Nickel-metal hydride (NiMH) batteries - these batteries are similar in construction to the NiCd battery with the exception of cadmium, which is a poisonous metal. The anode is made of metal hydride while the cathode is made of nickel hydroxide. The energy density is more than twice the energy density of a NiCd battery.

Advantages	***Disadvantages***
• Easy to store and transport • More environmentally friendly than NiCd	• Performance begins to decline after 300 cycles • Sensitive to faulty charge • High self-discharge

Table 3.8: Characteristics of different battery types

Type	***Lead-acid***	***Lithium-ion***	***Nickel-cadmium***	***Nickel-metal hydride***	***Nickel-zinc***
Cell voltage (V)	2	3.7	1.2	1.2	1.65
Specific energy (Wh/kg)	33–42	100–200	40–60	60–120	100
Energy density (Wh/l)	60–110	200–300	50–150	140–300	280
Self-discharge (% per month) at 20^{o}C	2–5%	8–15%	10%	20–30%	>40%
Cycles until 80% DoD	200–400	1,000–2,000	1,000	300–500	400–1,000
Operating temperature range (^{o}C)	-20°C–50°C	0°C–50°C	0°C– 60°C	0°C–60°C	0°C–60°C
Relative cost per Wh	NGN 60	NGN 200	NGN 600	NGN 400	NGN 120

Lead-acid battery - the lead-acid battery is a rechargeable battery in which the electrodes are grids of lead containing lead oxides that change in composition during charging and discharging. The electrolyte is dilute sulphuric acid. The lead-acid battery is the most common battery used in solar PV systems. It is an established technology that is robust and cheap compared to other types of batteries. With proper

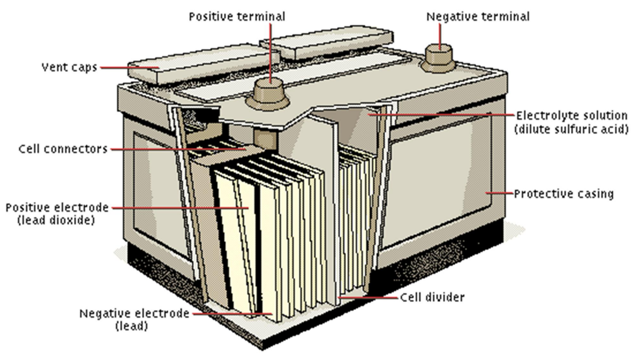


Figure 3.47: Components of a lead-acid battery

operation it can reach a long lifespan (up to 10 years). Lead-acid batteries are commercially available in 2 V, 6 V, 12 V and 24 V as they are made up of cells with nominal voltage of 2 V each. Hence, a 6 V battery is made up of three individual cells just as the 12 V and 24 V batteries are made of 6 and 12 cells, respectively.

DISCHARGE PROCESS

When the battery is connected to a load, at the positive plate the lead dioxide (PbO_2) reacts with the sulphuric acid (SO_4) ion to produce lead sulphate ($PbSO_2$) and two parts of water. At the negative plate, lead reacts with acid to produce lead sulphate. Since with the discharge reaction, acid is reduced and water is produced, the acid concentration in the cell drops with increasing discharge. The discharge process is defined by the following chemical reaction:

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{discharge} 2PbSO_4 + 2H_2O + 2\acute{e}$$

CHARGE PROCESS

When a current source is connected to a battery, it drives electrons through the battery causing the lead sulphate to become lead oxide (positive electrode), while the lead sulphate becomes lead (negative electrode). The charging process is defined by the following chemical reaction:

$$PbO_2 + Pb + 2H_2SO_4 \xleftarrow{charge} 2PbSO_4 + 2H_2O + 2e^-$$

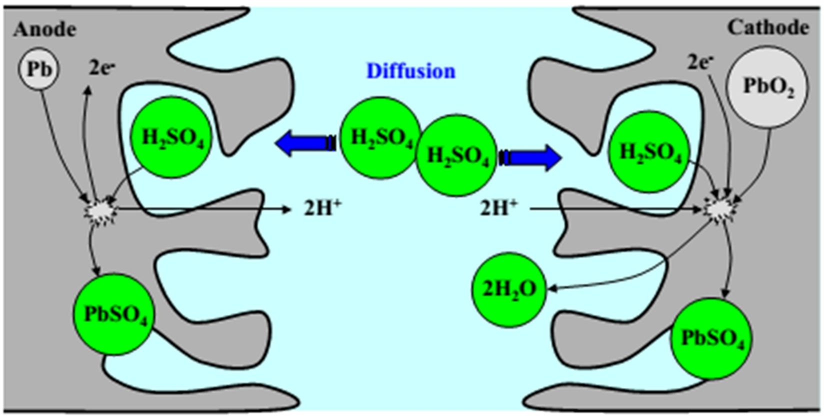


Figure 3.48: Chemical reaction in a lead-acid battery during the discharge process

Table 3.9: Advantages and disadvantages of a lead-acid battery

Advantages	*Disadvantages*
• Mature and dependable	• Heavy
• Cost-effective	• Low cycle and deep discharge stability
• Low self-discharge	• Cannot be stored in discharge mode
• Low maintenance	
• High cell voltage	
• Recyclable	

There are two main construction types for the lead-acid battery, namely:

FLOODED BATTERY

This type of lead-acid battery consists of a lead anode and lead-oxide cathode immersed in a liquid electrolyte such as sulphuric acid. The lead-acid battery is the most common type of commercially available battery and has been used for decades in various applications.

VALVE-REGULATED LEAD-ACID (VRLA) BATTERY

Also known as the sealed or dry battery, the VRLA battery operates based on the same basic chemistry as the flooded battery but it uses a semi-solid electrolyte. Sealed batteries are constructed to prevent gas development, which means that they do not require topping up with distilled water.

Figure 3.49: Typical 12 V dry cell battery – *Courtesy: Wellsee Solar Supply www.chargeinverters.com*

There are two common types of sealed batteries, namely:

- Absorbed glass matt (AGM) battery: Contains electrodes separated by a mat of glass fibres which completely absorbs the electrolyte. Most common type of sealed battery in the Nigerian market.
- Gel battery: Battery electrolyte contains silicic acid which forms a gel. Features a longer life cycle than the AGM battery.
- Gel battery with tubular plate: Features a high cycle stability and long lifespan

APPLICATION OF LEAD-ACID BATTERIES

Starter batteries - starter batteries are designed to deliver high currents for short periods of time. They are not designed to be discharged by more than 10% of their capacity. In the event of a deep discharge, the structure of the lead electrode changes and the lead sulphate which usually dissolves in the acid crystallises onto the lead electrode in a process known as *sulfation.* Starter batteries can be flooded or sealed. Car batteries are a common example.

Deep cycle batteries - deep cycle batteries are specifically designed for off-grid energy storage and deep cycling. Unlike starter batteries, deep cycle batteries can withstand a discharge of up to 80% of their rated capacity. This is because their electrodes are made of solid lead rather than sponge. The thicker plates thereby allow for more cycling of the battery. Deep cycle batteries can be flooded or sealed.

BATTERY SPECIFICATIONS

Capacity - capacity refers to the total amount of electrical charge that can be drawn from a fully charged battery until it is discharged to a specified voltage. It is measured in ampere-hours (Ah).

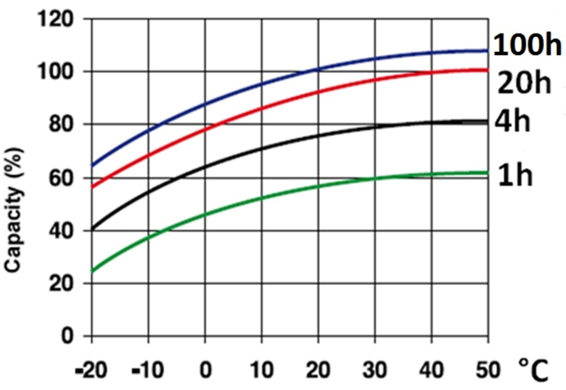


Figure 3.50: Relationship between temperature and battery capacity

A battery's rated capacity is measured under specific conditions, usually 20°C, whereas its actual capacity depends on a number of real-life factors including its charge mode, discharge current (a low discharge rate permits a greater actual capacity) and operating temperature. The graph below shows the relation between capacity, discharge rate (time) and temperature of a lead-acid battery.

State of charge (SoC) - state of charge refers to the charge level of a battery. It is expressed as a percentage. The state of charge is a battery's actual capacity in proportion to its rated capacity. If a 100 Ah battery is charged with only 60 Ah, then its SoC is 60%. The SoC can be determined by measuring the open-circuit voltage across the battery terminals. The table below shows the indicative SoC for different types of 12 V batteries that are common in PV and hybrid systems.

Table 3.10: Reference voltage levels depicting various SoC levels for different battery types

SoC	Type of battery		
	Gel	Absorbed glass matt (AGM)	Flooded
100%	12.95	>12.8	12.60
75%	12.74	12.55	12.36
50%	12.54	12.30	12.10
25%	12.34	12.20	11.90
0%	12.10	12.00	11.80

Note that determining SoC by measuring voltage is only accurate when the battery has been disconnected from charging or discharging for some time. For a small 8 Ah battery you should wait 30 minutes, while for a large 200Ah battery you need to wait several hours.

Depth of discharge (DoD) - depth of discharge refers to the amount of charge discharged from the battery in proportion to its rated capacity. It is expressed as a percentage. For example, if a battery is rated at 200 Ah and 160 Ah are discharged, then its DoD is 80%.

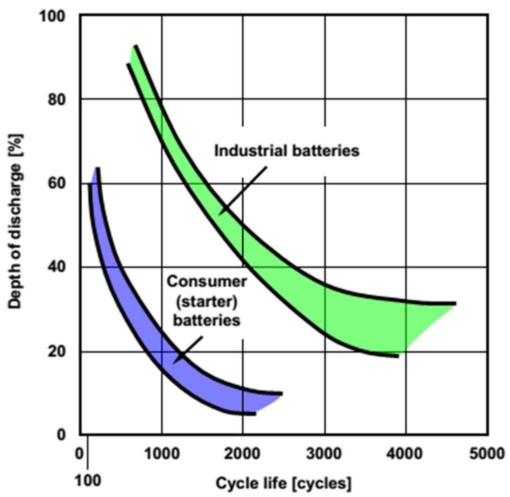


Figure 3.51: Relationship between cycle life and DoD for a lead-acid battery

Life cycle - the process of discharging and recharging is called a cycle. Battery life is expressed in cycle life, meaning a battery can be used for a certain number of cycles only. Manufacturers usually specify the number after which the battery's capacity is reduced to 80% of its rated capacity. The cycle life of a battery depends on the type and quality of the battery and on the daily rate of discharge. The deeper the battery is discharged during a cycle, the shorter the cycle life. In solar systems, a cycle is usually one day, as the battery is discharged during the night and recharged during the day.

Self-discharge - irrespective of whether it is connected to a load, a lead-acid battery will lose energy in a process called self-discharge. The rate of self-discharge of the battery depends on ambient temperature, as well as the battery type, quality and age.

Float life **-** the float or shelf life is the time that an unused battery will last when stored by maintaining a fully charged condition through periodic recharging. The float life depends on the battery quality and the storage temperature. A high storage temperature shortens the battery life significantly. For example, a high-quality long-life gel battery can have a float life of 20 years when stored at 20°C, but its lifespan is reduced to 10 years if stored at 30°C.

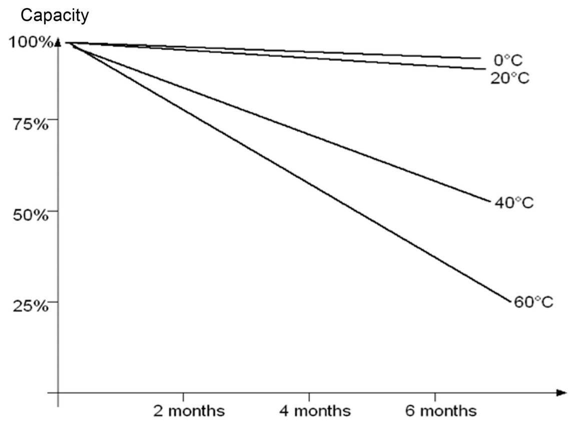


Figure 3.52: Self-discharge rate of lead-acid battery at different temperatures

Table 3.11: Float life of different lead-acid batteries at different temperatures

Average operating temperature	*AGM, deep cycle*	*Gel, deep cycle*	*Gel, long life*
20°C	7–10 years	12 years	20 years
30°C	4 years	6 years	10 years
40°C	2 years	3 years	5 years

CHARGE EFFICIENCY IN BATTERIES

Not every ampere-hour (Ah) going from the charger to the battery is used for charging. The charge efficiency depends mainly on the battery's state of charge. Up to a SoC of 70% the charge efficiency is almost 100%. Above a 70% SoC, the charge efficiency drops rapidly until it reaches 0 when the battery is 100% charged. Therefore, it is not possible to give a precise number for the charge efficiency as it depends greatly on the mode of operation and the type of charger. Overall, charge efficiency generally ranges from 70 to 95%.

Charging of lead-acid batteries **-** when a battery is being charged, it simply means that a voltage is applied across the battery which causes current to flow into the battery. As current flows, the voltage across the battery increases. This phase is called *bulk charging*.

When the *maximum charging voltage* is reached, the current must decrease so that the maximum charging voltage remains constant until the battery is fully charged and current almost zero. After that, the current and voltage are regulated to maintain the *float voltage.* The maximum charging current should not exceed 10% of the battery's Ah rating, meaning a 100 Ah battery should be charged with not more than 10 A, however, some manufacturers allow higher charging currents up to 30% of the Ah rating.

Charging voltages for different types of lead-acid battery cells are shown in the table below. However, it is necessary to study the data sheet of each battery as there might be differences among different manufacturers.

Table 3.12: Cell voltage of different battery types with respect to temperature

	Maximum charge absorption V/cell			
Battery type	0°C	10°C	20°C	30°C
Flooded	2.55	2.51	2.47	2.43
VRLA AGM	2.53	2.49	2.45	2.40

	Maximum charge absorption V/cell			
Battery type	0°C	10°C	20°C	30°C
VRLA gel	2.50	2.45	2.42	2.38

Discharging of lead-acid batteries **-** when discharging a lead-acid battery, the voltage across the terminals drops. The higher the discharge current, the greater the voltage drop. In order to promote a long battery life, the *final discharge voltage* should not drop below 11.8 V per cell; however, some manufacturers of high-quality batteries permit a value of up to 11.6 V per cell.

BATTERY BANKS

When a larger energy storage is needed, several batteries can be interconnected. In a series connection the voltages of the individual batteries will add up to determine the voltage while the capacity stays the same. When batteries are connected in parallel, the capacities (Ah) add up while the voltage remains the same.

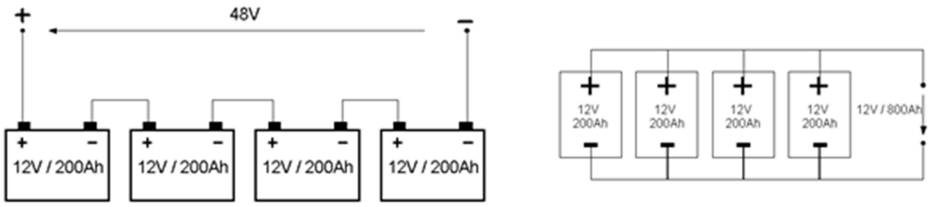


Figure 3.53: Connection of batteries in series (left) and in parallel (right)

Batteries can also be connected in a combination of series-parallel connections in order to simultaneously increase the voltage and capacity.

Note: Make sure to only connect identical batteries, i.e. of same type, age, and with the same ratings for voltage and capacity.

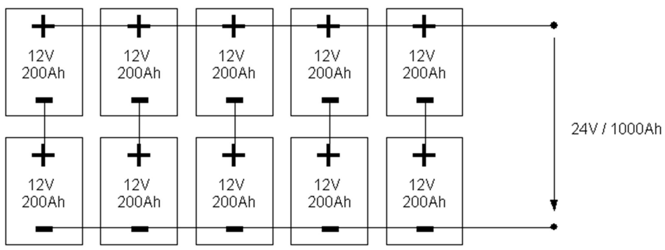


Figure 3.54: Connection of batteries in series-parallel combinations

However, if larger capacities and higher voltages are required, the more reliable solution is to build a battery bank of 2 V cells. Such cells are generally called OPzS batteries for flooded batteries or OPzV batteries for VRLA type batteries. When building a large battery bank, it is advisable to use as few cells as possible, since each cell is prone to fail.

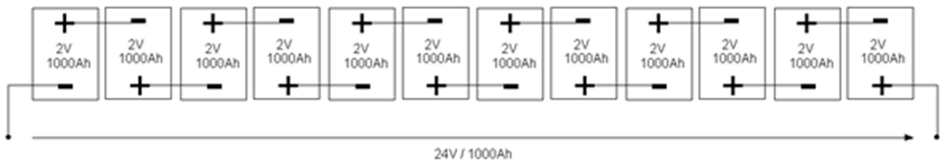


Figure 3.55: Series connection of 12 units of 2 V cells, forming a 24 V battery bank

For instance, to create a 24 V/1,000 Ah battery bank by combining 12 V/200 Ah batteries in series-parallel connections, 10 batteries are required. Since each 12 V battery consists of 6 cells, there are now 60 potential sources of battery bank failure. On the other hand, using

2 V/1,000 Ah batteries requires 12 batteries (cells). 2 V cells are available with capacities of up to 3,000 Ah.

Figure 3.56: 2 V/800 Ah to form a 24 V/800 Ah battery bank

LEAD-ACID BATTERIES IN OPERATION

Gassing - at the point during charging when the battery reaches 80% of its capacity, there is a slight development of gas in the battery. This occurs because most of the sulphuric acid has been withdrawn from the electrodes leaving behind lead peroxide (PO). Since the battery is almost fully charged, smaller portions of charge current are required for the charge process. The remaining current then splits the water molecules into oxygen and hydrogen which escape the battery as gas. In flooded batteries this gas escapes into the environment. This mixture of hydrogen and oxygen is highly combustible and thus the battery should be installed in a well-ventilated room.

In VRLA batteries, the gas stays inside the battery under low pressure and recombines to form water. If too much gas develops due to high charging voltages, the gas escapes into the environment through a valve. In VRLA batteries the escape of gas must be avoided as no battery water can be refilled to balance the loss of water.

Gassing leads to:

- Loss of electrolyte thereby increasing acid concentration
- Loss of electrode material as gasses blast of some of the electrode material
- Possible short circuit due to blasted electrode particles settling at the bottom of the cell
- Equalisation

Gassing in a flooded battery also mixes the electrolyte which creates a desirable effect for battery maintenance. Many chargers can perform a so-called equalisation programme. This activity increases the charging voltage slightly in order to start gassing for a period of approximately 1 hour. The recommended equalisation voltage for a flooded battery is in the region of 2.6 volts per cell at 20°C.

> ***Note:*** Do not apply equalisation to VRLA batteries, as it will result in loss of water which cannot be refilled.

Sulfation - sulfation occurs when large lead sulphate crystals grow on the electrodes (in contrast to tiny crystals that can easily be broken down during charging). These large crystals block the electrode pores thereby increasing the internal resistance of the battery. This in turn leads to a reduced surface for the chemical reactions taking place in the battery. Over time with extreme sulfation, the battery will stop working. Sulfation usually occurs when:

- A battery is stored too long in a discharged state;
- The electrolyte level is very low due to evaporation and gassing;
- The battery is never fully charged.

Take the following steps to prevent sulfation:

- Charge the battery completely as soon as possible.
- Increase the acid concentration in the cell, since lead sulphate becomes more soluble with lower acid density.
- Avoid excessive discharging of the battery.
- Equalise flooded batteries (but never VRLA types!).

BATTERY STORAGE AND MAINTENANCE

Follow these guidelines for battery storage.

- Never store a battery in a discharged state.
- Recharge batteries regularly to prevent sulfation.
- Store batteries at low temperatures since high temperatures increase the rate of self-discharge.
- In terms of battery maintenance, for lead-acid batteries make sure to clean the battery terminals periodically to avoid short circuits or surface leakage. Also check the connections periodically to make sure they are firm. Flooded batteries require the following additional maintenance procedures: Top up electrolyte with distilled water once it falls below the indicated threshold.
- Charge completely according to the recommended maximum charging voltage and allow gassing for an appropriate period to ensure that the battery acid is well mixed (equalisation).
- Disposal of old batteries

Batteries which have reached the end of their lifetime should be sent to recycling. Lead is a valuable resource. Disposal into nature is very harmful due to the corrosive sulphuric acid and poisonous lead contained in batteries. Always dispose of dead batteries properly.

» *Charge controllers*

In a solar photovoltaic system, a charge controller is a device that, as the name implies, regulates the state of charge of a battery bank. The charge controller performs the following functions:

- Charges the battery bank optimally
- Protects the battery bank from deep discharge which could damage the batteries
- Protects the battery bank from overcharging
- Protects the photovoltaic module from damage caused by reverse currents from the batteries
- Prevents unwanted discharge of the battery bank into the solar modules at night
- Indicates the state of charge (SoC) on a display or using LED indicators

Some charge controllers automatically schedule battery equalisation as a maintenance measure.

FUNCTION OF CHARGE CONTROLLER

Most solar charge controllers for lead-acid batteries use the three-stage charging algorithm:

- **Bulk stage:** Maximum current is supplied until the absorption voltage is reached. The absorption voltage for a 12 V gel battery is approximately 14.4 V.

- **Absorption stage:** Absorption voltage remains constant and current is reduced until the battery is fully charged.
- **Float stage:** Constant supply of reduced current for a float voltage of approx. 13.6 V to maintain charge.

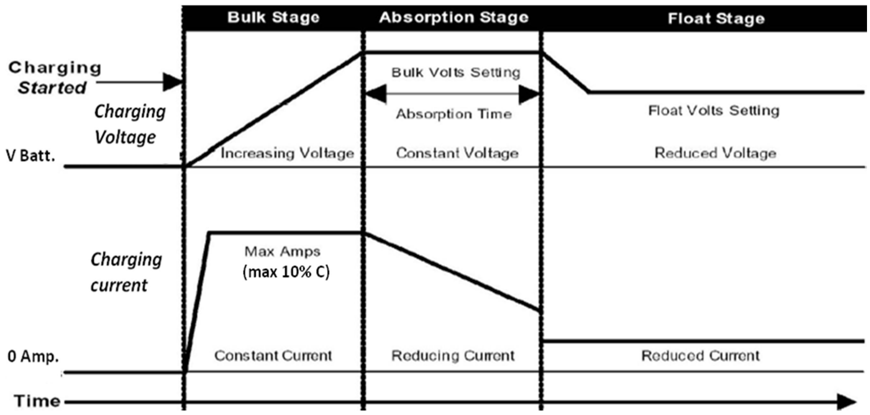


Figure 3.57: Three-stage charging algorithm

All charge controllers regulate the voltage from the solar modules to the battery via pulse-width modulation (PWM). Pulsing occurs at a high frequency with pulse lengths of a few milliseconds so that a constant voltage is provided.

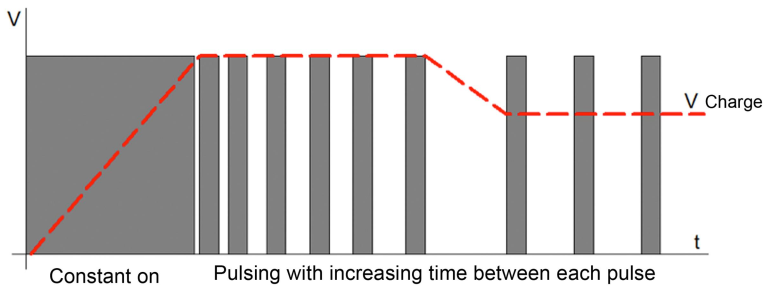


Figure 3.58: Pulse-width modulation

TYPES OF CHARGE CONTROLLERS

Series (linear) controller - the series controller provides the correct charging voltage by connecting and disconnecting the photovoltaic modules in pulses. Conversely, when the battery is discharged to a set point, and to prevent further discharge (deep discharge), the switch S_2 opens and isolates all loads from the circuitry (see Figure 3.59). This switch is automatically closed once a predetermined voltage level is exceeded during charging.

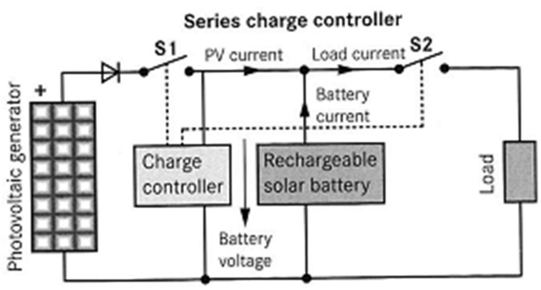


Figure 3.60: Basic electrical circuitry of a series charge controller – *Courtesy: Solar Energy Foundation*

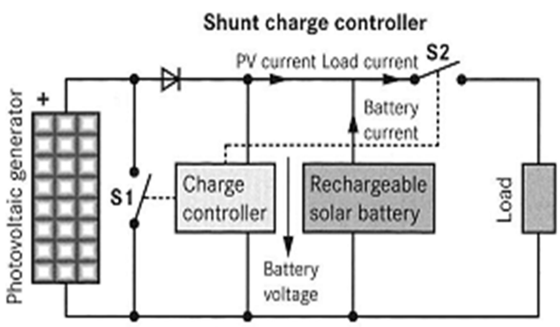


Figure 3.59: Basic electrical circuitry of a shunt charge controller – *Courtesy: Solar Energy Foundation*

Shunt (parallel) controller - the shunt controller provides the right charging voltage by short-circuiting the solar modules in pulses. To protect against deep discharge, as in the series controller, the switch S_2 is opened to disconnect the battery bank from the load (see Figure 3.60).

Table 3.13: Comparing shunt and series controllers

	Pros	Cons
Series	• No risk of hotspots on PV modules • Charging current from PV modules can be interrupted	• Higher charging currents lead to high system losses in the form of heat
Shunt	• Losses only occur when there is an excess of energy flowing from the PV array.	• Short circuit can create a hotspot on the PV module. • Charging current from PV module cannot be interrupted

Maximum power point tracking (MPPT) charge controller - this type of charge controllers is mostly used in systems larger than 1 kW$_P$. MPPT charge controllers allow solar modules to always operate in their maximum power point regardless of the required charging voltage for the batteries. MPPT regulation is performed by scanning and locating the characteristic I-V curve of the photovoltaic array and then determining the maximum power point. The device is essentially a DC/DC converter with a capacitor that releases stored energy to match the known maximum power point of the array.

Common MPPT charge controllers allow a PV input voltage of up to 150 V (depending on the type) and still charge at battery voltages of 12 V, 24 V, 48 V or 60 V. In this way the modules can be connected in series to a maximum open-circuit voltage of 150 V. MPPT charge controllers increase the efficiency of the system by up to 20%.

SPECIFICATIONS OF CHARGE CONTROLLERS

Charge controllers are rated based on their input voltage and current. Many charge controllers can operate at different system voltages, e.g. 12 V, 24 V and 48 V. Voltage detection usually happens automatically once the battery is connected.

The current rating is a fixed value. For example, a charge controller which can operate at a battery voltage of 12 V and 24 V could have a fixed current rating of 30 A which applies for both voltages. If the charge controller has a controlled load output, then that same current rating is also the maximum current which the load output can supply. Good quality charge controllers have a very low internal consumption of just a few milliamperes (mA) for the display or indicator lights.

FEATURES OF CHARGE CONTROLLERS

Many charge controllers have a setup function or control buttons for various options including:

- Battery type (flooded vs. VRLA)
- Specific charging voltages
- Low-voltage disconnect set points
- Manual or timed switching of load output
- Automatic or manual battery equalisation

Note: Factory settings for most adjustable charge controllers are adjusted for charging flooded batteries. This algorithm can be harmful for VRLA batteries.

Other features may include:

- Display of battery state of charge
- Display of solar charging parameters
- Temperature compensation

The optimised charging voltage for a lead-acid battery depends on the temperature and on the age of the battery. To monitor these conditions and adjust accordingly, many charge controllers have an inbuilt temperature sensor. Some controllers have a connection point for an external temperature sensor to be placed directly on the battery.

Figure 3.61: 30 A charge controller featuring an external temperature sensor connection

The diagram below shows the charging voltages for a new and an old 12 V lead-acid battery. At 30°C a new battery should be charged with approximately 14.3 V (absorption stage).

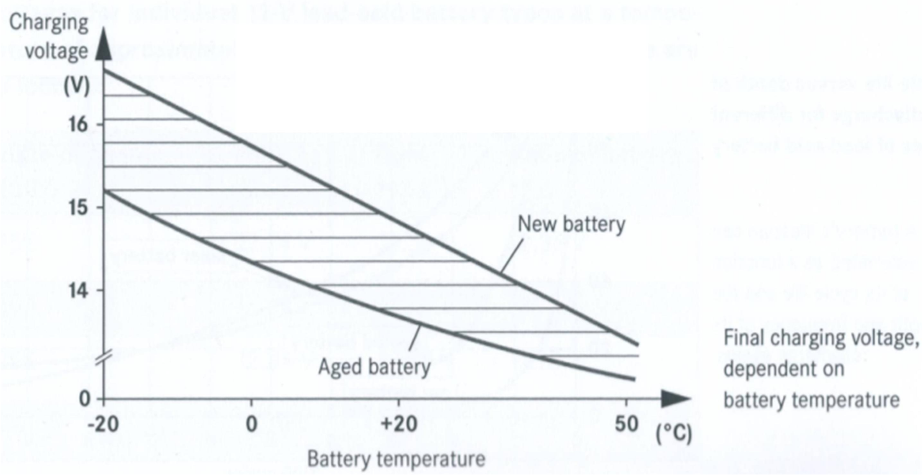


Figure 3.62: Charging voltage of lead-acid batteries based on temperature

CHARGE CONTROLLERS IN OPERATION

When connecting charge controllers it is important to always connect the battery first. This initial voltage determines the system voltage for charge controllers with variable system voltage. If by mistake the solar modules are connected first, then the high open-circuit voltage (21 V for use in 12 V systems) could set up an incorrect system voltage. It is also possible to damage a charge controller with the open-circuit voltage of the PV generator.

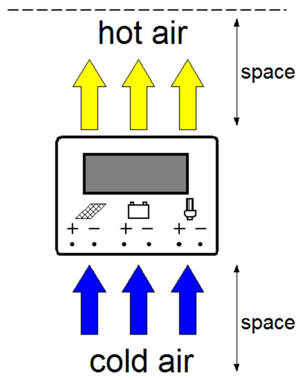


Figure 3.63: Air flow in a charge controller

During normal operation, charge controllers accumulate a considerable amount of heat and grow very hot. Proper ventilation must be provided at the installation site.

Connection of several charge controllers to one battery bank - if a single charge controller with the required rating is not available; it is possible to connect several charge controllers to the same battery bank. Each charge controller must then be connected to a separate array. The charging algorithm of the controllers must be the same. However, in such configurations scheduled automatic battery equalisation will not work properly as the timing of the controllers most likely will not match. In this case, equalisation must be done manually.

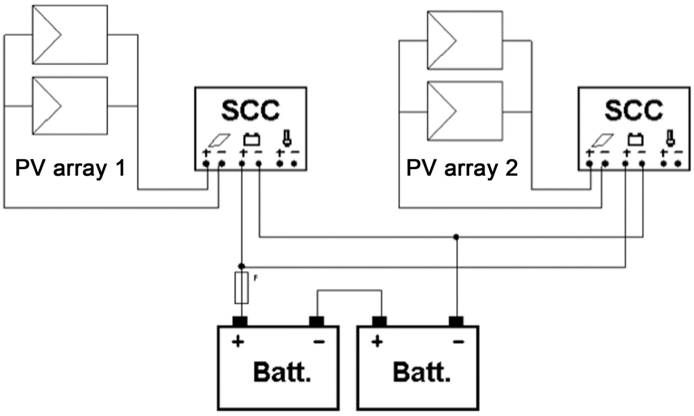


Figure 3.64: Schematic of two charge controllers connected to a battery bank

» ***Inverters***

Inverters are the essential step between a battery's DC power and the AC power required by standard household electrical systems. In a grid-connected home, an inverter connected to a battery bank can provide an uninterruptible source of backup power in the event of a power failure. It could also be used to sell extra power back to the utility company.

INVERTER FUNCTION

Batteries supply low-voltage DC power that cannot be used to run most modern household appliances. Utility companies and combustion engine generators, on the other hand, provide sine-wave alternating current (AC) power, which is suitable for most commonly available appliances. Inverters electronically convert DC to AC power.

Figure 3.65: Inverter – *Courtesy: Alessi*

In countries with a stable electricity grid, grid-connected homes can use inverters and alternative energy generators to sell power back to the utility company. When attached to solar photovoltaic, wind or hydro generators, the inverter can use the utility grid as its battery bank. Utility power will be used when alternative power sources are insufficient. In a stand-alone renewable power system, whether in residential, industrial, marine or recreational vehicle (RV) applications, the inverter allows AC electrical appliances to be run from the storage battery bank.

CLASSIFICATION OF INVERTERS

By waveform - apart from a variety of power ratings, inverters are distinguished primarily by the shape of the alternating current wave they produce. The major waveforms are square waves, modified sine waves and true sine waves. Square wave inverters are largely obsolete, as the waveform shape is not well suited for running many modern appliances. They are gradually being displaced by the superior modified sine wave and true sine wave inverters, whose prices have come down considerably.

Modified sine wave inverters - the least expensive type of modern inverter produces modified sine wave power. The waveform looks like a stair step, where power rises from zero to upper peak voltage, falls straight back to zero and then goes straight to lower peak voltage,

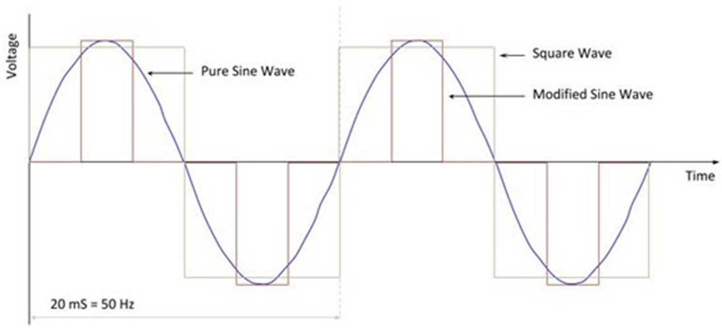


Figure 3.66: Comparison of output waveforms

resting for a moment at each point. Modified sine wave inverters will run many household appliances such as televisions, radios and microwaves with occasional minor electrical "noise" present. Sensitive equipment like some battery chargers, tools with variable speed motors, laser printers and certain heating controllers will run erratically or not at all with modified sine wave power. For a rural dwelling with only basic electrical appliances, a modified sine wave inverter is an economical choice. Modified sine wave inverters are also often well suited for solar-powered electrical systems.

True sine wave inverters **-** the power supplied by utility companies and combustion engine generators has a pure sine wave form. This is the most reliable waveform as it is suited for all AC appliances of the specified frequency. True sine wave power passes from the upper and lower peak voltages in a smooth curved wave, rather than in the stair-step pattern of the modified sine wave. True sine wave inverters will produce AC power in a quality that is consistent with or better than utility power, ensuring that even sensitive equipment will run properly. While true sine wave inverters are more expensive than modified sine wave models, the quality of their waveform can be an advantage. For office buildings considering a backup power inverter, a true sine wave model will allow proper functioning of all electronic office equipment and fluorescent lights. For residential applications, whenever battery chargers, electric drills, digital radio clocks or other sensitive electronics are in operation, a true sine wave inverter should be considered to ensure proper functioning of all household appliances as well. Various inverters may have different features making them better suited for specific applications. Very small inverters are available that connect to a vehicle cigarette lighter, with a single three-prong AC outlet as the output. Large inverters are generally designed to be hardwired into a building electrical system.

By application

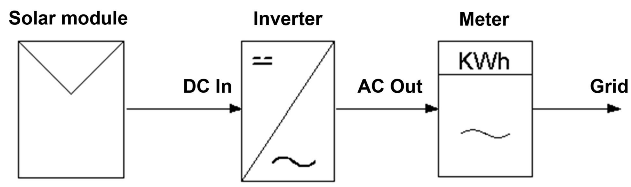


Figure 3.67: Connection of a PV inverter

PV inverters **-** PV (solar) inverter is an inverter optimised to convert DC power from the solar panels to the AC power grid. PV inverters are usually connected to the grid via an electricity meter, since they are used to sell electric energy to the utilities, hence the designation "grid-tied inverters". These inverters are also termed "grid following" because they are unable to generate the AC output power without the grid voltage, meaning that when the grid is off they are also off. This sort of inverter would be difficult to use in Nigeria since the grid is unstable, with frequent blackouts, hence most of the energy generated by the solar panels would be lost.

PV inverters are rated in terms of their input voltage range, input power, grid voltage and maximum output power. Another important parameter is efficiency, specifying which part of the solar-generated energy will actually be fed into the grid.

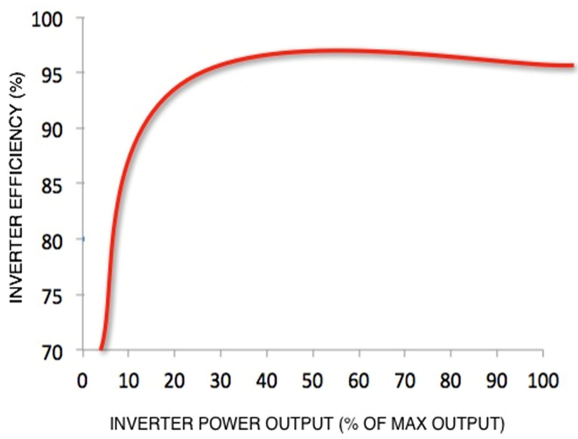


Figure 3.68: Relationship between inverter efficiency and output power

An additional important specification is the MPP voltage range. Grid-tied inverters are mostly equipped with maximum power point tracking. However, this tracking only works within a certain voltage range. With low-level sunlight and voltage, the MPPT feature does not work properly and the efficiency decreases. Moreover, below a certain voltage the inverter does not work at all. Good quality inverters can have an efficiency of more than 95%, but this efficiency can only be reached if the input power is above a certain percentage of the inverter's rated power. For example, if a 10 kW inverter only receives a solar input power of 1 kW, its efficiency can be as low as 80%.

PV inverter features include:

- Follows the grid
- Anti-island protection
- MPP tracking
- Single-phase or three-phase
- Low to medium voltage level

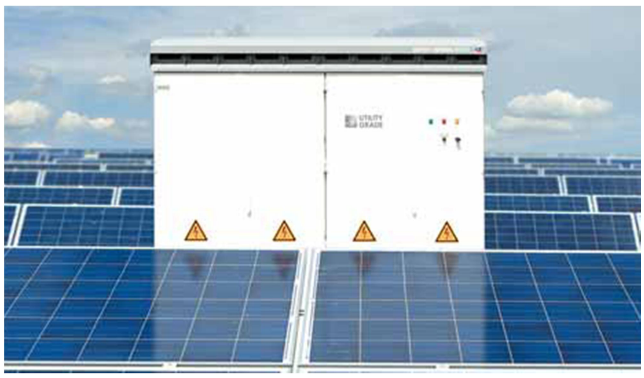


Figure 3.69: Central inverter in a PV power plant

PV INVERTER CONNECTION TYPES

PV inverters can be classified into three types according to their point of connection.

Central inverter: When one PV inverter is connected to a PV array which serves the whole system, it is called a central inverter. It is often the cheapest solution when designing a PV system to use a central inverter. However, there is a high risk of system blackout due to inverter failure. Central inverters in large-scale PV power plants usually have a PV input voltage of 1,000 V and an AC output voltage of up to 35 kV.

String inverter: A string inverter is an inverter which connects to one section of the whole array. For instance, a PV array may be composed of multiple strings, each string having its own inverter, which then feed into the grid. This configuration is more expensive than a central inverter due to the increased number of inverters as well as higher installation costs. On the whole, however, it is a more reliable system.

Module (micro) inverter: Module inverters are small inverters connected directly to individual solar modules. Each module has an AC output. While the most expensive solution, it is also the most reliable from an availability standpoint. Installation is simple as there is no DC wiring. This again saves costs, since AC wiring is cheaper than DC wiring because of the lower currents. However, the lifetime of these inverters is shorter compared to central or string inverters as they are constantly exposed to weather.

BATTERY INVERTER

A battery inverter is designed to convert the DC power from a battery to AC power as required by most common electrical appliances (230 V/50 Hz). It has a DC input and an AC output. In an off-grid standalone PV system, the battery inverter sets the parameters (frequency and voltage) for the mini-grid. Thus it is called the "grid forming" element of the system.

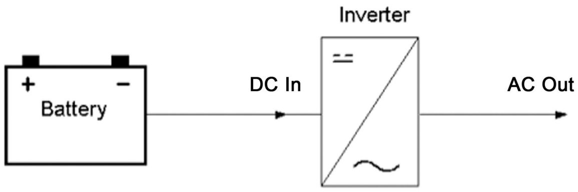


Figure 3.70: Battery and inverter relationship

Battery inverter specifications **-** battery inverters are rated according to their input voltage, output voltage and output power. For example, an inverter with the designation 24/1,200 connects to a 24 V battery and provides 1,200 VA output at 230 V_{AC}. The continuous output power is dependent on temperature. At high temperatures the power output from the inverter can be reduced drastically. Most inverters are capable of providing a brief power surge to supply power which is above their rating. This might be twice the nominal power of an inverter for one second, or four times the nominal power for 0.5 seconds. This information is useful for managing the high start-up currents often required by motors (e.g. fridges).

The DC input allows for a certain variance from the nominal voltage. For example, a 24 V inverter could operate at an input range between 19 V and 33 V. If the input voltage falls outside of this range, the inverter will disconnect and usually issue a warning.

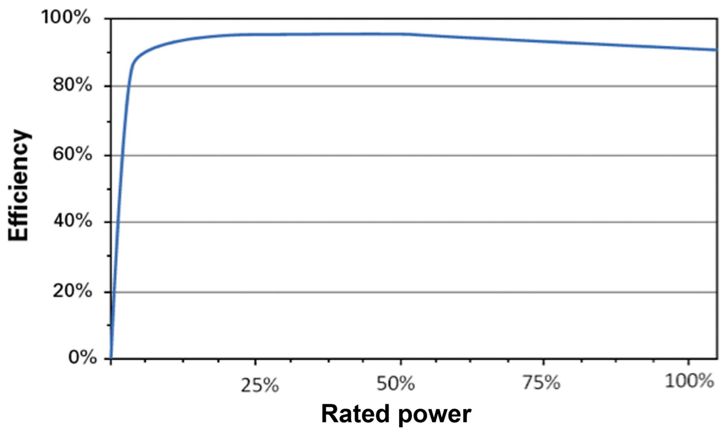


Figure 3.71: Typical inverter efficiency across the load spectrum

The efficiency of an inverter is defined as DC input power divided by AC output power. Some power is always lost, that is, converted to heat or used to drive the fan for cooling. The efficiency of a high-quality battery inverter can reach up to 95%; however, it always depends on the operation mode. At a low load the efficiency can be very poor. For instance, if a 1 kVA inverter is used to power only five CFL bulbs that add up to a total of 50 W, then the efficiency can be as low as 20%, meaning the DC power draw from the battery would be 250 W.

Battery inverter features

Most battery inverters have the following features:

- Low voltage disconnect
- Load detection mode (search mode)
- Overload protection
- Short-circuit protection
- Brief overload that exceeds rated power (even by several times)
- Status indication (normal, overload, over-temperature, overvoltage, under-voltage)

- Advanced features
- Relay output (programmable)
- Operation parameter setup
- 50Hz / 60Hz
- Parallel configuration
- Three-phase configuration
- Remote monitoring

Load detection **-** many modern inverters offer the feature of load detection which recognises whether a load is connected. If no load is connected, the inverter switches to standby mode to reduce energy consumption. In load detection mode the inverter sends a voltage pulse approximately once every second to the output and if a load is connected and current is flowing, the inverter switches to constant output. This requires a minimum load of a few watts. A high-efficiency modern LED lamp might not be recognised by this means of load detection. The load detection mode can be disabled, which means the inverter can be switched to constant power output.

Auxiliary output **-** advanced inverter chargers have a programmable auxiliary output, either a relay or a contact, which is energised with DC voltage in order to connect a relay or another low power consuming DC device (e.g. signal lamp). This auxiliary output can be used to start a diesel generator at a certain battery voltage level or to disconnect heavy loads.

Inverter charger **-** an inverter charger is a combination of a battery inverter and a charger. It has an additional AC input to connect to an external AC power supply such as the utility grid or a generator.

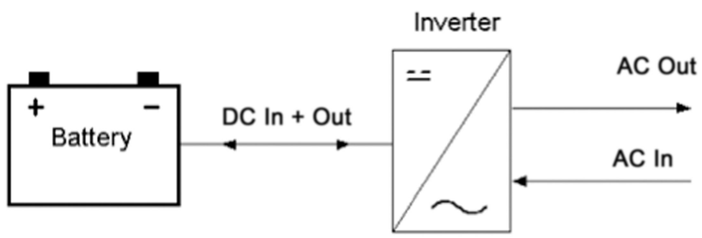


Figure 3.72: Battery and inverter charger relationship

An inverter used for backup power in a grid-connected home will use grid power to keep the batteries charged and, when the grid power fails, it will switch to drawing power from the batteries and supplying it to the building electrical system. This switching happens so quickly that consumers (especially electronic devices and computers) are not affected; thus it provides an uninterruptible power supply (UPS). For a business or home office, a reliable power source is invaluable for preventing data loss on computer systems.

Inverter chargers feature the following functions:

- Optimised charging and battery maintenance (battery temperature sensor)
- AC input detection
- Uninterrupted switching of AC output from DC to AC input and vice versa

MultiPlus 12 Volt / 24 Volt / 48 Volt	C 12/800/35 C 24/ 800/16	C 12/1200/50 C 24/1200/25	C 12/1600/70 C 24/1600/40	C 12/2000/80 C 24/2000/50	12/3000/120 24/3000/70 48/3000/35	24/5000/120 48/5000/70
PowerControl	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
PowerAssist	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Transfer switch (A)	**16**	**16**	**16**	**30**	**16 or 50**	**50**
Parallel and 3-phase operation	**No**	**No**	**No**	**No**	**Yes**	**Yes**
INVERTER						
Input voltage range (V DC)	9,5 – 17 V 19 – 33 V 38 – 66 V					
Output	Output voltage: 230 VAC ± 2% Frequency: 50 Hz ± 0,1% (1)					
Cont. output power at 25 ℃ (VA) (3)	800	1200	1600	2000	3000	5000
Cont. output power at 25 ℃ (W)	700	1000	1300	1600	2500	4250
Cont. output power at 40 ℃ (W)	650	900	1200	1450	2000	3350
Peak power (W)	1600	2400	3000	4000	6000	10.000
Maximum efficiency (%)	92 / 94	93 / 94	93 / 94	93 / 94	93 / 94 / 95	94 / 95
Zero-load power (W)	8 / 10	8 / 10	8 / 10	9 / 11	15 / 15 / 16	25 / 25
Zero load power in AES mode (W)	5 / 8	5 / 8	5 / 8	7 / 9	10 / 10 / 12	20 / 20
Zero load power in Search mode (W)	2 / 3	2 / 3	2 / 3	3 / 4	4 / 5 / 5	5 / 6
CHARGER						
AC Input	Input voltage range: 187-265 VAC Input frequency: 45 – 65 Hz Power factor: 1					
Charge voltage 'absorption' (V DC)	14,4 / 28,8 / 57,6					
Charge voltage 'float' (V DC)	13,8 / 27,6 / 55,2					
Storage mode (V DC)	13,2 / 26,4 / 52,8					
Charge current house battery (A) (4)	35 / 16	50 / 25	70 / 40	80 / 50	120 / 70 / 35	120 / 70
Charge current starter battery (A)	4 (12V and 24V models only)					
Battery temperature sensor	yes					
GENERAL						
Auxiliary output (A) (5)	n. a.	n. a.	n. a.	n. a.	Yes (10A)	Yes (25A)
Programmable relay or relay driver (6)	relay driver (7)	relay	relay driver (7)	relay driver (7)	relay	relay

Figure 3.73: Data sheet section for Victron MultiPlus inverter charger series

CONNECTING INVERTERS

Some advanced battery inverters or inverter chargers can be connected in parallel in order to increase the power output or to provide a three-phase power supply. This type of setup is usually called a *master-slave configuration.* In order to be connected in parallel, the inverters must communicate so that the phases of the individual inverters match exactly (single phase) or so that they have the correct phase sequence for three-phase systems. One inverter is the grid-forming inverter (master), while the other inverter is the grid-following inverter (slave). Usually the communication between the inverters flows via a network cable from inverter to inverter or to a central hub.

***Anti-island protection* -** if the grid fails or gets disconnected, the inverter must stop converting DC to AC. This is a safety measure which is required for all grid-connected inverters to protect technicians from hazardous voltages during maintenance work.

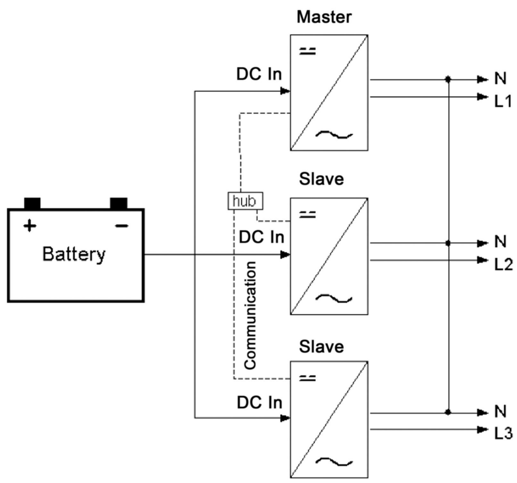


Figure 3.74: Three-phase inverter configuration

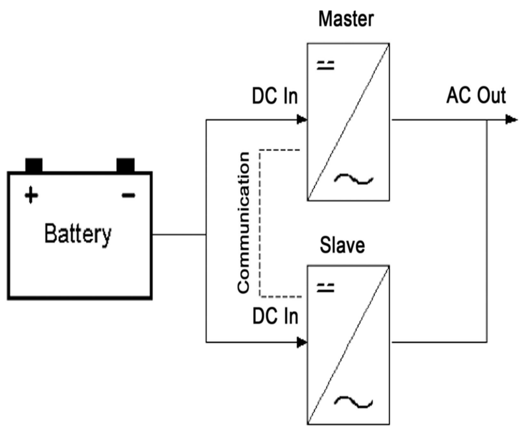


Figure 3.75: Single-phase connection of two inverters

StecaGrid 9000 3ph	
DC input side (PV-generator)	
Maximum start voltage	830 V
Maximum input voltage	830 V
Minimum input voltage	350 V
Minimum input voltage for rated output	350 V
MPP voltage	350 V … 680 V
Maximum input current	32 A
Maximum input power	10,500 W
Maximum recommended PV power	12,000 Wp
Derating / limiting	automatic when - input power is higher - the device is not cooled sufficiently - input currents > 32A (higher currents are limited by the equipment and therefore will not damage the inverter)
AC output side (Grid connection)	
Grid voltage	320 V … 480 V [depending on the regional settings]
Rated grid voltage	400 V
Maximum output current	17 A
Maximum output power	9,900 W
Rated power	9,900 W
Rated frequency	50 Hz
Frequency	47.5 Hz … 52 Hz [depending on regional settings]
Night-time power loss	< 1 W
Feeding phases	three-phase
Distortion factor	< 5 % (max. power)

Characterisation of the operating performance	
Maximum efficiency	96.2 %
European efficiency	95.3 %
MPP efficiency	> 99 %
Power derating at full power	from 50 °C (T_{amb})
Switch-on power	20 W
Standby power	9 W
Safety	
Isolation principle	no galvanic isolation, transformerless
Operating conditions	
Area of application	indoor rooms with or without air conditioning, outdoors with protection
Ambient temperature	-20 °C … +60 °C
Relative humidity	0 % … 95 %
Noise emission	< 60 dBA
Fitting and construction	
Degree of protection	IP 54
DC Input side connection	MultiContact MC4 (5 pairs)
AC output side connection	Wieland RST25i5 plug
Dimensions (X x Y x Z)	405 x 845 x 224,5 mm
Weight	42 kg
Communication interface	StecaGrid Vision interface
DC circuit breaker	yes
Cooling principle	temperature-controlled fan
Test certificate	CE mark

Figure 3.76: Specification of a StecaGrid 9 kW inverter

Inverters in operation - when connecting inverters, it is important to mind the polarity. Most inverters sustain immediate damage when the polarity is reversed. Inverters grow hot during operation, so adequate space for ventilation must be considered when choosing the installation site. Most inverters have a fan for cooling. The ventilation slots must never be covered.

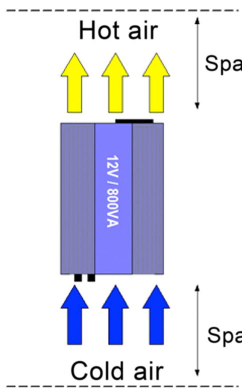


Figure 3.77: Airflow through an inverter during operation

» *Cables*

Cables on the DC side of a solar system, whether grid-tied or off-grid, require particular attention. This is because on the DC side, voltages are usually low and currents high. Cables can be a big part of the investment, especially if the solar array is far away from the battery or inverter. Ideally, the voltage drop on the DC side should not exceed 3%.

For example, if a 4 kW PV array feeds the inverter/charge controller via a 10-metre cable of 2 × 6 mm² into a battery bank at a 48 V system voltage, the voltage drop is 7%, which equals a 7% power loss. To mitigate this effect, you may step up from 48 V to a higher system voltage by using a DC-DC boost converter. This could reduce the required cable size and therefore the overall cost.

Figure 3.78: Male and female MC4 connectors (left) and solar module wiring with MC4 connectors (right)

Solar panels often come with a piece of solar wire with a so-called MC4 (multi-contact 4 mm^2) connector. These connectors are weatherproof and easy to plug together. There are male and female connectors for positive and negative terminals, which makes it convenient to connect solar modules in series.

» *Electrical protection of PV systems*

Renewable energy systems, like all electricity generating systems, are susceptible to faults and failures. To protect lives and property, various types of protective devices are used.

DC CIRCUIT BREAKERS AND FUSES

DC fuses and DC circuit breakers are different from their AC counterparts. When current is disconnected in a DC circuit, the resulting arc is much stronger than when disconnecting AC current. This arc can be long-lasting and very destructive. AC fuses and circuit breakers are unable to manage such an arc and might be destroyed or catch fire. Because DC fuses and circuit breakers are far more expensive than equally rated AC breakers and fuses, it might be tempting to buy the cheaper AC equivalent, but this must be avoided at all costs. DC circuit breakers and fuses must be chosen according to the DC system voltage.

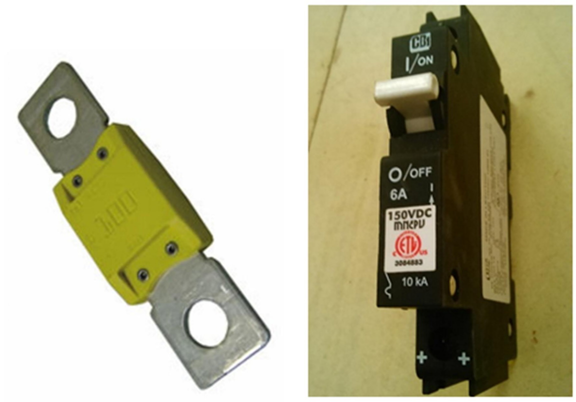


Figure 3.79: 100 A DC fuse (left), 150V/6 A DC circuit breaker (right)

SURGE PROTECTION DEVICES (SPDS)

A SPD is a device which under normal operating conditions isolates two connected potentials (e.g. PV+ and PV−) from each other. If a certain voltage is exceeded (e.g. due to a lightning-induced surge), a *varistor* inside the SPD becomes conductive, creating a short circuit and bringing the potential to zero. This short circuit remains for as long as the surge persists, which in the case of a lightning strike can last for some microseconds.

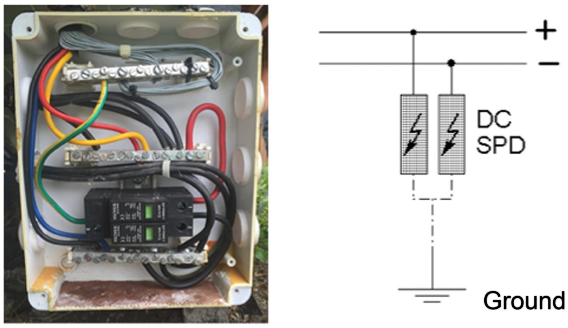


Figure 3.80: PV surge arrestor, max. 500 VDC in combiner box (left) and wiring of an SPD (right)

The DC input of charge controllers or inverters is very sensitive to overvoltage. Lightning-induced surges can destroy the device immediately. However, a short circuit of some microseconds is not dangerous for the DC input of a charge controller or inverter and also releases only minimal energy from the battery. For DC equipment a DC SPD with matching voltage must be chosen.

DC MAIN DISCONNECT

If a PV array is disconnected under full sunlight, the result will be a powerful arc which can ionise air and maintain itself over a large air gap. DC main switches are specially designed to extinguish that spark. AC equipment will not work in this case, as it cannot manage powerful sparks.

ENCLOSURES

Enclosures are all housings which protect the live parts of the system from environmental impacts and protect people from making accidental contact with system parts, for instance with junction boxes or the combiner box. Enclosures are usually rated with an IP code (ingress protection rating) consisting of two numbers, the first indicating the level of protection against water ingress, the second indicating the protection level against penetration by solid bodies.

SHIELDED CABLE

Shielded cables are available in many designs and sizes and for many purposes. While data cables are usually shielded to avoid electromagnetic induction, AC cables are shielded (armoured) to protect against mechanical impacts and even rodents. However, any metal shield around a cable also protects the inner wires from electromagnetic induction, for example due to nearby lightning strikes.

Figure 3.81: Shielded cable connecting inverter, charge controller and ground

Note: When using a shielded cable, ensure that the cable shield is grounded.

PROTECTIVE MEASURES ON THE DC SIDE

Large PV arrays can operate at high voltages and high currents. These high voltages and currents require appropriate protective measures.

Maximum system voltage - manufacturers specify a maximum system voltage for the solar module as the maximum voltage of the whole array which must not be exceeded. If a manufacturer specifies a maximum system voltage of 1,000 V, for example, the complete array in which the solar panel is installed must not under any conditions generate more than 1,000 V.

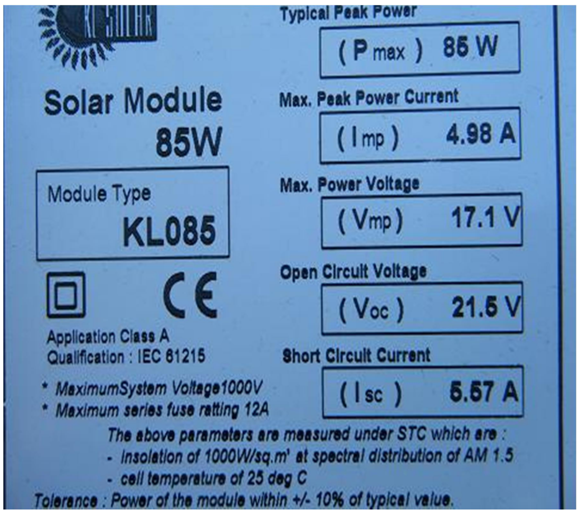


Figure 3.82: PV module specification label indicating maximum system voltage of 1,000 V

Disconnect device - for installation and maintenance work on powerful solar arrays, it will be necessary at one point to disconnect and reconnect the solar array input from the charge controller or inverter. One possibility is to use the DC circuit breakers in the array combiner box to disconnect individual strings. Another possibility is to install a DC main switch which is powerful enough to manage the array voltage and current.

String protection - in larger arrays with several strings connected in parallel, it is necessary to protect each string from reverse currents. Under certain conditions where the voltage of one string drops significantly compared to the other strings, for instance, when one module is lost due to a short circuit or complete shading, then the other strings with higher voltages will feed current into that string. Depending on the voltage difference and the number of strings, this reverse current can be several times the designed string current. To prevent damage to the modules and wiring, string fuses with a very exact rating to match the nominal string current must be installed. Alternatively, the string can be protected with string diodes in order to avoid reverse currents.

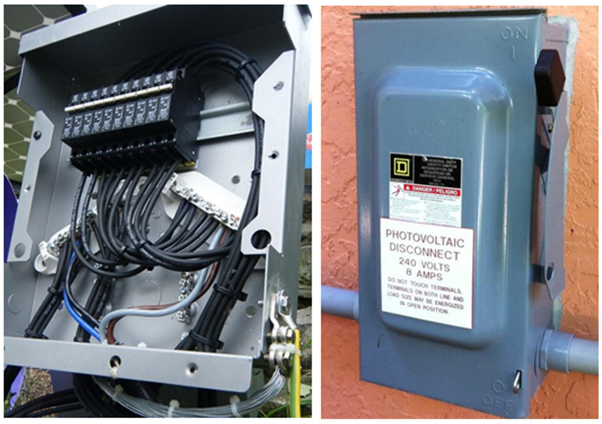


Figure 3.83: DC combiner box with string circuit breakers (left) and PV main disconnect (right)

Battery fuse **-** a short circuit of the two poles of a battery releases a very high current; the larger the capacity the higher the current. On a large battery this can easily melt connected wires and start a fire. Therefore, the battery or battery bank should be protected with a suitable DC fuse. DC circuit breakers can only be used if they are rated to manage the high short-circuit current which occurs in a battery short circuit. AC fuses cannot be used as they cannot handle DC sparks. For smaller batteries and smaller DC load currents, automotive fuses can be used. In contrast, larger currents and battery banks require DC fuses with higher ampere and voltage ratings.

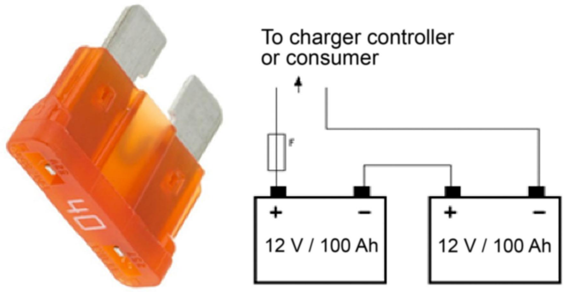


Figure 3.84: Automotive fuse (left) and sample wiring diagram in smaller DC circuits (right)

PROTECTIVE MEASURES ON THE AC SIDE

The AC side of a photovoltaic system is either connected to a common AC installation with AC appliances or directly to the national grid on a low or medium voltage level. If the inverter connects to a common AC installation, in a domestic, commercial or industrial environment, then the common protective measures according to the local regulations will apply. These could include a main disconnect, circuit breakers and residual current devices. If the inverter is connected to the grid, there must be a means to isolate it from the grid when performing maintenance activities.

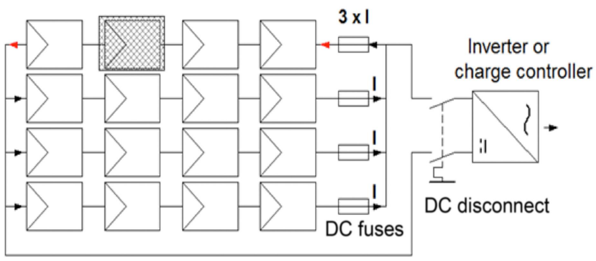


Figure 3.85: Array protected with string fuses and main disconnect

Anti-islanding protection **-** islanding of a grid-connected photovoltaic system occurs when a section of the utility system containing such a photovoltaic system is disconnected from the main utility voltage source. However, if the photovoltaic system continues to feed the utility lines in the isolated section, it is known as an island. Such isolated islands may cause serious danger to personnel, who may believe the load is inactive while, in reality, the photovoltaic system is feeding power to the utilities. Islands may also substantially complicate a normal reconnection of the section to the utility network due to damage to the load inside the island. Depending on the transformer connection, islanding may create an ungrounded system. An unidentified island is hazardous for maintenance work. Furthermore, for those utility customers located in the island, their connected equipment may be damaged, because the supplying power will not be able to maintain the required power quality. For these reasons, islanding is considered one of the most important issues in designing photovoltaic systems, and in maintaining reliable utility grid operation.

Formation of islands must be swiftly detected and the generators energising the island disconnected. This is commonly known as anti-islanding protection or loss-of-main protection. Passive methods for detecting islanding conditions make use of undervoltage relays and overvoltage relays. The downside of voltage relays is their slow detection speed.

AC surge-protection devices (SPD) - the AC output of an inverter is very sensitive to voltage surges such as those caused by the switching of inductive loads (motors) or lightning-induced surges. Many photovoltaic inverters have inbuilt SPDs, whereas battery inverters are usually not equipped with an SPD.

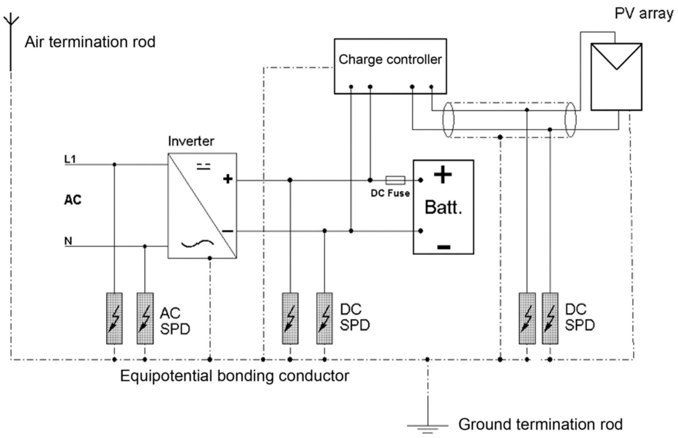


Figure 3.86: External and internal lightning protection systems with equipotential bonding of all metal housings, shielded and grounded cables and AC and DC surge protective devices

MEASURES TO PROTECT AGAINST LIGHTNING-INDUCED SURGE VOLTAGES

The tropical belt around the Equator is the area with the highest risk of lightning strikes on Earth. In Nigeria, on average, each square kilometre is hit by 10 to 50 lightning strikes each year. Buildings exposed in their surroundings are much more likely to be hit by lightning than non-exposed buildings. Nearby lightning strikes are a much more common source of damage than direct lightning strikes; however, direct lightning strikes are often much more devastating.

Lightning protection - in photovoltaic systems, the need for lightning protection depends on the risk of lightning strikes and the value of the system. A home solar PV system in an area with a low lightning risk and with a value of not more than NGN 100,000 will not need a lightning protection system (LPS) which costs NGN 60,000.

Sometimes, certain types of buildings require an LPS due to their function and relevant regulations (e.g. public buildings or certain industries). If lightning protection is required for a building, the photovoltaic system must be integrated in the LPS. System installation does not increase the risk of lightning striking into a building as long as it does not significantly change the building's shape.

Primary measures to protect against surge voltages include cable shielding, grounding, equipotential bonding, laying conductors to be as short as possible and avoiding loops. In practice, however, ideal conditions in accordance with the above-mentioned primary measures cannot be achieved. It is therefore also necessary to install SPDs. Complete equipotential bonding requires the inclusion of all active conductors such as the power supply and data lines.

Figure 3.87: Equipotential bonding of module frames (left), laying a ground termination conductor (right)

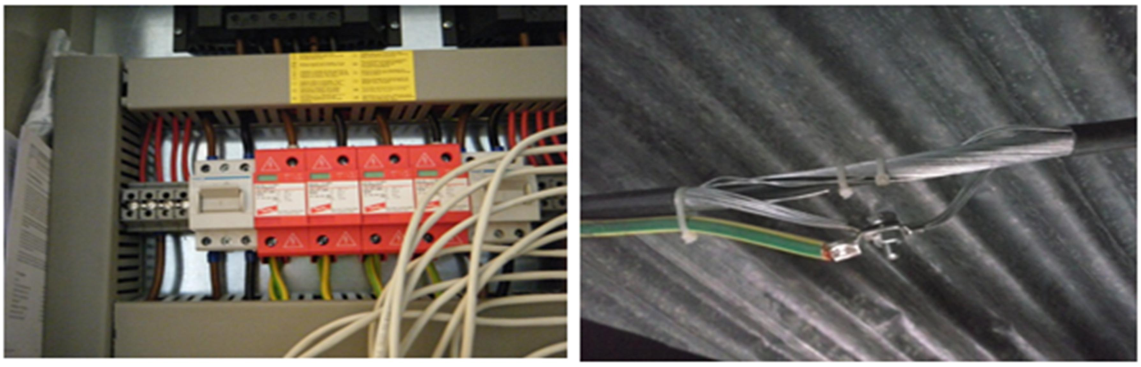


Figure 3.88: DC surge arrestors (left) and ground connection of cable shield (right)

Note: If the cable length between two pieces of equipment is longer than 10 metres, the installation of an SPD on both ends is recommended. For instance, a main cable from the combiner box to the charge controller which is longer than 10 metres should have one SPD in the combiner box and one at the charge controller.

External lightning protection **-** the function of external lightning protection is to prevent physical damage to a structure and risk to life due to lightning current and sparks resulting from a direct lightning strike into the structure. An LPS for external lightning protection to lead a lightning strike safely to the ground consists of these components:

- Air termination rod (lightning arrestor)
- Down conductor
- Ground termination system (earthing rod)

Internal lightning protection **-** the function of internal lightning protection is to prevent risk to life and damage to electrical and electronic systems due to lightning-induced voltages from nearby lightning strikes. An LPS for internal lightning protection consists of these components:

- Equipotential bonding of all metal housings and structures
- Equipotential bonding of conductors by surge protection devices (SPD)
- Shielding of equipment and conductors against electromagnetic induction
- Appropriate installation site for equipment in order to reduce electromagnetic induction and to prevent flashover from sparks

Chapter 4.4 explains in detail the occurrences and reasons for adequate lightning protection.

» *Application and configuration*

GRID-TIED AND OFF-GRID PHOTOVOLTAIC SYSTEMS

Grid tied solar systems are connected directly to the electricity grid and rarely include a battery bank. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Residential, grid-connected systems are designed to meet the load demand of most consumers and feed excess power into the grid for consumption by other users. This feedback is done through a meter to monitor power transfers. The photovoltaic wattage that is generated may be less than a household's consumption, in which case the consumer will continue to purchase grid energy, but in a lesser quantity than before. If generated photovoltaic wattage substantially exceeds the household's average consumption, the energy produced by the panels will far exceed the demand. In this case, the excess power can be sold back to the grid to yield revenue. Utility-scale solar power plants, in contrast, are designed for the sole purpose of selling electricity to consumers via the national grid.

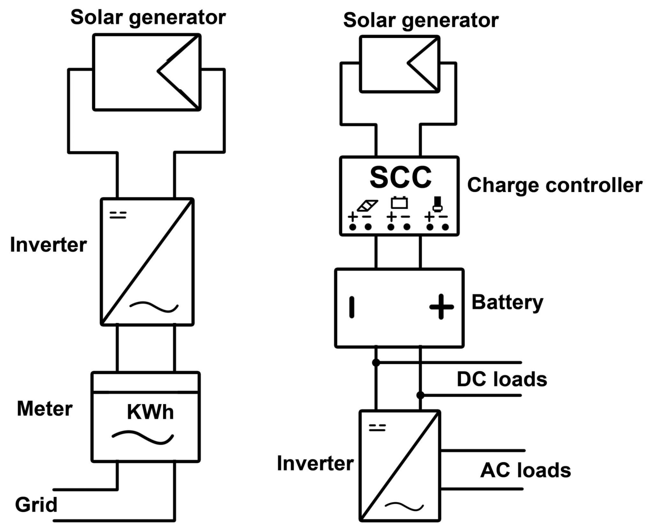


Figure 3.89: Grid-tied PV system (left) and off-grid system (right)

Off-grid systems or stand-alone systems are systems that are not connected to the national grid. These systems are mostly used in remote areas where an electricity supply is important but the grid is not present. Some examples of applications include telecommunication repeater sites, rural electrification, community lighting, etc.

» *Grounding*

Photovoltaic systems as with all electrical systems pose a threat due to electrical shocks due to surges caused by equipment malfunction, hence the need ground them. There are two ways to ground solar systems:

EQUIPMENT GROUNDING

This means connecting all metal bodies of the equipment to the ground electrode. These include solar panel frames, inverter and charge controller housings, metal junction boxes as well as potential earth conductors on the AC side of the installation. When grounded properly, in the event of lightning strike the induced high voltages on all metal parts of the system are on the same voltage and zero potential to earth. No current flow is possible, which can injure people and damage equipment.

SYSTEM GROUNDING

Of a solar system means connecting either the positive or the negative wire of the battery to ground. System grounding is necessary when manufacturers demand it for the proper function of their equipment. Certain types of PV modules must be negatively grounded, otherwise they lose power output due to the accumulation of electrostatic charge. Also, some protective devices such as DC RCDs will not function without system grounding.

WHEN TO GROUND STAND-ALONE SOLAR PHOTOVOLTAIC SYSTEMS

In locations where the PV array is exposed and could be susceptible to lightning strikes the array should be grounded by connecting the negative terminal to ground. Even for smaller systems such as our example, a bare copper cable of minimum size 10 mm^2 should be used to connect the metal frame of the PV array to a grounding electrode. If the solar panel array is installed on a roof of a building with an existing lightning arrester, it is usually not required to ground the metal frame of the solar panel array. Otherwise, grounding the metal frame of the solar panel array is not necessary.

Figure 3.90: Grounded solar array: Ground mounted (left) and roof mounted (right)

STAND-ALONE SYSTEM SIZING

» *Sizing a PV system*

TERMINOLOGY

1. Worst month: Month of the year in which the available solar resource is lowest with respect to energy demand.
2. Total energy demand: Energy consumption of all electrical equipment which has to be powered. Includes losses due to DC/AC conversion by an inverter.
3. Days of autonomy: Maximum number of days that the system can work without the battery bank being recharged.
4. Peak power: Amount of power of the solar panel array (W_P).
5. Runtime: Duration that an electrical load is used. For instance, for a TV set, the daily runtime could be 8 hours, but for a bathroom lamp no more than 1 hour.
6. Performance ratio (PR): Measure of the efficiency of a photovoltaic system. It is represented as a percentage and describes the relationship between the actual energy output and theoretical energy output of a PV array. The performance ratio is a factor which takes into account all losses (due to heat, dust, charge and discharge efficiency, losses in cables etc.) inherent in the system. Factors that influence performance ratio include:
   - Ambient temperature
   - Module and cell temperature
   - Wiring losses
   - Shading

- Efficiency factor during battery bank charging and discharging
- Orientation of PV array
- Difference between solar module MPP and battery charging voltage

A realistic performance ratio for a stand-alone solar system would be 60%.The performance ratio of a photovoltaic system is calculated as:

$$PR = \frac{Actual\ plant\ output\ of\ array\ in\ kWh}{Calculated, theoretical\ output\ of array\ in\ kWh}$$

Some criteria to consider when designing and selecting components for a stand-alone system:

- *Low life-cycle cost:* Cost of the system over its lifetime (initial investment, maintenance and replacement costs). Can be up to three times the initial investment, with battery life extensions having a strong impact on life-cycle cost reduction.
- *Tolerance of load and insolation variations:* Seasonal climatic variations are a key factor as they will determine how much electricity can be generated in the rainy season months.
- *Modularity and flexibility:* How flexible is the system? Can it be expanded with a subsequent increase in loads?
- *Ease of maintenance and repair:* Maintenance information for selected system components is important. Are spares readily available? Is the technology easy to maintain by the consumer?
- *Quality of power supply:* Different load types to be powered determine the type of inverter (modified or pure sine wave) to be used.
- *Reliability:* Expected system reliability is another consideration. When powering telecommunications equipment, for instance, a system is expected to be 100% reliable.

Table 3.14: Role of system components

Component	Role
Inverter	Converts DC to AC for use with conventional appliances
Battery	Primary energy storage device in a stand-alone system
	Stores energy generated by the solar generator
	Releases the stored energy to the inverter or directly to DC loads when needed.
Charge controller	Regulates the charging and discharging of a battery
	Prevents overcharging
	Prevents deep discharge by disconnecting the load whenever the battery is empty
	Indicates state of charge
	Schedules battery maintenance measures

DECISION-MAKING ALGORITHM

When choosing equipment to meet certain power needs, you will need to determine the following:

- Minimum capacity of the battery, which is determined by the load demand to be met. The battery bank stores enough energy to provide power at night and through days with little sunlight, and will determine your number of days of autonomy.

- Number and type of solar panels required to capture enough solar energy to provide adequate energy to the loads and charge the batteries.
- Specifications of all other components (regulator, wiring, etc.) needed to support the amount of power generated and stored.

Three main steps must be followed to calculate the proper size of a photovoltaic system:

Step 1: Estimate the required electrical energy (the demand)

Develop a load profile by recording the power consumption of the equipment as well as the estimated usage time. Then calculate the electrical energy required on a monthly basis. Consider the expected usage fluctuations due to variations between the rainy and dry season, school and vacation periods, etc. The result will be 12 energy demand values, one for each month of the year. The power consumption must include the inverter efficiency in the case of DC-AC conversion.

Step 2: Determine the available solar energy (the resource)

Based on statistical data of solar irradiation available from meteorological institutes or websites, determine the solar energy available while paying attention to the orientation and optimal inclination of the solar panels. Solar energy data is usually stated in monthly intervals, reducing the statistical data to 12 values. This estimation is a good compromise between precision and simplicity.

Step 3: Combine energy demand and energy offer (the matching)

The so-called "worst month" is the month with the least favourable relationship between the energy demand and the available solar energy. To determine that ratio, divide the energy demand by the energy resource (peak sun hours). The month with the highest resulting figure is the month with the least favourable relation between energy demand and availability. Solar energy and energy demand data from that month are what we use to size the photovoltaic system. For the table below, solar irradiation data for the Kainji Dam in Nigeria was used.

Table 3.15: Example comparing resource, demand and match

Month	*Resource (kWh/m²/d)*	*Daily demand (kWh)*	*Match*
January	5.73	11	1.92
February	6.02	12	1.99
March	6.27	12	1.91
April	6.13	12	1.96
May	5.75	11	1.91
June	5.17	9	1.74
July	4.65	9	1.94
August	4.38	8.5	1.94
September	4.83	9	1.86
October	5.39	10	1.86
November	5.73	11	1.92
December	5.74	11	1.92

As the table shows, in February we have the least favourable relationship between available solar energy and energy consumption: 6.02 peak sun hours have to cover an energy demand of 12 kWh per day. Using solar energy data and energy demand data for this particular month we calculate:

- Necessary energy storage capacity of the battery bank
- Energy generation capacity of the solar array
- Size, number and type of solar panels
- Required electrical characteristics of the regulator
- Length and diameter of cables required for electrical connections

SIZING THE BATTERY BANK

System voltage is determined by the battery bank, which needs to provide enough capacity to meet the energy demand when there is not enough solar radiation. The energy demand is the amount of energy which is supplied from the battery and provided to the DC loads or converted to AC via an inverter. To estimate the required battery capacity, you need to know the load demand on the solar system in the worst month as well as the desired days of autonomy. When sizing a battery bank in Nigeria, the following should be taken into account:

- Batteries should discharge no more than 30% of their rated capacity each day (DoD = 30%), assuming a deep cycle or "solar" battery is used.
- Total number of days of autonomy should be at least one and can increase depending on the application and the holdover time required.
- Energy demand should be chosen from the "worst month" according to definition above.

The total energy required to be stored in the battery bank can be calculated using

$$E_{battery} = \frac{E_{load} T_{aut}}{DOD}$$

Where

$E_{load} = Load\ energy\ demand$
$T_{aut} = Days\ of\ autonomy$

Example: The consumer energy demand of a small residence in the determined worst month is 12 kWh/d. Energy storage capacity of the battery: (12 kWh × 1)/30% = 40 kWh. To determine the battery capacity, divide the energy storage capacity by the system voltage.

CHOOSING THE SYSTEM VOLTAGE

The higher the energy demand, the higher the currents from the photovoltaic array and from the battery to the loads. Choosing a higher system voltage will allow the system to operate with lower currents and reduce costs for the charge controller and cables.

Table 3.16: Recommended system voltage based on peak energy demand

Mean daily energy consumption (kWh/d)	*Peak power in minutes (kW)*	*Peak power in seconds (kW)*	*Minimum system voltage (V)*
0–2	0–1	0–2	12
2–4	1–2	2–4	24
4–14	2–4	4–8	48
10 and above	4–8	8–16	60

Example: For our solar system which has to cover a daily energy consumption of 12 kWh, we choose a system voltage of 48 V. The battery capacity will be 40 kWh/48 V = 833 Ah.

CHOOSING THE RIGHT TYPE OF BATTERY

Batteries used in stand-alone photovoltaic systems must fulfil the following requirements:

- High capacity
- Low maintenance
- Long cycle life
- Capability to withstand deep discharge up to 80%
- Low self-discharge
- Good ampere-hour efficiency

Example: For our solar PV system, we need a battery bank of 48 V/833 Ah. However, that exact size will be difficult to find on the market. We could choose a smaller battery bank with 48 V/800 Ah and accept a slightly deeper DoD or we could move up to the next available size and choose 48 V/1,000 Ah. The battery bank could be configured as shown in Figure 3.91 below.

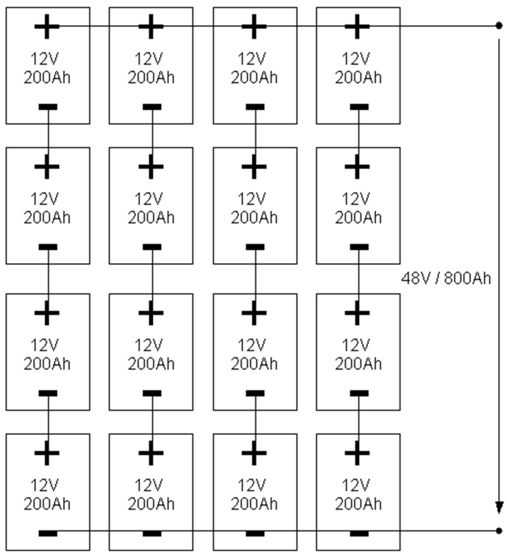


Figure 3.91: Series-parallel interconnection of 12 V/200 Ah batteries for a 48 V/800 Ah battery bank

The problem here is that designing a battery bank out of 16 units of 12 V batteries results in a 96-cell battery bank, which is an unreliable configuration. The far more preferable solution is to use as few cells as possible to build the battery. The diagram below shows a more robust and redundant configuration:

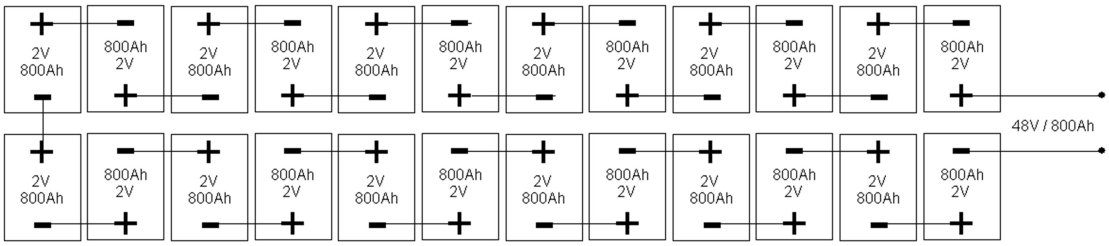


Figure 3.92: Series-parallel interconnection of 2 V/800 Ah batteries for a 48 V/800 Ah battery bank

As a rule of thumb, always try to use the lowest number of strings possible – that is, if using a battery with smaller capacity would give a large number of strings in parallel. The above configuration is a single string.

Example: We decide to build the battery bank out of 2 V/800 Ah cells to achieve an increased reliability and lifetime. Below is part of a data sheet for the "OPzV Solar Power" series by Hoppecke. The expected cycle life at 30% DoD is estimated to be 3,600 cycles, which is approximately 10 years, assuming one cycle per day.

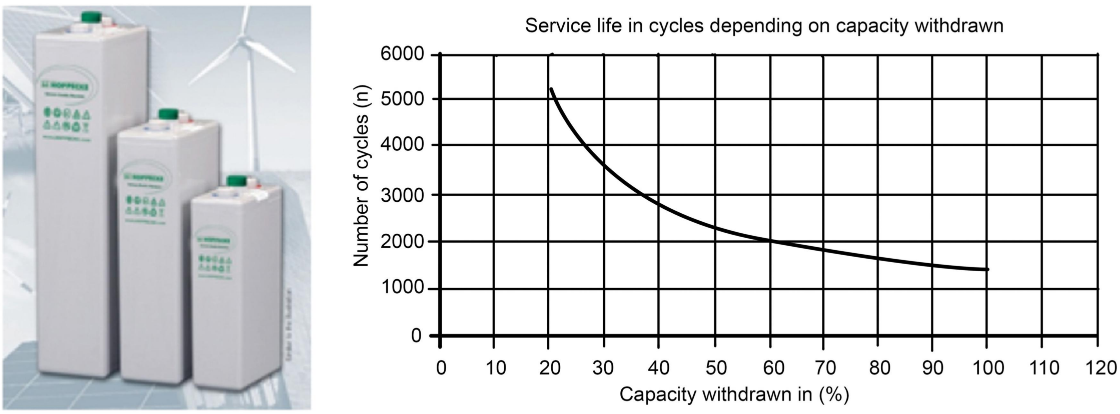


Figure 3.93: Hoppecke 2 V/ 800 Ah battery (left) and service life chart (right)

SIZING THE PV ARRAYS: YIELD CALCULATIONS

The size of the solar array depends on the energy demand of all electrical consumers, the available solar irradiation at the site of installation and the performance ratio of the solar system. Whenever energy demand varies throughout the year, we choose the data from the *worst month,* determined as described above; the same applies for the available solar energy. To calculate the solar energy availability we use *peak sun hours*. The performance ratio for a stand-alone photovoltaic system is approximately 65%.The size (required power) of the solar panel array can be calculated as follows:

- We divide the daily energy demand (kWh) by the performance ratio in order to get the theoretical daily energy output of the solar array (energy generated if there were no losses).
- We divide this theoretical energy output (kWh) over the peak sun hours, as these hours indicate the length of exposure of our solar array to full sunlight (1,000 W/m²). The result is the array size in kW_P.

Example: Our photovoltaic system will be installed at Kainji Dam and needs to cover a daily consumer energy demand of 12 kWh. The performance ratio is 65%.

⇒ *Theoretical energy output of the PV array = 12 kWh/65% = 18.46 kWh.*

⇒ *Available solar energy in Kainji Dam in the worst month = 6.02 kWh/m²/d.*

⇒ *Required power of the solar array: 18.46 kWh/6.02 PSH = 3.066 kWP.*

CHOOSING THE CORRECT TYPE AND NUMBER OF PV PANELS

After calculating the required size of the photovoltaic array, the system designer must select appropriate modules. Considerations include:

- The maximum power voltage (V_{MPP}) of the solar panels must be larger than the nominal system voltage.
- Proper battery charging requires a higher voltage than the battery nominal voltage.
- Voltage loss due to high solar panel temperatures during intense sunlight should also be considered.

The figure below shows the effect of a voltage decrease on the maximum power point of a solar panel with a nominal voltage of 12 V as well as its relation to the battery charging voltage range.

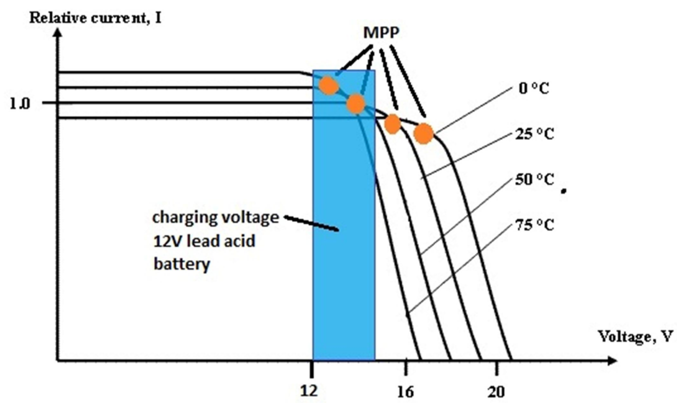


Figure 3.94: Relationship between voltage decrease and maximum power point of solar panel

By combining solar panels in series and in parallel, we can obtain the desired voltage and current. When panels are connected in series, the total voltage is equal to the sum of the individual voltages of each module, while the current remains unchanged. When connecting panels in parallel, the currents are summed together while the voltage remains unchanged. It is important to use panels of identical characteristics when building an array. It is also advisable to use modules that are as large (and powerful) as possible, since this will reduce the number of modules required to complete the array and make wiring easier and less costly.

Example: Our battery bank with a system voltage of 48 V shall be charged by the solar system. The maximum charging voltage (absorption stage) for this type of battery is approximately 2.45 V per cell.

⇒ *Charging voltage for the whole battery bank: 24 × 2.45 V = 58.8 V.*

⇒ *We assume the solar panel heats up to 65°C when exposed to intense sunlight and the solar panels can therefore achieve only 85% of their STC voltages. In order to properly charge the battery we need solar panels which have a MPP voltage at STC of no less than 58.8 V/85% = 70 V.*

⇒ *By consulting the table below, we can determine the required system voltage to be 48 V.*

Table 3.17: Guideline values for MPP voltage of solar panels

System voltage	*MPP voltage of solar panels*
12 V	17–19 V
24 V	34–38V
48 V	68–76 V
60 V	85–95 V

Most solar panels on the market are designed for a system voltage of either 12 V or 24 V. In order to enable a 48 V system voltage, we need to connect two 24 V modules in series and we will always have an even number of solar modules in the array.

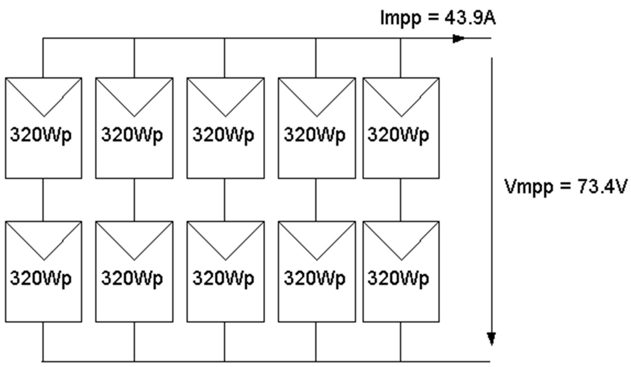
Example: Our 3.32 kWP solar array shall be built of an even number of modules, using as few solar panels as possible.

⇒ *Next even integer = 3,200 WP.*

⇒ *Figure 3.94 below shows part of a data sheet for a Solarworld SW320XL PV module. Two of these modules connected in series would result in a maximum power voltage of 73.4 V at STC. Losses due to high temperatures would bring the MPP voltage down to 63.9 V, which is more than adequate to charge the 48 V battery.*

⇒ *Ten of these solar panels would combine to form a PV array of 3.2 kWP. The maximum current (IMPP) would be of 5 modules in parallel: 5 × 8.78 A = 43.9 A*

⇒ *A suitable configuration is shown in the diagram below:*



SIZING THE CHARGE CONTROLLER

The charge controller must be able to control the maximum array current under any conditions. A photovoltaic module operating under real-life conditions can generate a much higher current than that specified for STC. Unlike the voltage, the current of a solar module increases slightly as the temperature rises. Moreover, midday solar radiation can, in some regions and under certain weather conditions, be much stronger than 1,000 W/m². To ensure safe and proper performance, a solar charge controller needs to be able to operate with a current at least 20% greater than the maximum power point current of the array.

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

Maximum power	P_{max}	320 Wp
Open circuit voltage	V_{oc}	45.9 V
Maximum power point voltage	V_{mpp}	36.7 V
Short circuit current	I_{sc}	9.41 A
Maximum power point current	I_{mpp}	8.78 A
Module efficiency	η_m	16.04 %

*STC: 1000 W/m², 25°C, AM 1.5

1) Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 2% (TUV Power Controlled).

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.042 %/°C
TC $_{Voc}$	-0.304 %/°C
TC P_{mpp}	-0.43 %/°C
Operating temperature	-40°C to 85°C

Figure 3.95: Data sheet of Solarworld SW320XL

Example: Our 3.2 kWP solar array generates under STC a maximum current (IMPP) of 43.9 A.

⇒ *Minimum rating of the charge controller: 43.9 A + 20% =52.7 A.*

Below is a part of the data sheet for the Steca Power Tarom series. The 4055 model would be the right choice; otherwise the next possible controller would be the 70 A controller.

		2070	2140	4055	4110	4140
	Characterisation of the operating performance					
	System voltage	12 V (24 V)		48 V		
	Own consumption	14 mA				
	DC input side					
	Open circuit voltage solar module	< 47 V		< 82 V		
	Module current	70 A	140 A	55 A	110 A	140 A
	DC output side					
	Load current	70 A	70 A	55 A	55 A	70 A
programmable	End of charge voltage	13.7 V (27.4 V)		54.8 V		
	Boost charge voltage	14.4 V (28.8 V)		57.6 V		
	Equalisation charge	14.7 V (29.4 V)		58.8 V		
	Reconnection voltage (SOC / LVR)	> 50 % / 12.6 V (25.2 V)		> 50 % / 50.4 V		
	Deep discharge protection (SOC / LVD)	< 30 % / 11.1 V (22.2 V)		< 30 % / 44.4 V		
	Operating conditions					
	Ambient temperature	-10 °C … +60 °C				
	Fitting and construction					
	Terminal (fine / single wire)	50 mm² / 70 mm² - AWG 1 / 00				
	Degree of protection	IP 65				
	Dimensions (X x Y x Z)	330 x 330 x 157 mm	360 x 330 x 157 mm	330 x 330 x 157 mm	360 x 330 x 157 mm	
	Weight	10 kg				

Technical data at 25 °C / 77 °F

Figure 3.96: Steca Power Tarom charge controller (left) and data sheet (right)

SIZING THE INVERTER

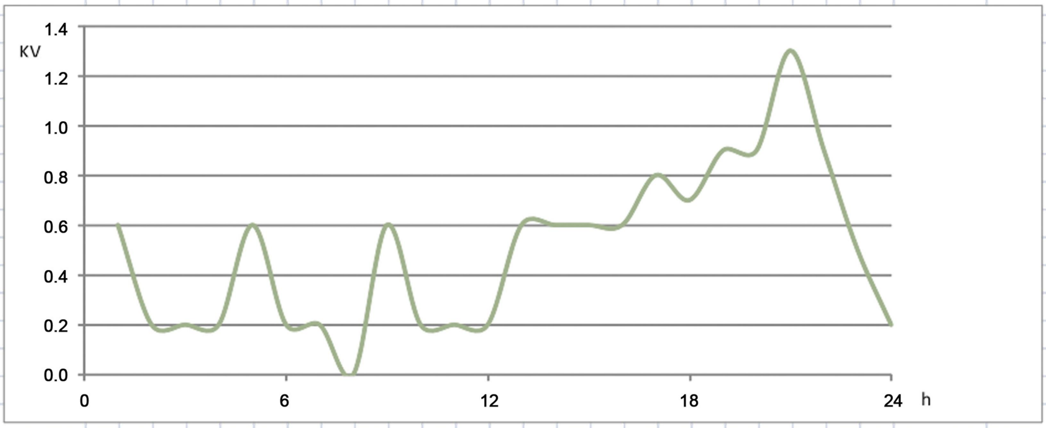
When choosing an inverter, keep in mind that the inverter performance varies according to the quantity of power requested. Oversizing an inverter not only leads to inefficient operation but also adds unnecessary costs. Correct inverter sizing is important for optimal system performance. In addition, the size (or nominal output) of an inverter cannot be raised or upgraded once purchased. In the point, the inverter differs from modules and batteries, which can be added at a later time in case the system design or sizing proves to be insufficient.

When choosing an inverter, the inverter's output capacity must be matched to the size of the electrical loads it will run. By choosing which electrical circuits the inverter will power (all circuits or only selected essential circuits), the power draw of all electrical loads on each circuit can be added together to arrive at a minimum necessary inverter capacity. Extremely power-hungry appliances such as electric water heaters and electric clothes dryers should either be replaced with gas-powered energy-efficient models, or be run on non-inverter supplied power.

Example: Our daily 12 kWh energy consumption is distributed over the day according to the load profile shown below. The peak consumption rate of 1.3 kVA occurs at around 9 pm.

Minimum inverter characteristics: at least 1.4 kVA continuous power output with 48 V DC input. The inverter must also supply the high start-up power of the fridge for a short peak. Below is a part of the Steca XPC series data sheet, from which we can see that the 2200-48 model would be the right choice. Its peak power can easily supply the start-up power of the fridge.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	Power consumption in KVA																								daily energy	
Lights																		0.3	0.3	0.3	0.3	0.3	0.3		1.8	KVAh
TV														0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4			3.6	KVAh
Fridge	0.4				0.4				0.4				0.4				0.4				0.4				2.4	KVAh
Sec. lights	0.2	0.2	0.2	0.2	0.2	0.2	0.2												0.2	0.2	0.2	0.2	0.2	0.2	2.6	KVAh
Laptops									0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2									1.6	KVAh
Peak power	0.6	0.2	0.2	0.2	0.6	0.2	0.2	0.0	0.6	0.2	0.2	0.2	0.6	0.6	0.6	0.6	0.8	0.7	0.9	0.9	1.3	0.9	0.5	0.2	12	**KVAh**



Minimum inverter characteristics: at least 1.4 kVA continuous power output with 48 V DC input. The inverter must also supply the high start-up power of the fridge for a short peak. Below is a part of the Steca XPC series data sheet, from which we can see that the 2200-48 model would be the right choice. Its peak power can easily supply the start-up power of the fridge.

	1400-12	2200-24	2200-48
Characterisation of the operating performance			
System voltage	12 V	24 V	48 V
Continuous power	1,100 VA	1,600 VA	1,600 VA
Power 30 min.	1,400 VA	2,200 VA	2,200 VA
Power 5 sec.	3,300 VA	4,800 VA	4,800 VA
Max. efficiency	94 %	95 %	95 %
Own consumption standby / ON	0.6 W / 4 W	0.9 W / 7 W	1.3 W / 7 W
AC input side			
Input voltage	adjustable: 150 V AC … 230 V AC		
Charging current adjustable	0 A … 45 A	0 A … 37 A	0 A … 20 A
Max. current / power on transfer system	16 A / 3.7 kVA		
Switching time transfer relay	< 20 ms		
DC output side			
Battery voltage	9.5 V … 16 V	19 V … 32 V	38 V … 64 V
Battery monitoring	LVD, HVD, floating and equalisation voltage adjustable by user via optional remote control RCC-01		
AC output side			
Output voltage	230 V AC +0 / -10 % (true sine wave)		
Output frequency	50 Hz +/-0.05 %		
Load detection (standby)	adjustable: 1 W … 25 W		

Figure 3.97: Steca XPC inverter (left) and data sheet (right)

CABLE SIZING AND SELECTION

Cable sizing is an extremely important, yet often neglected, part of system design. This neglect stems partly from conventional AC wiring systems in households, where currents and voltage drops are relatively small compared to low-voltage DC systems. For solar systems, cables need to be purposefully sized, considering not only the maximum current for each part of the system but also the length of the connection. Cross-sections are usually much higher than those used in conventional AC wiring in households.

Once you know the number of panels and batteries, along with the type of regulator and inverter to be used, it is necessary to calculate both the length and the thickness of the cables to connect the components. Cable lengths should be minimised, as this reduces power loss and the cost of cables. The maximum voltage drop on the DC side of a PV installation should not exceed 3%, meaning that from the solar modules to the battery no more than 3% should be lost. This source of voltage loss depends on four factors:

- Length of cable
- Current on cable
- Thickness of cable
- Material of cable

The absolute voltage loss can be calculated using the following formula:

$$\Delta V = \frac{2 \times L \times I}{\varkappa \times q}$$

Where:

L =	Cable length (m)
I =	Current (A)
ϰ =	Conductivity (µS/m). The conductivity of copper is 58 µS/m
A =	Cross-sectional area of cable (mm²)

The voltage loss is calculated as a percentage by dividing the absolute voltage loss by the system voltage. The minimum cross-sectional area of the cable can be calculated as follows:

$$A = \frac{2\rho L_{cable} I_{rated}}{\gamma V_{system}}$$

Where:

A =	Cross-sectional area of cable (mm²)
ρ =	Resistivity of copper (0.0179 Ωmm²)
L_{cable} =	Length of cable of run (m)
I_{rated} =	Maximum current flowing through the cable (A)
γ =	Maximum power loss allowance

Example: Our 3.2 kW_P solar array generates under STC a maximum current (I_{MPP}) of 43.9 A. The cable length from the combiner box to the battery via the charge controller is 12 m.

⇒ *The required cable cross-section is (2 × 0.0179 Ωmm²m-1 × 12 m × 43.9 A) / (= 0.3 × 48 V) = 13 mm². We need a cable with a minimum 13 mm² cross-section; the next available size would be a 2×16mm² cable.*

⇒ *The voltage drop for a 16mm² cable would be (2 × 12 m × 43.9 A) / (58 µS/m × 16 mm²) = 1.14 V. The voltage drop would be 1.14 V / 48 V = 2.4%, which is within the permissible range.*

» ***System design***

ORIENTATION OF SOLAR PANELS

Solar panels should be positioned to face the Sun. However, it changes its position during the day and also during the year. The angle of incidence of the Sun at noon in January is different than in June and this must be taken into account when siting the array. To capture most of the available sunshine all year round, advanced tracking systems are employed. In practice, however, most systems are mounted in a fixed position, which requires some level of compromise. In this case, the best mounting angle for the solar panel is facing the Sun directly at noon. The orientation of the photovoltaic modules depends on the azimuth (α) and inclination (or elevation) (β) of the Sun.

Azimuth (α): During the day, the Sun travels from east to west. In the Northern Hemisphere, the Sun travels from east to west via south, reaching its zenith in the southern position at noon. Irradiance is strongest at noon. Therefore, in the Northern Hemisphere, where Nigeria is situated, solar modules should always face south.

Inclination (β): During the day, the Sun rises over the horizon, reaches its highest point at noon and sets at the edge of the horizon in the evening. At noon when the irradiance is strongest, the solar modules should be installed so that the angle of incident of the sunrays on the solar module is 90°.

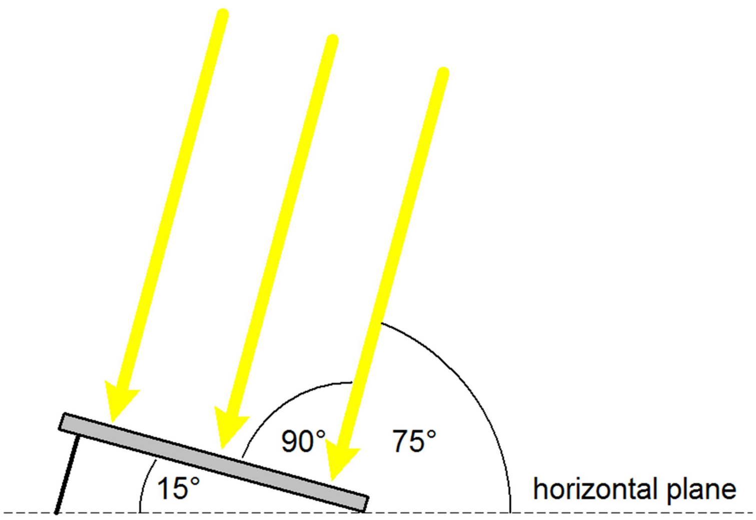


Figure 3.98: Inclination of Sun and tilt of solar module

The maximum height that the Sun reaches every day varies during the year. At or near the Equator, even the Sun's direction can change from south to north and back again. For installations with consistent (or nearly consistent) consumption throughout the year, it is preferable to optimise the installation to capture the maximum radiation during the months of the rainy season. The panel inclination should never be less than 15° to minimise the accumulation of dust and allow condensing humidity to run off. For specific sites, the inclination angle can be found online. Data sets from NASA Surface Meteorology and Solar energy are particularly recommended.

Example: Our 3.2 kWP solar array shall be installed at Kainji Dam. Below we have listed the inclination data for that site obtained from the NASA website. Latitude: 9.863°; longitude: 4.613°

⇒ *August is the month with the least sunshine in Kainji (according to data from an irradiation table from the same website). In August the angle of incidence at noon is 86°. The perfect mounting angle for the solar modules in August would be: 90° – 86° = 4°. In order to facilitate rainwater runoff, we will choose a slightly larger angle of 15° to 20°.*

Table 3.18: Monthly averaged maximum solar angle relative to the horizon

Month	*Average angle*
January	59.3°
February	67.7°
March	78.3°
April	89.8°
May	81.0°
June	76.7°
July	78.6°
August	86.0°
September	83.2°
October	71.6°
November	61.9°
December	57.2°

When deciding on a suitable location for solar panels, it is very important that no part of the panel is ever shaded. The location and effect of structures such as trees, buildings, walls, as well as other panels must be factored into the decision, including the position of their shadows throughout the seasons. Make sure to rule out all sources of shade on the panels for all times of the day and year.

The complete solar PV system from our example would look like this:

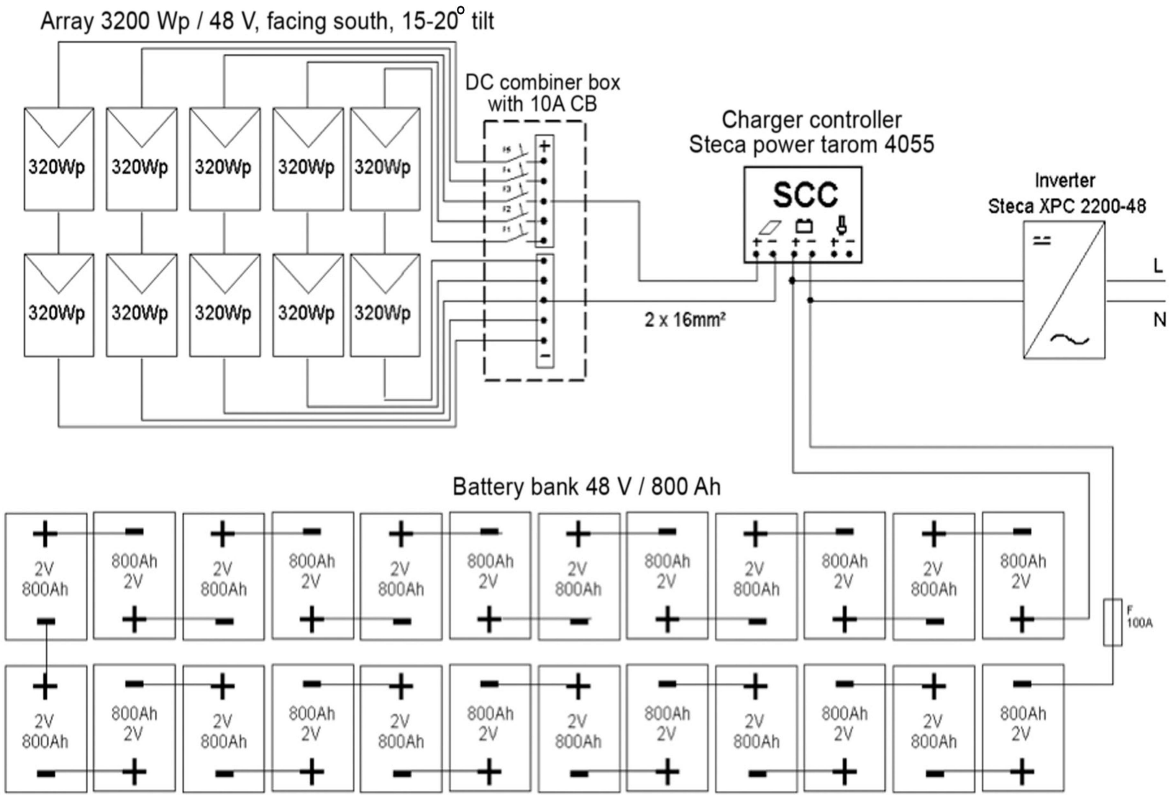


Figure 3.99: Wiring for our 3.2 kWP solar system

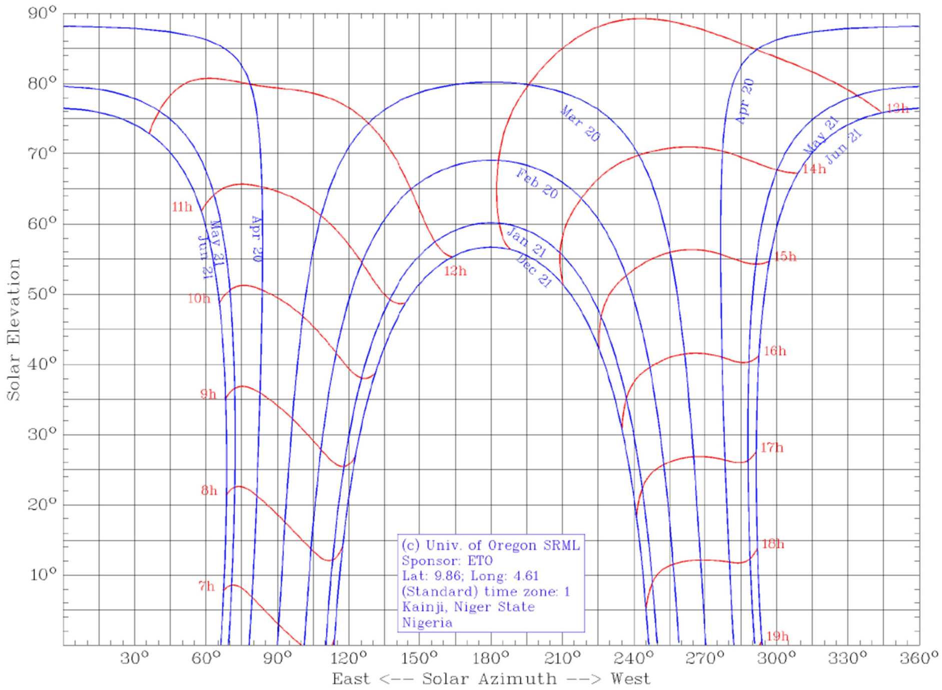


Figure 3.100: Sun chart for Kainji, Nigeria – *Courtesy: University of Oregon (June to December)*

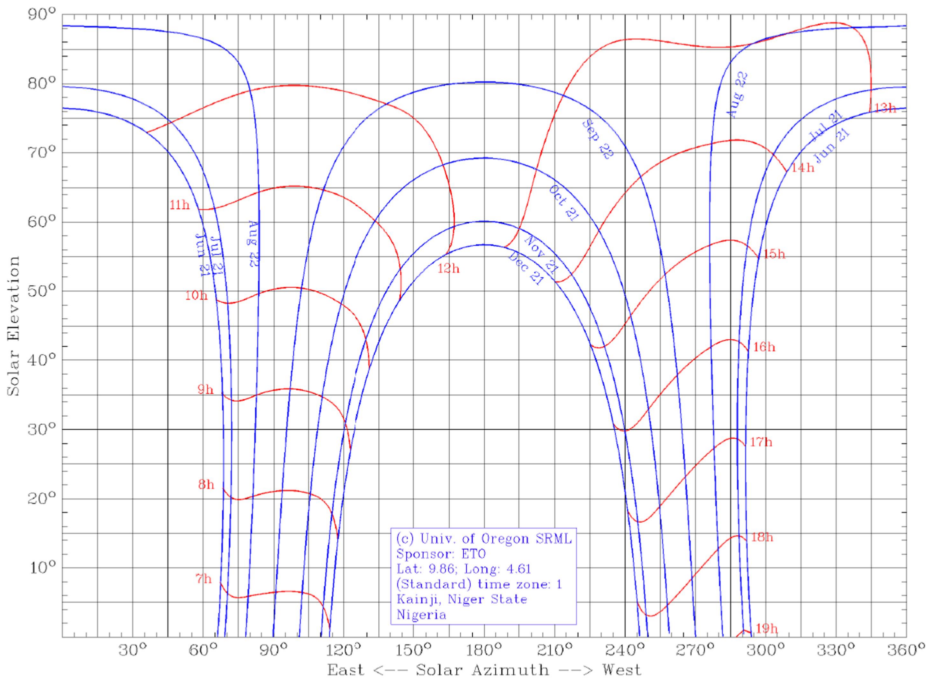


Figure 3.101: Sun chart for Kainji, Nigeria – *Courtesy: University of Oregon (January to June)*

SHADE ANALYSIS AND SUN PATH CHART

As described above, when deciding on the location of a solar PV array, you must always consider the possibility of shading caused by trees and nearby man-made objects such as buildings, poles and telecommunications towers. The Sun chart is a useful tool which allows system designers and installers to understand the availability of sunshine throughout the year as well as to understand the shadow that would be cast by the PV array. The Sun chart has two axes, the solar elevation and the solar azimuth.

The first Sun path chart explains the location of the Sun in the sky for 7 months (December through June) in Kainji, Niger state, Nigeria. The solar azimuth axis (horizontal axis) indicates the direction of the Sun in the horizontal plane for a given location. Accordingly, the north is defined to have an azimuth of 0° while the south has an azimuth of 180°. The east and west, where the Sun rises and sets, have an azimuth of 90° and 270°, respectively.

On the other hand, the solar elevation axis (vertical axis) indicates the height of the Sun over the sky during the day. These two axes are connected via the blue lines which indicate a particular day of the year in which the values were measured. In this case, the 20th, 21st or 22nd day of every month.

The Sun path chart would be incomplete without information on the time of the day at which the Sun is at a particular location. By tracing the intersection of the red lines, which show the time of day, and the blue lines, which show the day of the year, you can reasonably deduce the location of the Sun all year round. When working on site, a Sun path analysis instrument such as a solar pathfinder may be used to determine the shading effect of trees and other objects (houses, telecoms equipment) in the vicinity of the PV array.

From the chart above, we can deduce that at 9.00 am on April 20, the Sun is at an elevation of 36° to the horizontal and at an azimuth of 83°.

Note: For every project, the Sun charts need to be generated and reviewed.

INTER-ROW SHADING

When you install a solar PV array with numerous strings, you have to consider the possibility of inter-row shading. This effect occurs when the solar PV module in front casts a shadow on the module behind it.

Figure 3.102: Shadow caused by poorly spaced solar PV modules

When considering inter-row shading, you should assess the following criteria:

- Effective period of operation: PV modules will work whenever there is sunlight. Determine the times at which some shading is acceptable. It is recommended that if there is shading, it should *not* be between the hours of 8.00 am and 4.00 pm (8 hours without shading).
- Installation latitude for the PV array: The latitude (φ) determines the location of the Sun in the sky at different times, which in turn affects the length of the shadow that could be cast.
- Size of the solar panels: The length and width of solar PV modules also directly correlates with the length of the shadow that is cast.
- Orientation of the PV array: The angle of inclination and azimuth of the array play a major role in the occurrence of inter-row shading. At a larger angle of inclination, a longer shadow will inevitably be cast by the preceding photovoltaic module.

Required area for inter-row spacing - as discussed earlier, inter-row shading could drastically reduce the amount of energy that is obtained from a PV array. To mitigate this effect, you will need to apply the Sun path diagram or use industry-accepted rules of thumb. But first you need to identify the following parameters:

- Module length and width
- Required array length, width and area
- Module orientation
- Tilt angle
- Sun path chart

Once you have the above parameters, determining the distance between rows becomes a simple case of multiplication. As a general rule, in Nigeria a row spacing factor of 1 is recommended when determining the row space to be used between 8.00 am and 5.00 pm. For example, if you have an array (module) table of a height of 2 metres, the minimum spacing required to the next module is 2 metres.

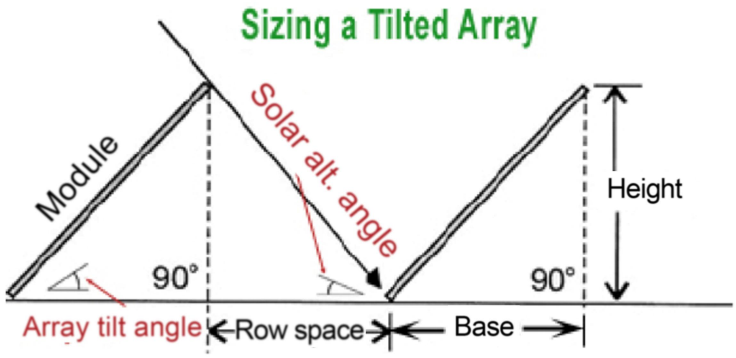


Figure 3.103: Calculating for inter-row shading – *Courtesy: TheSolarplanner.com*

In situations where the solar array does not face true south, a more complicated method must be used to determine the required row spacing. Here, you would need to read values off the Sun path chart and interpret them using trigonometric laws and principles. To do this, you must apply the following formula:

$$Space\ between\ rows = \frac{Module\ height}{tan(solar\ altitude\ or\ elevation\ angle} \times \cos\ (corrected\ solar\ azimuth)$$

The module height is the vertical distance from the module to the ground and may be calculated it using Pythagoras' theorem as follows:

$$Module\ height = module\ length \times \sin\ (array\ tilt\ angle)$$

$$Space\ between\ rows = \frac{Module\ height \times \sin\ (array\ tilt\ angle)}{tan(solar\ altitude\ or\ elevation\ angle} \times \cos\ (corrected\ solar\ azimuth)$$

Combining the two formulae above, the space between rows can be calculated as described in the following example.

Example: Spacing calculation

Using the Sun path charts provided above for Kainji, Nigeria, calculate the spacing required if inter-row shading is to be avoided between 8.00 am and 4.00 pm on December 21st, the day when the Sun is at its lowest point in the Northern Hemisphere. Let us assume that the PV modules to be used are each 1.985 m by 0.955 m and that only one row of solar panels is to be installed.

⇒ *From the Sun path chart we obtain:*

⇒ *Elevation angle at 8.00 am = 15°; azimuth angle at 8.00 am = 120°;*

⇒ *Elevation angle at 4.00 pm = 31°; azimuth angle at 4.00 pm = 235°*

⇒ *Elevation angle at 5.00 pm = 20°; azimuth angle at 5.00 pm = 240°*

⇒ *With the formula above for 8.00 am, 4.00 pm and 5.00 pm, respectively, we obtain*

$$Space\ between\ rows = \frac{1.985 \times sin\,15°}{tan\,15°} \times cos(180° - 120°) = 0.95\,m$$

$$Space\ between\ rows = \frac{1.985 \times sin\,15°}{tan\,31°} \times cos(235° - 180°) = 0.5\,m$$

$$Space\ between\ rows = \frac{1.985 \times sin\,15°}{tan\,20°} \times cos(240° - 180°) = 0.7\,m$$

Once you have calculated the required inter-row spacing, you can determine how many solar photovoltaic modules you can install in the area that you have available.

Thus, in order to design your solar PV array in a way that would harness most of the Sun during the day, you would require a substantial amount of space to mitigate inter-row shading. Therefore, there must a trade-off between how much of the Sun's energy you wish to harness and the amount of space that is available to you.

Exercise: Calculate the minimum inter-row spacing required for August 22 at 7.00am and 5.00 pm

» *Photovoltaic system costs*

The initial costs of a solar system often seem high in relation to the energy demand they are supposed to cover, especially when compared with the investment costs of a diesel generator which could do the same job. Yet when factors such as reliability, sustainability, life-cycle costs and noise pollution are considered, solar photovoltaic systems clearly come out on top.

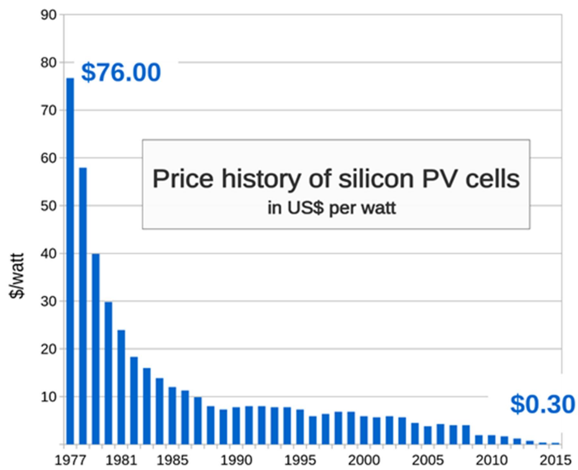


Figure 3.104: Photovoltaic module prices since 1977 – *Courtesy: Wikipedia*

This was not the case three decades ago when photovoltaic modules were sold at USD 30 per watt and as such were only used for military or research activities. Fortunately, the prices for solar modules have been declining over the past three decades, largely due to the improved commercialisation of PV modules as well as technological advancements along the production chain. Below you will see a graph indicating the price development for solar photovoltaic cells since 1977. Note that these figures are not module prices, which are approximately triple the cell price on average. The US market price for a 100 W_P solar module is about USD 90 or 0.9 USD/W_P. Module prices in Nigeria are about NGN 300/W_P, which is comparable, albeit slightly higher than US pricing for the same components.

When costing a system, the following criteria must be applied:

- Initial investment: Sum of the cost of all components including installation costs.
- Running costs: Applies to paid labour for maintenance work such as cleaning, scheduled replacement of limited-lifetime components such as batteries, repair or replacement of faulty components, system inspections.

- Cost of generated energy: Cost of the whole system over its entire lifetime in relation to the electrical energy generated during its useful life.
- Lifetime of system: Solar systems are usually assigned the same lifetime as the solar modules, which is at least 20 years.

Example: Life cycle cost

Example: For our 3.2 kW_P solar system, we want to create a cost estimate in order to determine the total investment, lifetime cost, daily running cost and energy generation cost.

Initial investment			
Item	***Quantity***	***Cost/Unit (NGN)***	***Total costs (NGN)***
Solar module 320 W_P	10	96,000	960,000
Battery OPzV 2 V/800 Ah	24	120,000	2,880,000
Charge controller Steca 48 V/55 A	1	90,000	90,000
Inverter Steca 48 V/1.6 kVA	1	100,000	100,000
DC combiner box including circuit breakers	1	30,000	30,000
Cable 2x16 mm^2/m	12	1,500	18,000
Mountings for solar modules	10	2,500	25,000
Connectors, fasteners (lump sum)	1	15,000	15,000
Labour	1	40,000	40,000
		Sum total	**4,158,000**

Running costs over 20 years			
Item	***Quantity***	***Cost/Unit (NGN)***	***Total costs (NGN)***
Weekly cleaning	1,040	500	520,000
Quarterly system check	80	4,000	320,000
Replacement of faulty charge controller	1	90,000	90,000
Replacement of faulty inverter	2	250,000	500,000
Replacement of batteries	1	2,880,000	2,880,000
		Sum total	**NGN 4,310,000**
		Total costs	**NGN 8,468,000**
		Cost / year	423,400
		Cost / month	17,642
		Cost / day	1,160
		Energy generation/day	12 kWh
		Cost / kWh	96.67

A battery-based stand-alone solar power supply system, where the most expensive part is energy storage, cannot compete with the energy prices of the utility grid. Battery prices have not followed the same trend as prices for solar modules and have not decreased over time. This is not expected to change in the near future.

Example: Comparison with generator

Instead of our 3.2 kWP solar system we consider another generation source and calculate the costs of energy generation by a petrol-driven generator of 2 kVA:

Power generation by petrol driven 2 kVA generator, with a 10-year lifetime		
Initial investment	NGN	140,000
Replacement after 10 years	NGN	140,000
Maintenance over 20 years	NGN	300,000
Petrol over 20 years	NGN	15,000,000
Sum total	**NGN**	**15,580,000**
Daily running cost	NGN	2,134
Cost / kWh	NGN	177.85

Conclusion: The initial investment in a petrol generator is extremely low – not even 5% of the initial investment for a solar power PV system; however, the daily running cost over the 20 year period and the cost per kWh of generated electric energy are 2 to 3 times higher than those for the solar generator. Considering the life-cycle costs, the solar PV system costs less than the petrol generator.

SOLAR THERMAL ENERGY

This is a form of technology that deals with harnessing the energy from the Sun and converting it into thermal or electrical energy. Solar thermal systems for electricity require high temperatures for operations in the range of 300°C – 1,500°C whilst systems for heating (domestic and commercial), lower temperatures in the region of 65°C – 70°C are more common.

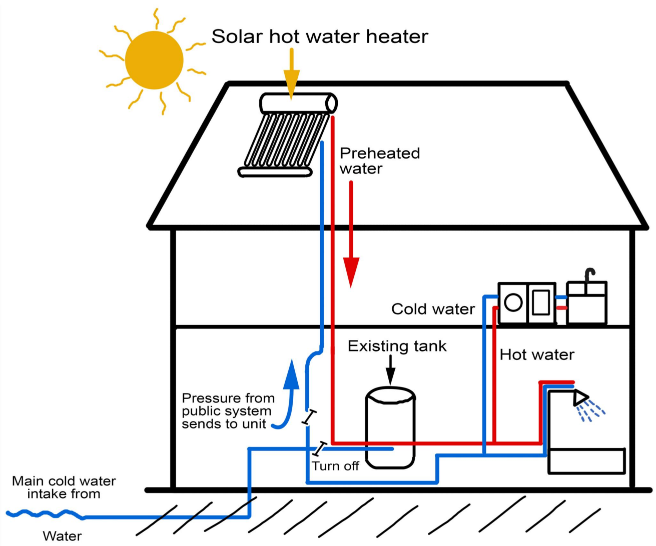


Figure 3.105: Residential solar water heating system

Collectors are the main component of most solar thermal systems. The collector absorbs sunlight and converts it into heat energy. Other components in a solar thermal system include the solar circuit which transfers the heat energy via a transport medium (fluid) to the heat store. These heat stores such as in insulated water tank ensure that the generated thermal energy is available when needed. Solar thermal energy systems can be divided into the following groups:

» Solar water heating system

A solar water heating system consists of a flat plate or an evacuated tube solar collector, a storage tank and connecting pipes. The system is generally installed on a rooftop or on open ground, with the collector facing the Sun and connected to a continuous water supply. In the Northern Hemisphere, The collectors are generally mounted on a south-facing roof. Water stored in the tank remains heated overnight as the storage tank is insulated and heat loss is minimal. Two main collector technologies are employed in its application.

SOLAR FLAT PLATE COLLECTOR

The flat-plate collector consists of an absorber, a transparent cover, a frame, and insulation. Usually a low-iron safety glass is used as a transparent cover as it lets through a great amount of the radiation from the Sun. Simultaneously, most heat emitted by the absorber stays trapped beneath the cover (greenhouse effect) and only very little escapes. In addition, the transparent cover prevents wind from cooling the absorber. Together with the frame, the cover protects the absorber from adverse weather conditions. The insulation on the back of the absorber and on the side walls lessens the heat loss through conduction. On better quality panels insulation usually consists of mineral fibre-based insulating materials like glass wool or rock wool.

Figure 3.106: Solar water heater with flat plate collector

EVACUATED TUBE COLLECTOR

For greater efficiency as well as for colder climates and higher water temperatures, evacuated tube collectors are used. Unlike flat plate collectors, their efficiency does not drop with ambient temperature, making them less dependent on ambient temperature. In this type of solar collector, evacuated glass tubes are used instead of copper, thus eliminating the need for a separate cover sheet and insulating box. Water flows through the tubes, where it absorbs solar heat and is then stored in a tank. This type of solar collector can reach temperatures as high as 150^0.

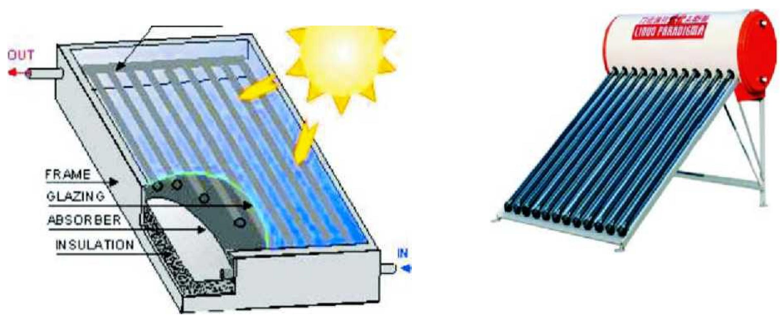


Figure 3.107: Evacuated tube solar thermal collector

Evacuated tube collectors consist of two concentric glass tubes fused at the ends as shown in the figure below. Air is evacuated from the gap between the tubes. The evacuated double-walled glass tube provides thermal insulation similar to that of a thermally insulated thermos bottle. The outer glass tube is clear, and the surface of the inner glass tube is coated with a special heat material that absorbs the Sun's energy.

Sunrays penetrate the clear outer glass and heat energy is absorbed by the coated inner glass. The vacuum permits the heat radiation to enter the outer tube. The absorbent coating on the inner tube converts shortwave radiation to longwave radiation, thus preventing re-radiation into atmosphere. Since conduction cannot take place in a vacuum, heat loss due to conduction back to the atmosphere is also prevented. Because of this principle, more heat is trapped compared to a flat plate collector. The heat loss in an evacuated tube collector is less than 10% compared to 40% for a flat plate collector. Water flows in through a third, innermost concentric feeder tube and hot water flows out through the annulus outside the feeder tube in contact with the absorber tube surface.

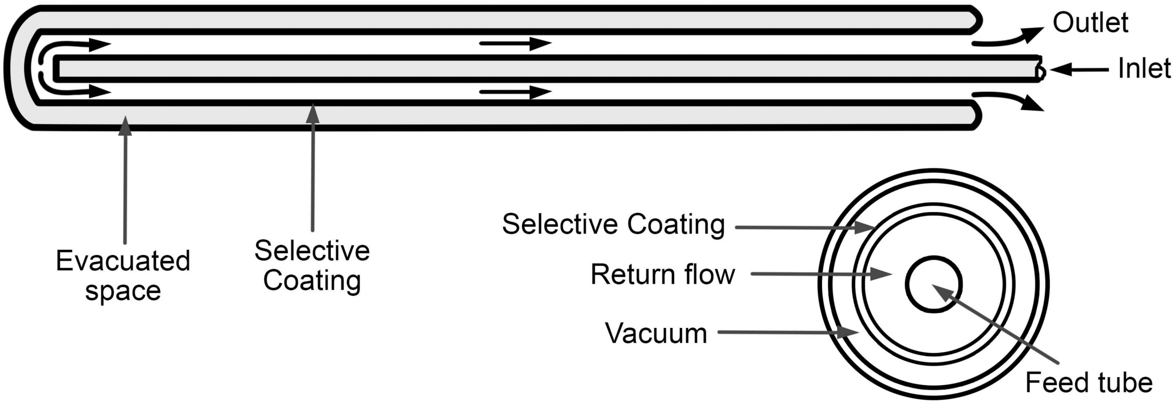


Figure 3.108: Cross - section of evacuated tube

Sunrays penetrate the clear outer glass and heat energy is absorbed by the coated inner glass. The vacuum permits the heat radiation to enter the outer tube. The absorbent coating on the inner tube converts shortwave radiation to longwave radiation, thus preventing re-radiation into atmosphere. Since conduction cannot take place in a vacuum, heat loss due to conduction back to the atmosphere is also prevented. Because of this principle, more heat is trapped compared to a flat plate collector. The heat loss in an evacuated tube collector is less than 10% compared to 40% for a flat plate collector. Water flows in through a third, innermost concentric feeder tube and hot water flows out through the annulus outside the feeder tube in contact with the absorber tube surface.

» ***Concentrated solar power***

Generating electricity via solar thermal processes requires higher temperatures than those that can be achieved using the flat plate or evacuated tube collectors. In this case, concentrated solar power (CSP) is the preferred method. Concentrated solar power refers to the generation of electricity and process heat via the concentration of sunlight which is beamed to a receiver usually located on a tower; the method is achieved with reflecting concentrators. There are two main CSP technologies, power towers and parabolic trough collectors:

POWER TOWERS

Typical power tower operation can be described as follows:

- Sunlight is collected by a large field of heliostats (mirrors) and reflected to a receiver on a tall tower. At the tower, the sunlight received from all heliostats is in a very concentrated form.
- Molten salt from the cold salt tank is pumped through the central receiver where it is heated to more than 550°C.
- Heated salt from the receiver is stored in the hot salt thermal storage tank.
- Molten salt is pumped from the hot salt tank through a steam generator that creates steam, which drives a steam turbine to generate electricity.
- Salt heated to nearly 300°C flows back to the cold salt thermal storage tank and is re-used.

PARABOLIC TROUGH COLLECTOR

Parabolic trough collectors are currently the most proven solar thermal electric technology. This system uses a series of specially designed parabolic trough-shaped reflectors that focus the Sun's energy onto a receiver tube (or trough) running at the focus of the reflector as shown in the figure below. Because of their parabolic shape, the troughs can focus sunlight at 30 to 60 times its normal intensity onto the receiver pipe. Heat transfer fluid (such as water) in the receiver is heated to a temperature of about 400°C.

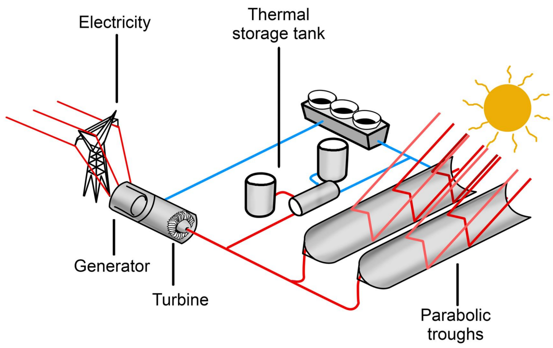


Figure 3.109: Parabolic trough collector system

Large arrays of these collectors are coupled to provide high-temperature water for driving a steam turbine. The collectors are aligned on an east-west axis and the troughs are rotated to follow the Sun to maximise the Sun's energy input to the receiver tube. Such power stations can produce several megawatts of electricity, but are confined to areas where there is sufficient solar insolation.

CURRENT TECHNOLOGIES AND TRENDS

» PV modules

The main trend and most important news in solar module manufacturing industry today is that module prices are expected to continue to drop. This is mainly due to increasing mass production and cheaper manufacturing processes. Most installations in the future will use the more efficient monocrystalline modules. Technologies such as the bifacial silicon cells, which are basically ordinary silicon cells but can capture light from both sides, either reflected from the roof or when vertically installed, can catch both morning and afternoon sun and more diffuse radiation compared to conventional cells. Other emerging cell technologies use different semiconductors to decrease costs or create multi-junction cells to increase efficiency by trapping a wider range within the spectrum of light. Concentrated photovoltaic solar (CPV) is one of these emerging technologies. CPV solar modules use a lens or a mirror to focus a large area of solar radiation on a small high-efficiency solar cell. Under laboratory conditions, cell efficiencies of 46% and module efficiencies of 38% have been reached

» Batteries

Storage batteries are becoming an increasingly viable option even for grid-tied systems in Western countries with reliable utility grids, a development which has made photovoltaic system owners more or less independent. This is due to price drops for storage systems but decreasing feed-in tariffs for photovoltaic power. At a certain point it becomes more economical for system owners to store and consume the energy generated by their systems.

In grid-tied systems, lithium batteries are leading the market. New technologies include quick-charging lithium batteries which can reach 70% SoC in just two minutes. These batteries present a useful option for electric vehicles, for example. Redox flow batteries, another new alternative, are comparable to fuel cells as they offer energy storage in two different electrolytes.

» *Inverters*

Currently, there are no new major advances in inverter technologies. There has been an observable increase in the installation of three-phase inverters for smaller grid-tied systems up to 35 kW, due to the sinking costs of these inverters.

REVIEW QUESTIONS

i. Differentiate between solar thermal systems that employ flat plate collectors and those that employ evacuator tube collectors.

ii. What is concentrated solar power? How does it differ from solar photovoltaics?

iii. What is doping?

iv. Describe the basic structure of a solar cell.

v. Explain the photovoltaic effect.

vi. A 1 MW solar power plant was constructed using crystalline silicon and required one hectare of land. Another 1 MW solar power plant was to be constructed beside it using amorphous silicon but it was found to require two hectares. Explain the difference in required land size.

vii. Describe how increased temperature and irradiance affect the output of a solar cell.

viii. Explain the relationship between the maximum power point of a PV cell and the rated power of the same cell.

ix. How does a charge controller function?

x. Describe the operation of an inverter.

xi. You are to install a battery bank for an 18 kW load. The inverter system voltage is 48 V. Sketch a diagram of a battery bank, showing connections for the system layout. Consider that the available battery is 200 Ah at 12 V.

xii. You are to install a PV array to supply power to a 1 kW load. How would you interconnect 125 W_P/12 V panels to supply power to the load? Provide a sketch.

xiii. Why do you need to create a load profile to size a system?

xiv. What is the electromagnetic spectrum?

xv. Describe the instruments are used to measure the solar resource at a given location.

xvi. Why is it advisable to store batteries in a well-ventilated room?

xvii. How do you mitigate corrosion and sulfation in a battery?

FURTHER READING

1. *Statistical Review of World Energy* • BP Global (2015): www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html (accessed Aug. 30, 2016)

2. *Planning and Installing Photovoltaic Systems: A guide for installers, architects and engineers, (2nd edition)* • German Energy Society [Deutsche Gesellschaft Für Sonnenenergie, DGS LV Berlin BRB], 2008

3. *Africa Energy Outlook 2014: A Focus on Energy prospects in Sub-Saharan Africa. Paris: World Energy Outlook Special Report* • IEA (2014): www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf (accessed Aug. 30, 2016)
4. *Renewable and Efficient Electric Power Systems* • M. Gilbert, Hoboken, NJ: Wiley & Sons, 2000
5. *Hybrid Energy Systems: Resource Book (edition 1b)* • M. Paul (ed.): Red Hill Qld: Renewable Energy Centre, Ithaca Campus, Brisbane Institute of TAFE, 2001
6. *Wind and Solar Power Systems: Design, Analysis and Operation (2nd edition)* • M.R. Patel, B. Raton , FL: Taylor & Francis, 2006
7. *Stand-alone Photovoltaic Systems: A Handbook of Recommended Design Practices* • Sandia National Laboratories (1995): (www.wbdg.org/ccb/DOE/TECH/sand87_7023.pdf – accessed Aug. 30, 2016)
8. *Renewable Energy Resources (2nd edition)* • J. Tidwell, and T. Weir, New York: Taylor & Francis, 2006
9. *Financing Renewable Energy in Developing Countries: Drivers and Barriers for Private Sector Finance in Sub-Saharan Africa* • Paris, UNEP Finance Initiative, 2012 (www.unepfi.org/fileadmin/documents/Financing_Renewable_Energy_in_subSaharan_Africa.pdf – accessed Aug. 30, 2016)
10. *Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries* • United Nations Framework Convention on Climate Change, Bonn, Germany – UNFCCC 2007 (www.unfccc.int/resource/docs/publications/impacts.pdf – accessed Aug. 30, 2016)
11. *Applied Photovoltaics (2nd edition)* • W. Stuart, and M. Green et al, London: Earthscan, 2007

3.2. MICRO HYDROPOWER (FOCUS TOPIC)

Chapter focus

Nigeria has an abundance of hydropower resources. This module introduces the participant to the basics of small hydropower. It provides participants with the necessary information for selecting a hydropower site and the components to be used for such a site.

Learning outcomes

At the end of this chapter, the participant is able to

- List and describe small hydropower system components with an emphasis on mechanical and electrical components
- Conduct a resource and site assessment
- Select an appropriate turbine design
- Understand the potential, risks and issues of small hydropower development

» What is small hydropower?

Small-scale hydropower is one of the most environmentally harmless forms of energy generation available to us today. When it comes to defining "small" hydro, there is no international consensus. Most countries generally accept a definition that assumes a total capacity ranging from 10 MW to 30 MW. Many hydroelectric plants, in contrast, are built on a massive scale – the Three Gorges Dam in China has a capacity of 22,500 MW – making it the largest in the world.

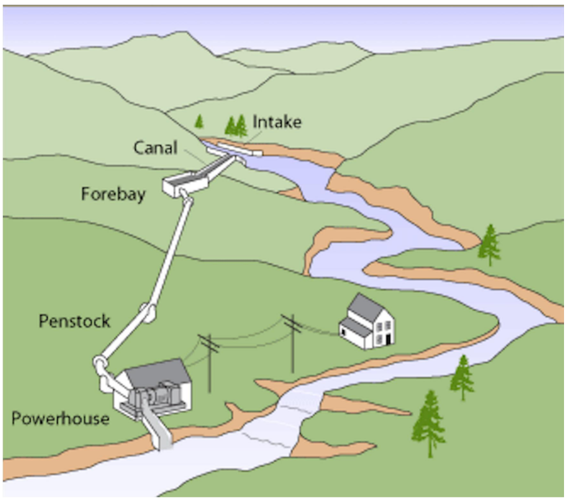


Figure 3.110: Layout of a typical micro hydropower system – *Courtesy of Winrock International*

Small hydro plants may feed into conventional electrical grids as a source of low-cost renewable energy. Alternatively, small hydro projects can supply isolated areas where grid-based electricity would be uneconomical or areas where there is no national grid or distribution network for electrical power. Since small hydro projects usually involve minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production. A well-designed small hydropower system can blend with its surroundings with a near to nil impact on the environment.

SUB CLASSIFICATION OF SMALL HYDRO

Small hydro can be further subdivided into mini hydro, usually defined as less than 1,000 kilowatts (kW), and micro hydro, generally defined as less than 200 kW. Nevertheless, strict boundaries do not exist. Micro hydro ordinarily refers to the use of hydroelectric power for smaller communities, single families or small enterprises.

Micro hydro plants may use custom-built turbines or mass-produced centrifugal pumps, connected in reverse to act as turbines. While these machines rarely have optimum hydraulic characteristics when operated as turbines, their low purchase cost makes them attractive for micro-hydro class installations.

HOW DOES IT WORK?

Hydropower systems use the energy in flowing water to produce electricity or mechanical energy. The water flows through a canal or penstock to a turbine where it strikes the bucket of the wheel, causing the turbine shaft to rotate. The rotating shaft is connected to an alternator or generator, which converts the motion of the shaft into electrical energy. This electrical energy may be used directly, stored in batteries, or inverted to produce utility-grade electricity. A small hydroelectric plant requires a sizeable flow of water and its descent from a considerable height, called head. These conditions are obtained without building elaborate and expensive facilities. Small hydropower plants can be developed at existing dams and have been constructed in connection with water-level control and irrigation schemes for rivers and lakes. By using existing structures, the need for new civil works remains minor, which reduces the engineering costs of a scheme.

To generate energy from water, two main factors are required:

Gross head **-** the vertical distance between the water tapping point and the water delivery point in a power scheme is called gross head. It is usually measured in metres. Gross head provides the potential energy which, when converted into kinetic energy, drives the turbine.

Flow rate **-** the quantity of water which passes through the turbine is called the flow rate.

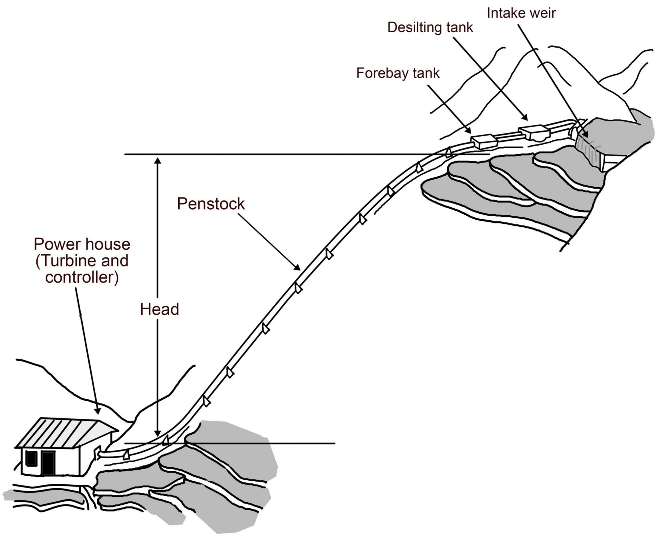


Figure 3.111: General layout of a hydro scheme

Power equation:

$$Power = Pressure \times Head \times Flow \times efficiency \times g$$

$$P = \rho \times H \times Q \times \eta \times g$$

Where Q is in m³/s and H is in metres. Simplifying this equation, we get:

$$P = 1000 \times H \times 9.81 \times \frac{Q}{1000} \times 0.51$$

$$P = 5 \times Q \times H$$

Where Q is in litre/s and H is in metres, P in watts

The efficiency of a scheme is calculated by taking into account the efficiency of every individual component in the process of converting water to power:

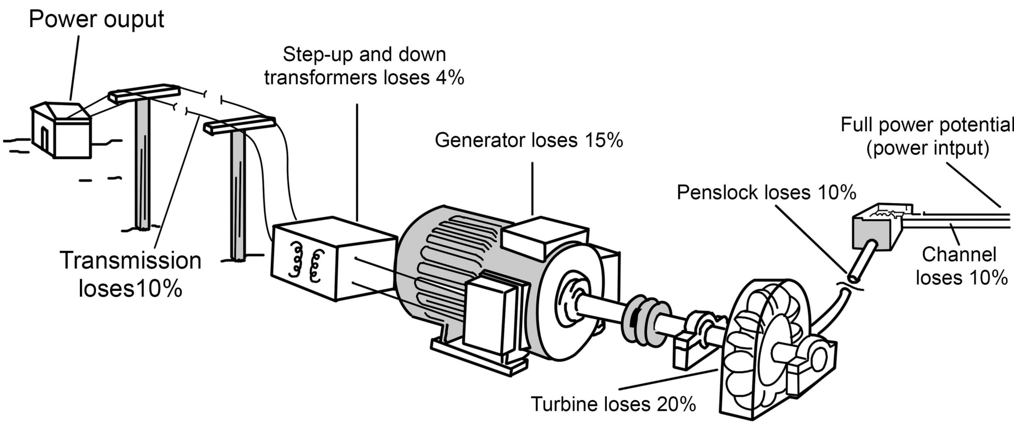


Figure 3.112: Efficiencies of different components in a SHP

$$P_{out} = e_{civil\ works} \times e_{penstock} \times e_{turbine} \times e_{generator} \times e_{transformer} \times e_{line} \times power\ input$$

Table 3.19: SWOT analysis for hydropower

Strengths	*Weaknesses*	*Opportunities*	*Threats*
• Cheapest renewable energy option • Water remains available for other purposes after use • Continuous availability of power on demand • Concentrated energy source given a reasonable head • Predictable quantity of available energy • Requires no fuel and only limited maintenance for low running costs (compared with diesel power) • Long-lasting and robust, systems can last 50+ years without major new investments • Simple enough to be transferred to and used in remote rural areas	• Mostly site-specific • Reliable site data must be collected to guarantee output • Lengthy planning and permit procedures • Seasonal variations affect performance • Dams and rivers collect water for electricity production, which alters the natural water flow system and thus deprives other needs. • Potential for serious disputes caused by changes to the river pathway and water shortages	• Large demand and supply gap • Major opportunities in hydroelectric consultancy in Nigeria and abroad • New sources of power generation • Opportunity to go global through tie-ups	• Rising cost of production • Competition from other new and environmentally friendly sources of power • Local opposition to environmental impacts and displacement of people

TYPES OF HYDROPOWER SCHEMES

» Schemes types based on flow condition

The capacity, unit size and selection of equipment, along with equipment characteristics and specifications for the design of a hydro power station all depend upon the type of hydroelectric scheme and its classification with respect to head and size. There are three main types of hydropower schemes that can be categorised in terms of how the flow at a given site is controlled or modified. These are:

- Run-of-river (ROR) plants (no active storage scheme in Nigeria)
- Plants with significant storage (for example, Kainji Dam)
- Pumped storage

ROR plants are completely different in design and appearance from conventional hydroelectric projects. Traditional hydro dams store enormous quantities of water in reservoirs, necessitating the flooding of large tracts of land. In contrast, most run-of-river projects do not require a large impoundment of water.

A small dam is required to ensure that there is enough water to enter the penstock pipes that lead to the turbines.

In the second type of scheme, plants with significant storage, the annual yield from the catchment (the area of land from which water flows towards a river) is stored completely or partially and then released according to some plan for the utilisation of storage. Water storage may serve a single purpose such as power development or it may target multiple purposes including irrigation, flood control, etc. Therefore, storage design will be governed by the intended use(s) of the stored water. If the scheme is only for power development, then the best use of the water will be to release controlled quantities based on power demand. Schemes with limited storage may be designed as peaking units. If the water project forms part of a large grid, then the storage is utilised for meeting the peak demands.

In the third scheme discussed here, pumped storage, the basic principle is to convert the surplus electrical energy available in a system in off-peak periods to hydraulic potential energy.

The method stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the losses occurring in the pumping process make the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest.

Taking into account evaporation losses from the exposed water surface and conversion losses, energy can be recovered at a rate of 80% or more. This technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.

» ***Based on head***

There are three types:

1. Low head (up to 30 metres)
2. Medium head (30 to 300 metres)
3. High head (more than 300 metres)

Low-head schemes are typically built in river valleys. Two technological options can be selected. Either the water is diverted to a power intake with a short penstock as in the high-head schemes or the head is created by a small dam provided with sector gates and an integrated intake powerhouse.

Medium-head and high-head schemes use weirs to divert water to the intake, from where it is conveyed to the turbines via a pressure pipe or penstock. Penstocks are expensive and consequently this design is usually uneconomical. An alternative is to convey the water by a low-slope canal, running alongside the river, to the pressure intake or forebay, and then in a short penstock to the turbines. If the topography and morphology of the terrain does not permit the easy layout of a canal, a low-pressure pipe, with larger latitude in slopes, can be an economical option. At the outlet of the turbines, the water is discharged to the river via the tailrace.

» *Schemes based on load and interconnection*

A base load plant operates continuously and generates constant power throughout the year. Examples of this type of plant include storage plants and ROR plants. On the other hand, a peak load plant supplies power during the peak hours only.

If a power station works independently it is referred to as an isolated plant. These plants are generally installed in industrial settings (i.e. captive power plant). If a power station is connected with grid, however, it is called an interconnected plant.

SYSTEM COMPONENTS

» *General layout*

A typical small hydropower plant will have the following components: Reservoir, diversion structure, spillways, desilting arrangements, headrace canal, forebay (for micro hydro) or surge tanks, penstock (a pipe), powerhouse consisting of electromechanical equipment and controllers, tailrace to channel the water back to the riverbed and a transmission network to evacuate the power generated. In smaller schemes, some of these components could be eliminated by designing a single structure that incorporates more than one function. For example, the desilting and spillway functions could be integrated into one structure.

RESERVOIR

A reservoir is created by building a dam – a barrier that stops and stores water. The reservoir not only suppresses floods but also provides water for various needs that include irrigation, human consumption, industrial use, aquaculture and navigation. Hydropower is often used in conjunction with dams to generate electricity.

In micro hydro schemes, the term weir is used instead of dam; because these schemes generally do not include a storage function. A weir is a low diversion structure built on the stream bed to divert the required flow while allowing the rest of the water to continue on its natural path.

INTAKE STRUCTURES

An intake structure is an arrangement that diverts water for a specific purpose or use. The intake allows water to be taken from its source and then discharged into the conveyance system, from where it is led to the desired application (e.g. for hydropower generation). Arrangements for routing high flood discharge are also made. Extreme care must be taken when selecting an intake location for the development of small-scale hydropower, as the intake facilities are a significant part of the project cost.

Figure 3.113: Desilting basin

SPILLWAYS

Spillways are designed to permit controlled overflow at certain points along the channel. Flood waters flowing through the intake can reach up to twice the normal channel flow, so the spillway must be large enough to divert this excess flow. The spill flow must be fed back to the river in a controlled way to prevent damage to the channel foundations.

DESILTING / SETTLING BASIN

The desilting or settling basin is one of the most effective devices for removing sediment particles from flowing water. It is used to trap sand or suspended silt before water enters the penstock. It may be built at the intake or at the forebay. Two effects must be avoided in the design of this component: Turbulence which stirs up the silt and does not allow it to settle down and flow separation which carries water quickly through the settling basin and also does not allow enough time for silt to settle.

HEADRACE

The headrace for a small hydropower plant is usually designed as an exposed channel structure that is open or covered. It runs from the desilting tank to the forebay or the surge tank and carries silt-free water. Headrace channels may be of the following types:

- Open channel made of reinforced concrete cement (RCC) or cut-and-cover and steel pipes are used along stretches where the slopes are geologically unstable
- Earthen canals
- Polyvinyl chloride (PVC), high-density polyethylene (HDPE) or fibreglass
- Steel pipe
- Tunnel

Figure 3.114: Examples of masonry: Lined (left), earthen (middle) and wooden (right) channels

FLUME FOR CIRCUMVENTING OBSTACLES

Canals can present various obstacles along their alignment. Bypassing these obstacles requires solutions that go over, around or under them.

A flume is required to cross a stream. This element prolongs the canal while retaining the same slope. Support for the flume can be provided by concrete or steel piles or it can span a given distance as a bridge. Steel pipes are often the best solution, since they may be used as the chord of a truss, which can be fabricated on site. Flumes do involve one potential problem: They make it hard to remove sediment deposited in the canal when it is filled with standing water.

FOREBAY / POWER INTAKE

The main advantage of a forebay tank is to store sufficient water to prevent large fluctuations of the water level during turbine operation. In case the water level drops, balancing of the water volume prevents air from entering the penstock pipe, which would cause damage.

PENSTOCK

Penstocks are pipes that are installed above or below ground, depending on factors such as the nature of the terrain, the penstock material, the ambient temperatures and the environmental requirements to convey the water to the turbine.

Figure 3.115: PVC penstock

From an environmental point of view, a buried penstock is optimal because the ground can be returned to its original state, and the penstock does not constitute a barrier to the movement of wildlife.

A penstock installed above ground can be designed with or without expansion joints. Variations in temperature are especially important if the turbine does not function continuously, or when the penstock is dewatered for repair, resulting in thermal expansion or contraction.

Today there is a wide choice of materials for penstocks. For the larger heads and diameters, fabricated welded steel is probably the best option. Nevertheless, spiral machine-welded steel pipes should be considered due to their lower price, provided they are available in the required sizes. For high heads, steel or ductile iron pipes are preferred, but at medium and low heads steel becomes less competitive, because the internal and external corrosion protection layers do not decrease with the wall thickness and because there is a minimum wall thickness for the pipe to be handled.

POWERHOUSE

The powerhouse is a building that protects the electromechanical equipment in the hydropower scheme from the adverse effects of weather. The number, type, configuration and power of the turbo-generators, along with the head of the overall scheme and the geomorphology of the site are the relevant factors that control the shape and size of the powerhouse.

TAILRACE

After passing through the turbine the water returns to the river through a short canal called a tailrace. Impulse turbines can have relatively high exit velocities, so the tailrace should be designed to ensure that the powerhouse would not be flooded and its integrity weakened. Rock riprap or concrete aprons should be provided as a safeguard between the powerhouse and the stream. The design should also ensure that during relatively high flows the water in the tailrace does not rise to a level that interferes with the turbine runner function.

TURBINE SELECTION

The hydraulic turbine is a mechanical device that converts the potential energy of water into rotary mechanical energy. Although this handbook does not define guidelines for the design of turbines (a role reserved for turbine manufacturers), it is appropriate to provide a few criteria to assist in choosing the right turbine for a particular application and even to provide appropriate formulae to determine its main dimensions.

The conversion of potential energy happens in one of two fundamental and basically different mechanisms employed in different turbine types:

- Water flows through the turbine expending its pressure along the runner surface. Turbines that operate in this way are called *reaction turbines*. The turbine casing is also exerted to the full operating pressure.
- Water pressure is converted into kinetic energy through high-speed jets which hit the runner blades or buckets that are mounted on the periphery of the runner. These are called *impulse turbines*. Because the water falls into the tailwater with little remaining energy after striking the buckets, the casing can be lightweight and serves the purpose of preventing splashing.

» *Specific speed*

For a given head, a turbine will have one speed for peak efficiency. This is the speed that yields the smoothest water flow around the turbine. If the head is then increased, the water will flow faster, and the optimum speed will be faster, but the directions of flow within the turbine will remain the same.

Now imagine the turbine is run on a 1-metre head. There would be a runner speed at which the water flowed in the same pattern, and this would be the optimum speed under that head. You could also scale down the turbine so that it only produced one unit of power, and still keep the same flow pattern.

This principle can be used to compare different turbine designs. By mathematically scaling down turbines to a standard head and power you can compare different types and designs.

The specific speed for a particular turbine design is defined as the speed (in rpm) at which the turbine, with its valves fully open, would give the best efficiency with a 1-metre head and with its size scaled down to yield an output of 1 kW.

$$N_{s-metric} = \frac{1.166 \times N \times \sqrt{P}}{(H_n)^{5/4})}$$

Where:

H = Head (m)

P = Power (kW)

N = Rotational speed (rpm)

CHOOSING A TURBINE

Turbines with higher specific speeds run, as would be expected, faster, and are usually lighter and smaller than turbines with lower N_s values. Thus, it makes sense to use a turbine with the highest possible specific speed. Advances in turbine designs and materials usually increase the specific speed of individual models.

Nevertheless, specific speed is by no means the only criteria for selecting a turbine. The other major factor is head, and high-flow turbines such as propeller turbines generally only operate with low heads. Pelton turbines, on the other hand, have low specific speeds but perform efficiently under very high heads.

Other limiting factors for turbine operation and performance:

- Efficiency at partial flow: If the turbine is required to run for substantial periods at partial flow, its efficiency away from its optimum point is important.
- Strength and hydraulic stability: Under certain conditions, the turbine may not actually be able to function over the full range of powers and speeds deduced from its specific speed and head limitations.
- Site-specific features: It may not be possible to excavate deep enough to fit a particular type of turbine, or the generator design may limit the allowable turbine speed.

TRANSMISSION / ISOLATED GRIDS

Hydropower plants that feed mini-grids should be constructed to be safe, efficient and, if increases in loads should seem possible, expandable. They should not present any greater hazard to the public than the ordinary power grid in urban areas. This means they should be designed in compliance with the *spirit* of any electrical codes or standards in use in the country.

Note: The word "spirit" is critical here because accepted standards are sometimes designed for conditions not present in rural areas where mini-grids might be found. For example, to reduce cost and thereby increase accessibility to electricity in rural areas, small conductors may be recommended as appropriate where loads will not, in the foreseeable future, even approach those found in urban areas. But the same conductor might be deemed unsafe according to the codes adhered to in an urban environment because increased current demand there could lead to a fire hazard. In such cases, blindly abiding by these standards makes electrification unnecessarily more expensive and less accessible to rural populations. – Mini Grid Design Manual", Allen R. Inversin, National Rural Electric Cooperative Association.

LOAD CONTROL AND PROTECTIVE DEVICES

» Electronic load controllers

Electronic load controllers (ELC) are used in small hydropower plants to govern the rotational speed of the turbine and the frequency of the voltage generated. The speed of the turbine is directly related to the speed of the generator. The turbine is generally connected to the generator by a drive which could be directly driven, belt driven, or in some cases gear driven. The turbine speed is selected for optimal performance; the generator speed is selected to run at the rated speed indicated on the name plate. This rotational speed will generate the electricity indicated on the name plate and it will be similar to that supplied by the grid. The three-phase ELC will work at 415/240 volts AC and at 50 Hz.

There are two methods to control the speed of a water turbine. One is to regulate the amount of water entering the turbine to keep the speed constant over the full range of the load. The other is to keep the water entering the turbine unregulated or at a pre-regulated position and keep the load applied to the turbine equal to that generated by the turbine. The second case is known as load control. In this case, the speed is set by the ELC and the controller maintains the speed constant at 3,000 rpm (50 Hz) by loading the generator into a ballast load. The ballast load is a dummy load, electrically connected to the ELC and made up of a set of heaters. The ELC diverts the power generated by the turbine generator into the ballast to maintain a constant speed. The amount of power diverted into the ballast load is adjusted by the voltage across the ballast load. This is shown in the diagram below.

The generator is connected directly to the ELC. The ELC, contained in a panel fitted on the wall, consists of a set of thyristors, a control circuit board, meters, a main contactor and a power supply.

The ELC will monitor the generator speed and divert power to the ballast load to maintain the supply frequency at 50 Hz.

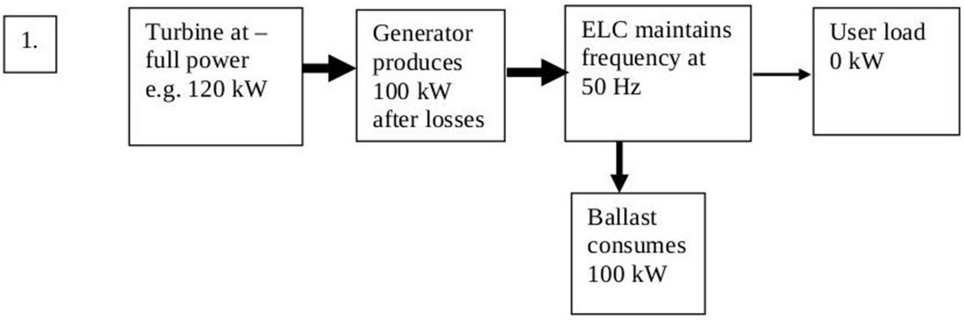


Figure 3.116: ELC case 1: No load conditions

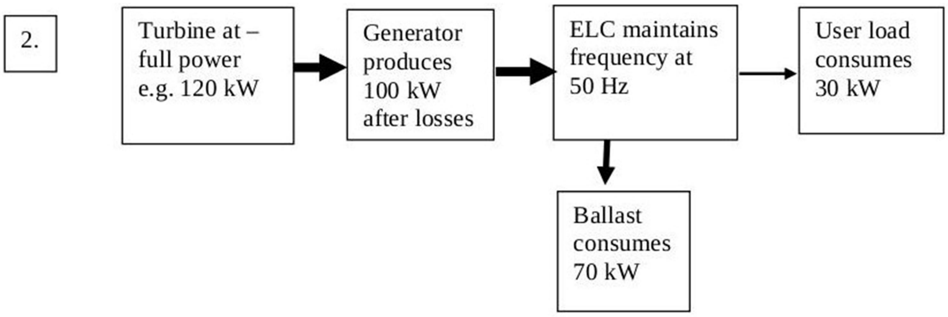


Figure 3.117: ELC case 2: 30% load conditions

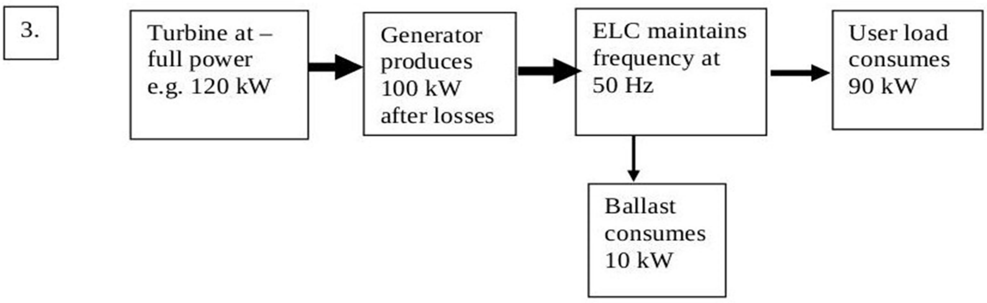


Figure 3.118: ELC case 3: 90% load conditions

The three block diagrams above show how the ELC will maintain the generator frequency at the required 50 Hz. The ELC continuously monitors the generator frequency; if it rises above the set value of 50 Hz, the ELC will begin to increase the ballast load. This increases the load on the generator causing the frequency to drop. If the frequency drops below the set value due to an excess user load, the ELC will reduce the ballast load to compensate for this loss in frequency.

As shown in Figure 3.118, the user load is switched off and therefore does not consume any electricity. This will cause the ELC to divert all the power generated by the turbine into the ballast, which is about 100 kW. Figure 3.118 illustrates part of the power generated by the turbine, in this case 30 kW, being consumed by the user load. As a result, the ELC diverts the balance, 70 kW, into the ballast. Figure 3.119 shows the case where the user load consumes 90 kW and the ballast only has 10 kW. At all times in the above cases, the water entering the turbine remains constant and the generator produces 100 kW. The ELC balances this power output between the ballast and load to ensure that the generator runs at the required frequency.

During the dry period of the year, the turbine may operate on a partial flow and the ELC will continue to control the frequency as shown in the diagram below. If the generator is overloaded by the user load, there is no additional power available in the ballast to supply this extra need. At this point, the generator frequency will begin to drop below the set value.

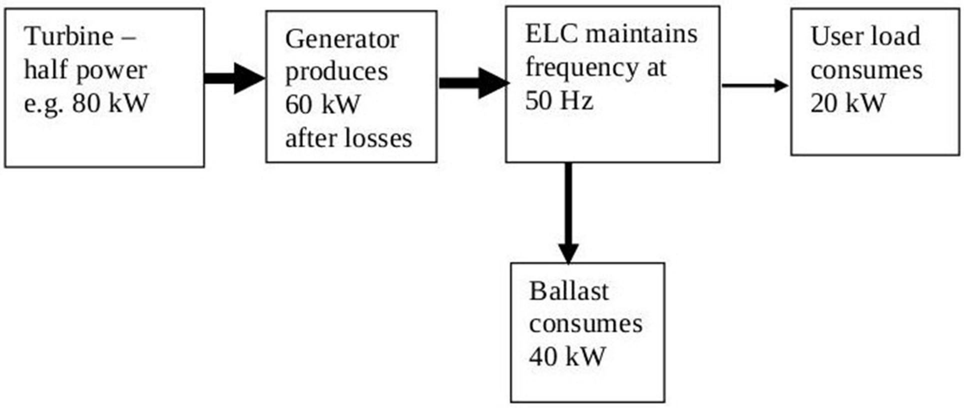


Figure 3.119: ELC operation during dry season

The ELC has an electronic circuit board which senses the frequency of the generator and sends a signal to a set of thyristors. These thyristors are connected to the ballast load, which is a large resister. To maintain the frequency at the pre-set value of 50 Hz, the ELC will continuously change the voltage across the ballast load. If the frequency tends to rise, there will be corresponding increase in ballast volts and therefore the power dissipated in the ballast will increase. This will increase the load on the generator and bring down the frequency. In the same way, if the speed drops the ELC will reduce the ballast volts allowing the generator to return to its set frequency.

The ballast load should be rated 15 to 20% higher than the turbine output. It should be installed in a well-ventilated place as it will get hot. For powers of 100 kW the use of water-cooled heaters is recommended.

The electronic load controller works in conjunction with a synchronous generator and is used only to control the speed of rotation of the turbine-generator set. It is not an automatic voltage regulator (AVR) for the synchronous generator and therefore it will not regulate the voltage of the generator. The AVR is generally part of the generator and is installed inside the generator. Its function is to maintain a constant generator voltage. But in some cases there are static or transformer-type AVRs which will maintain the voltage constant only if the speed is constant.

» *Protective devices in micro hydropower systems*

VIBRATION DETECTION

Vibration detection is very important and often neglected on small hydropower schemes. The objective is to make sure that if machine vibration rises significantly above normal, the machine trips off. This feature does not need to be complicated or expensive; a simple electronic vibration switch is often quite sufficient.

EARTHING OR GROUNDING

The objective of an earthing system is to make sure that under heavy earth fault conditions, no dangerous voltages arise that could cause electric shock or damage equipment. This requires all metalwork to be connected to the same earthing system (equipment grounding) and the earthing system to have the lowest possible resistance to the body of earth.

The most effective earthing is achieved by using the steel reinforcing steel bars of the powerhouse building and other concrete structures as the main ground connection.

Compared to buried cables or rods, the conductive area of reinforcing bars is enormously greater and, in earthing terms, mass concrete is a good and consistent conductor of electricity. In addition, the earthing system is virtually indestructible because there are no cables between the equipment and an earthing system outside the powerhouse could be damaged or stolen. The earthing system should be connected to main reinforcing bars at several points around the building. Practical experience has demonstrated that the many contact points between the main reinforcing bars and crossbars are more than adequate to carry and distribute the earth fault current.

Note: Earthing must be installed as first level (fundamental) protection for all electrical networks. It works with MCBs, fuses and other protective equipment to ensure that any fault current on metallic enclosures would be directed to earth.

FUSES

A fuse is a device for opening a circuit by means of a conductor designed to melt when an excessive current flows through it. Two types are commonly used: The rewirable fuse and the cartridge fuse. An advantage of a rewirable fuse is that, once the fuse has blown, the wire can be easily replaced at minimum cost. While these fuses may be convenient, inexpensive, and popular, a principal disadvantage is that any inexperienced person can easily replace the blown fuse wire with an incorrectly sized wire or an ordinary piece of wire. Such an action would completely negate the purpose of the fuse to open the circuit when current reaches an unsafe level and would place the system in jeopardy. Another disadvantage of the rewirable fuse is that it does not discriminate between a momentary but acceptable current surge (e.g., due to a motor starting) and a continuous overload current that must be interrupted.

MINIATURE CIRCUIT BREAKERS (MCBS)

A circuit breaker is an electromechanical device with the main function of automatically opening a circuit when currents in excess of its design rating pass through. Under normal conditions, a mechanism within the breaker holds the contacts in the closed position. The contacts are automatically separated when the release mechanism in the breaker is operated by magnetic and/or thermal means. While it is costlier than a fuse, a circuit breaker provides numerous advantages:

- It is easy to use and considerably more precise and more sensitive than a fuse.

- It can also be quicker acting; when small overload currents occur, the circuit breaker is likely to operate before the fuse blows.
- It can be tripped by a small sustained overload current but not by a harmless transient overcurrent such as the switching surge which accompanies the starting of a motor.
- The breaker on a faulty circuit is easy to detect, because this is indicated by the position of the switch, and the breaker cannot be switched on as long as the fault condition remains.
- It can more conveniently be used as a switch when repairs have to be done to the circuit. It can be reset manually after a fault has been corrected, and no stock of fuses is necessary.
- It is factory-calibrated and cannot readily be changed.
- Under fault conditions, a breaker positively disconnects all poles of the circuit it controls.

RESIDUAL CURRENT DEVICES (RCDS)

An RCD, also called a ground-fault circuit interrupter (GFCI), is a device that is inserted in the circuit between the power supply and the circuit along which protection is sought, usually on the premises of the consumer. This device is an automatic switch that senses the incoming current for the circuit to be protected (I_i) and compares it with the outgoing current for this circuit (I_o). Under normal operating conditions, these two currents should be equal and the switch then maintains the supply.

However, under fault conditions, such as when a person touches the live conductor, a portion of the current passing through the RCD into the protected circuit would then pass through that person (I_l), leak into the ground, circumvent the RCD, and return through the ground back to the supply, either through a system ground if there is one, through any fault, or simply through the capacitive coupling between the circuit and the ground. As soon as the RCD senses a difference between the incoming and outgoing currents, it trips and isolates the protected circuit.

An RCD operates by detecting the difference in current flowing into and out of the protected circuit, independently of how well the generator is grounded or whether it is grounded at all. But incorrectly grounding the consumer circuit can prevent an RCD from detecting fault currents.

Note: In high voltage installations malfunctioning or inadequate ground fault protection pose a danger to life and property. For AC installations therefore an RCD is generally recommended for protection against ground faults. This also applies to inverter and AC micro-hydro fed circuits. For the DC side however, the low voltage may not merit consideration of an RCD.

The most common and least expensive type of RCD is the AC-type. An A-type by comparison is sensitive to AC and pulses while a B-type is sensitive to AC, pulses and DC. For this reason the B-type is well suited for inverter installations, where, apart from AC, residual DC currents could persist in case of faults. This risk is particularly prevalent with transformer-less inverters which lack galvanic separation between the AC and DC sides. The B-type however is also the most expensive of all.

LIGHTNING ARRESTORS

When lightning discharges in the vicinity of a distribution line, a high voltage is induced in the line which can break down the insulation on the windings of transformers or generators connected to the line or damage electronic equipment in the home or powerhouse. The associated high currents may also generate large amounts of heat and release a considerable mechanical force. The purpose of a protective system is to divert these very high transient voltages and currents into the earth where they can be safely dissipated or to shunt these around, rather than through, devices that need protection.

Commercially available lightning arresters come with a weatherproof enclosure, connection leads, and a mounting stud or bracket. They should be connected to the distribution line, close to the equipment or accessory requiring protection, such as just outside the powerhouse or the home.

***Note*:** Nigeria is located in the tropical belt around the equator, an area with the highest numbers of lightning strikes on earth. In Nigeria, each square kilometre is hit by 10 to 50 lightning strikes every year. Buildings with exposed surroundings are far more likely to be hit by lightning than relatively sheltered buildings. However, damage due to nearby lightning strikes is far more common than damage due to direct lightning strikes. Nevertheless, the damage caused by direct lightning strikes is often significantly more devastating. Thus, lightning arrestors must be installed on the tallest structure (e.g. building) within this 10 km radius.

PLANNING A HYDROPOWER SCHEME

» *Resource measurement*

NATIONAL AND REGIONAL LEVELS

For national and regional resource assessment, satellite images are used to develop a GIS database for water source identification, site selection, environmental planning, digital terrain model data (DTM), and the transmission line network and ranking of the sites. Generally, such exercises for large-scale resource assessments are carried out by a team comprised of experts in GIS, hydrology, hydropower, etc.

Geographic information systems (GIS) are computer-based information systems used to digitally represent and analyse the geographic features present on the Earth's surface. The hydropower potential for a region can be assessed using the following methods.

REGIONAL FLOW DURATION MODELS

A flow duration curve is a simple graphical depiction of the variability of water flow at a given location without any reference to the sequence in which this flow would be available. Flow duration curves for the prospective sites for which adequate flow data is available can be directly developed. This curve can be used to estimate the flow for various levels of dependability for the gauged site. However, in real life situations, most of the prospective sites for hydropower projects are likely to be ungauged where the sites either have insignificant data or no flow data available for such analyses.

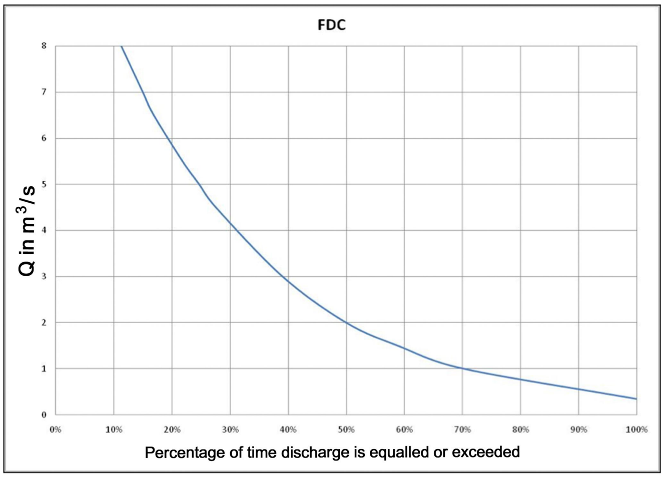


Figure 3.120: Flow duration curve

To derive a flow duration curve for a location on a stream for which adequate flow data are not available, a regional flow duration curve may be used. Regional flow models are developed using data available for a few other gauged catchments in the same region or transposed from a similar nearby region. Such models are employed to compute flow duration curves for ungauged catchments in that region. The availability of such regional flow duration models is of paramount significance (for example in estimating the potential of hydropower in remote hilly regions of the country).

The annual flow duration model provides the pattern of flow at an ungauged catchment. For the development of a flow duration model, the physiographic characteristics of the catchment such as area, perimeter, length of main channel, elevation of highest and lowest points, site geology and hydrogeology, land use pattern, climate and other parameters should be taken into account. Depending upon the data availability, the flow duration obtained from the above regional flow models may be used only for pre-feasibility studies. This can be followed up with a detailed site feasibility study (for potential sites) based on the actual measurement of the discharge from the river or stream.

REMOTE SENSING DATA FOR CATCHMENT ANALYSIS

Remote sensing technology is an effective tool for the identification of suitable sites for new hydropower projects, especially in inaccessible areas like the Himalayas where the water recourse potential is high. Remote sensing data available in the near infrared range (0.8 um to 1.1 um) clearly illustrates the contrast between land and water features and is therefore best suited for mapping perennial streams. IRS-1C/1D LISS III geocoded FCC (false colour composites) may be used for the identification of catchment boundaries, drainage networks, perennial streams, land use and vegetation cover for such assessments. The elevation contours and spot heights from topographic maps can used to generate a digital elevation model (DEM) of these catchments using any of the several GIS software packages available (Manifold, ARC-INFO, MapInfo, etc.). For further analysis, the catchment boundary, drainage network and location of major habitation types can be overlaid on these DEMs.

DIGITAL TERRAIN MODELS (DTMS)

Digital terrain models can be used to compute the slope, channel length, catchment area, head available for power generation and the location of suitable sites for civil structures of small hydropower projects. Such structures and components include the diversion weir, feeder and headrace channel, desilting tank, forebay tank, powerhouse building, etc. Satellite imagery and GIS can further be used to generate a profile analysis and suitable (optimal) pathway diagrams, engineering designs for towers and wires and cost estimates for the transmission line network or feeder line to the nearest substation.

» *Resource estimation at local levels (site-specific)*

The only resource needed for a small/micro hydropower plant is water flowing at a gradient. Planning for any small hydro plant begins with the (near to) accurate estimation of the head and flow available at the proposed site. In the following subsections, various methods for measuring the available head and discharge are described in detail.

MEASUREMENT OF HEAD

There are several methods to measure the head which is available at a site. Some methods are more suitable on low-head sites, but are too tedious and inaccurate for high heads. It is always advisable to take several separate measurements of the head at each site. A further very important factor is that the gross head does not remain constant but instead varies with the river flow. As the flow in the river increases, the tailwater level often rises faster than the headwater level, thus reducing the total head available. Although this head variation is much less than the variation in flow, it can significantly affect the power available, especially in low-head schemes where even 0.5 metres are critical. To accurately assess the available gross head, headwater and tailwater levels need to be measured for the full range of river flows. Some of the more common methods or techniques used for head measurement include:

Figure 3.121: Total station

Digital instruments - Nowadays with digital theodolites, electronic digital levels, laser levels and especially electronic total stations, it has become much easier to measure the head at a given site. Modern electronic digital levels provide an automatic display of height and distance within about 4 seconds. They have a height measurement accuracy of 0.4 mm and an internal memory that can store approximately 2,400 data points.

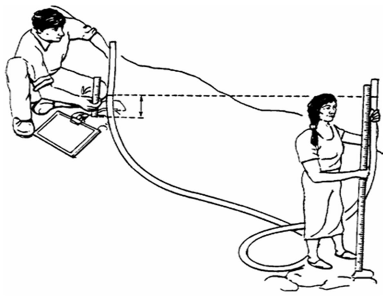
A total station or TST (total station theodolite) is an electronic theodolite integrated within an electronic distance meter (EDM) to read slope distances from the instrument to a particular point. Angles and distances are measured from the total station to points under survey, and the coordinates (X, Y, and Z or easting, northing and elevation) of surveyed points relative to the total station position are calculated using trigonometry and triangulation.

Figure 3.122: Dumpy level

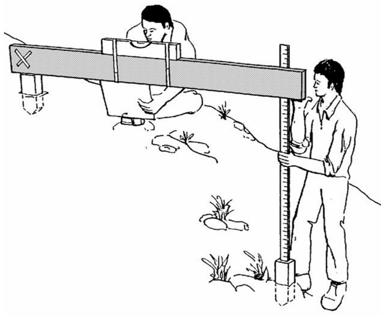
Dumpy levels and theodolite - The use of a dumpy level (or builder's level) is the conventional method for measuring head and should be used wherever time and funds allow. These devices require precise calibration and should be used by experienced operators. Dumpy levels are used with staffs to measure head in a series of stages. A dumpy level is a device which allows the operator to take sight on a staff held by a colleague, knowing that the line of sight is exactly horizontal. Stages are usually limited by the length of the staff to a height change (usually of no more than 3 metres). A clear, unobstructed view is necessary for the use of the dumpy level, making sites with ample vegetation generally difficult to assess with this method. Dumpy levels only allow a horizontal sight but theodolites can also measure vertical and horizontal angles, giving greater versatility and accelerating the measurement process.

Sighting meters - hand-held sighting meters (also called inclinometers or Abney levels) measure the angle of inclination of a slope. They are small and compact, and sometimes include a range finder which eliminates the problem of measuring linear distance. The error in estimation is typically between 2 and 10% depending upon the skill of the user.

Water-filled tube and pressure gauge - this is probably one of the simplest methods for measuring the available head, although it does have certain shortcomings. The two main sources of error which must (and can) be avoided are out-of-calibration gauges and air bubbles in the hose. To avoid the first error, the gauge should be recalibrated both before and after each major site survey. To avoid the second, a clear plastic tube should be used so that the bubbles can be seen. This method can be used on high heads as well as low ones, but the choice of pressure gauge depends on the head to be measured.



Water-filled tube and rod **-** This method is well suited for low-head sites. It is cheap, reasonably accurate and does not report many errors. Two or three separate attempts should be made to ensure that the final results are consistent and reliable. In addition, the results can also be cross-checked with measurements made by another method, for instance by the water-filled hose and pressure gauge.



Spirit level and plank **-** this method is similar in principle to the water-filled tube and rod method. In this method, a carpenter's spirit level is placed on a reliably straight plank of wood and the horizontal sighting is established. On gentle slopes this method tends to be very time-consuming, but it is useful on steep slopes. Taking two readings at each step (by marking on end of the plank and turning it around) cancels the errors. The margin of error is generally around 2%.

Maps **-** as discussed in the earlier section on regional assessments, large-scale maps are useful for approximate head values, but are not always available or totally reliable. For high-head sites (>100 m), 1:50,000 maps are useful for pre-feasibility studies and are also generally available.

Altimeters **-** altimeters are quite useful for high-head pre-feasibility studies. Surveying altimeters generally give errors in the range of as little as 3% per 100 metre range Atmospheric pressure variations need to be allowed for, however, and this method cannot be generally recommended except for approximate readings (i.e. it is best suited for pre-feasibility studies).

Hand-held GPS device **-** this is a very useful tool for site visits. It can help to locate and mark the major components of the scheme. The data can be then easily laid over a map and compiled. The elevation readings are not precise but usually in the range of ± 7 metres.

MEASUREMENT OF FLOW

The purpose of a hydrology study is to predict the variation in water flow throughout the year. Since water flow varies from day to day, a one-off measurement is of limited use. In the absence of any hydrological analysis, a long-term measuring system may be set up. Such a system is often used to reinforce the hydrological approach and is also the most reliable way of determining the actual flow at a site. One-off measurements are useful as a spot check that can be compared to hydrological predictions.

The flow measuring techniques discussed here are:

Velocity-area method **-** this is a conventional method for medium to large rivers, involving the measurement of the cross-sectional area of the river and the mean velocity of the water flow; it is a useful approach for determining the stream flow with minimal effort. An appropriate point must be selected on a relatively straight, smoothly flowing portion of the river to be gauged. The river at this point should have a uniform width, and the area must be well defined and clean. The top water level (or stage of the river) will increase and decrease with variances in discharge. Observe the stage at the same time each day. A measuring board – or large ruler with metre and centimetre markings can be used for this purpose.

MEASURING THE AREA

To compute the cross-sectional area of a natural watercourse it should be divided into a series of trapezoids. Measuring the trapezoid sides, by marked rules, such as figure below illustrates, the cross-section would be given by

$$S = b \times \frac{h_1 + h_2 + \cdots + h_n}{n}$$

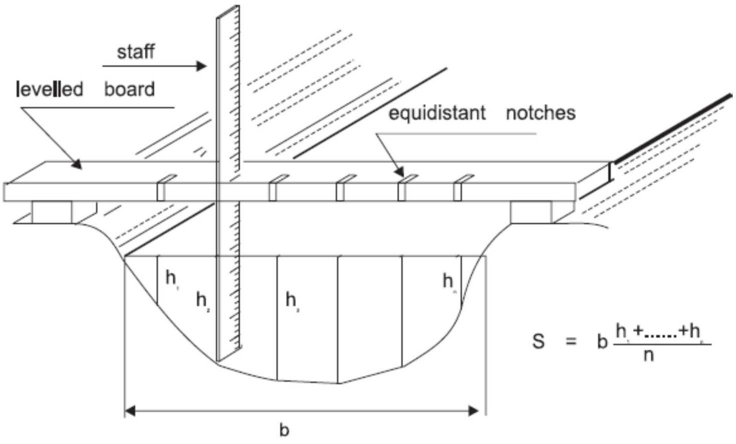


Figure 3.123: Measuring the cross-section of the river

MEASURING THE VELOCITY

Since the velocity both across the flow and vertically through it is not constant, it is necessary to measure the water velocity at a number of points to obtain a mean value. There are several ways of doing this, two of which are discussed below.

Float method **-** a series of nearly submerged floats, like wooden plugs or partially filled bottles, are placed in the centre of the stream flow and then timed as they move over a measured length of stream. A flow velocity is obtained by averaging the results over a large number of trials. This velocity must then be reduced by a correction factor which estimates the mean velocity as opposed to the surface velocity. By multiplying averaged and corrected flow velocity, the volume flow rate can be estimated.

Propeller current meters **-** this is more accurate than the float method. A current meter consists of a shaft with a propeller or revolving cups connected to one end. The propeller is free to rotate and the speed of rotation is related to the stream velocity. A simple mechanical counter records the number of revolutions of a propeller placed at a desired depth. By averaging readings taken evenly throughout the cross-section, an average speed of the stream can be obtained.

In the case of medium to large rivers, observations are made by lowering the meter from a bridge, though if the bridge is not a single-span construction there will be divergence and convergence of the streamlines caused by the piers, which can result in considerable errors. In many instances, however, the gauging site will have no bridge. But it should be placed in a section of the river that is as straight and uniform as possible. And if it is deep and the river is in a flooded state, a cable must be provided to stabilise the boat, together with a lighter measuring cable to determine the horizontal position in the cross-section.

Electromagnetic current meters **-** an electromagnetic current meter is an instrument that measures electrical induction. It is free of moving parts and mounted in a fully enclosed, streamlined probe. The probe can be mounted on rods and held at various depths or suspended on a cable.

This meter has the advantages of being smaller and having a wider measurement range than the propeller meters. It is particularly useful at very low velocities when propeller meters become erratic. Its sensitivity and lower vulnerability to effects from weeds and debris make it attractive for use in heavily polluted or weedy streams.

Figure 3.124: Conductivity meter

Salt dilution method **-** this method is relatively easy to perform, reasonably accurate (error probability is less than 7%), and reliable for a wide range of stream types. It gives better results if the stream is more turbulent. Using this approach, a spot check of the stream flow can be taken in less than 10 minutes with very little equipment.

The method involves the following steps: first, a bucket of heavily salted water is poured into the stream. The cloud of salty water in the stream starts to spread out while travelling downstream. After having moved some distance downstream, it will have filled the width of the stream. The cloud will have a leading part which is weak in salt, a middle part which is strong in salt and a lagging part which is weak again. The saltiness (salinity) of the water can be measured with an electrical conductivity meter. If the stream is small, it will not dilute the salt very much, so the electrical conductivity of the cloud (which is greater the saltier the water) will be high. Therefore, low flows are indicated by high conductivity and vice versa. The flow rate is thus inversely proportional to the degree of conductivity of the cloud.

The above phenomenon assumes that the cloud passes the probe in the same amount of time in each case. But the slower the flow, the longer the cloud takes to pass the probe. Thus, flow is also inversely proportional to the cloud-passing time. For this flow measurement, also called the "salt gulp" method, you need a bucket, table salt, a thermometer and a conductivity meter (range 0 to 1000 μS).

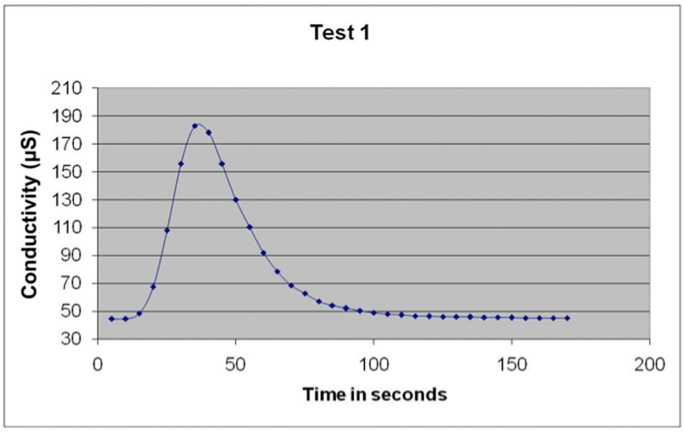


Figure 3.125: Dilution graph

Weir method **-** a flow measurement weir is a weir containing a notch through which all the water in the stream is made to flow or pass. The flow rate can be determined from the difference in height between the upstream water level and the bottom of the notch. For reliable results, the crest of the weir must be sharp and sediment must be prevented from accumulating behind the weir.

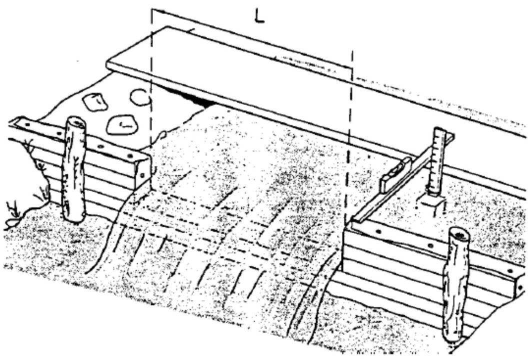


Figure 3.126: Measurement weir

Weirs can be made of concrete, metal or even timber and must always be oriented at right angles to the stream flow. The weir should be located at a point where the stream is straight and free from eddies. Upstream, the distance between the point of measurement and the crest of the weir should be at least twice the maximum head to be measured. There should be no obstructions to the flow near the notch and the weir must be perfectly sealed against leakage.

» *Pre-feasibility report*

For a pre-feasibility report, you will need to obtain a rough estimate of the following:

- General feasibility of small-scale hydropower plant construction near the power demand area
- Quantity and location of power that can be generated
- Method for selecting a potential site among the candidate sites.

The initial examination is basically a desk study using the available reference materials and information. The procedure involved and important issues to be addressed are explained below.

The main goal of this study is to assess the fundamental compatibility at an early stage of the project in order to avoid sinking money into an unrealistic endeavour. This pre-feasibility study helps to shorten the overall planning process and has proven to be an important element in the initial stages.

Main reference materials

- Topographical maps: scale 1:50,000
- Rainfall data
- Geological data
- Demand and supply condition of the national grid

Tasks involved in a pre-feasibility study

- Conduct preliminary investigation of identified sites, including geological observations, and determine the suitability of the sites for construction.
- Prepare a layout for selected sites indicating the location of the main components of the proposed small hydropower scheme.
- Define technical and economic criteria.

Once a site has been identified, site visits are essential to obtain a more accurate indication of the available flow, topography and geological conditions. At least one survey should be done during the dry season to get some idea of the minimum flow. During every visit the flow in the stream should be measured using a flow meter.

A geological overview is needed to establish the risk of landslides and settlement in any structures. When these studies are complete, you can start drafting a design of the headrace, spillways and waterways. For the powerhouse, you will need to determine the type of generating plant and the number of units in order to establish the approximate size of the powerhouse. The route and costing of the transmission line and the main features of the switchyard and transformers also need to be defined.

Cost estimates must then be prepared using a contingency sum of at least 30% in order to evaluate the preliminary economics of the scheme.

» *Feasibility report / detailed project report*

If the preliminary economics are favourable, a full feasibility study is necessary to identify the best locations for the various structures, understand the geological and hydrological risks, produce a preliminary layout and provide more accurate cost estimates.

An accurate survey to establish the water level at the intake, power station and along any canal is essential. If possible, clearly identified benchmarks should be established at all critical places. Note that a standard GPS is quite sufficient for establishing horizontal distances at a preliminary stage. However, it is not sufficient to establish heights because the accuracy of a consumer type GPS for horizontal distances is in the region of ±10 metres and the accuracy for altitude is no better than ±15 metres, which results in a very large error band for the calculation of head.

Establishing the available flow is extremely important because the flow is used to calculate the income. Ideally, more than 20 years of records of river flow are needed. Errors of 10% or more are possible if the records cover less than 20 years (give or take). It is important to establish from the start if it will be necessary to maintain some flow down the river bed (compensation flow), or a fish pass, as both can result in a significant reduction in the water available for power generation.

You will need to assess readily available information such as large-scale topographical and geological maps, aerial photography and other published records. If good geological information for the region is publicly available, this assessment can be carried out without the need for a field visit.

In most countries there are environmental constraints on any development efforts and, because hydropower schemes disturb rivers, real and perceived environmental effects often have a significant influence on hydropower development. If the project will be subject to environmental constraints imposed by laws or regulations, these will need to be studied carefully to evaluate the probable effect on the scheme and to establish the scope of studies that they require. Even if there are no laws and regulations, the impact the scheme will have on the local people and environment deserves serious consideration and the developer and engineer should act in a socially and environmentally responsible manner.

For costing, the best option is to try to find costs from a similar station recently built in the same part of the world. If this can be done, it is not difficult to scale the costs for the new scheme.

Therefore, the feasibility study must essentially include a comprehensive description of the scheme, including its physical aspects, hydrology, energy output, expected power prices and a description of all the investigations carried out and the conclusions drawn from them. The feasibility study must describe the scheme, outline the options considered and explain why the chosen option was selected. The document must also describe all risks inherent in the project. These include the risk of cost overruns, the possibility of unforeseen geological problems, the uncertainties associated with the hydrology, and the cost estimates.

ENVIRONMENTAL AND SOCIAL CONSIDERATIONS

» *Environmental aspects*

QUALITY OF WATER

Changes in water quality may occur within and downstream of the development as a result of impoundment. The residence time of water within a reservoir is an influence on the scale of these changes, along with bathymetry, climate and catchment activities. The main issues include reduced oxygenation, temperature, stratification potential, pollutant inflow, and propensity for disease proliferation, nutrient capture, algal bloom potential and the release of toxicants from inundated sediments.

Water temperatures in the discharged water can differ from ambient temperatures, and can also fluctuate in the short term depending on operating patterns. Temperature can have a major influence on biological health and be instrumental in providing migration cues for some species. Turbidity issues can arise due to the erosion of riverbanks, incoming sediments, and re-suspension of bottom sediments in shallow lakes.

FLOOD MITIGATION

Reservoirs can help to mitigate peaks of floods through the provision of retention volume and/or the ability to deviate large quantities of water into a different catchment area. Run-of-the-river plants are usually less suitable for flood mitigation unless they provide access to detention areas.

AQUATIC LIFE

Too little or no minimum flow poses serious constraints on fish habitats, making it impossible for them to survive. On the other hand, hydropeaking creates habitat characteristics that are too rough for most riverine fauna.

GREENHOUSE EMISSIONS

When rainforests are inundated without prior cutting of the forests, large amounts of methane can be emitted. Hydropower developments modify existing terrestrial and aquatic habitats. The protection of biodiversity and threatened species populations must be a consideration long before construction, at both the siting and design stage, and options for mitigation must be identified and assessed. Habitats of critical importance need to be identified within a wider regional context. Scheme siting and design can help minimise the environmental footprint of hydropower schemes and avoid their construction in areas with very high biodiversity values.

» *Social aspects*

REHABILITATION

Population displacement is an issue of high sensitivity with some new hydropower developments, and it needs to be a central consideration in the planning, siting, assessment, design and management of any scheme.

When large reservoirs are built they inundate a large area of both agricultural and forested land. Human settlements along the banks upstream are also submerged. In some cases the land has served as the home and the spiritual, social and economic resource base for local communities. Of particular concern has been the involuntary displacement and resettlement of minority groups who have a specific attachment to land because of its cultural significance. Land provides for material needs such as food supplies and timber for housing and cooking, as well as traditional medicinal remedies. Loss of land can be associated with a loss of cultural identity and spiritual belonging.

Those affected by land loss may be vulnerable to social deprivation through being ill-equipped to deal with an unfamiliar way of living, and having few transferable and usable skills or support networks. Women and children in particular may be vulnerable if they have no means of support.

Resettlement of people is consequently a sensitive issue, and needs to be planned and managed from the project outset through a process of engagement and economic support.

LOSS OF AGRICULTURAL LANDS

Effects on agriculture vary from the provision of irrigation to the loss of land through submergence. The local population bears the negative impacts while more distant agricultural businesses benefit from irrigation.

POTENTIAL RISKS AND ISSUES

» Risks

HYDROLOGY FAILURE

Rainfall data and runoff calculations can be incorrect due to various unknown factors. Poor measurements will prohibit the scheme from running to its full potential. Overtopping due to increased rainfall or cloud bursts can also result in enormous damage.

Mitigation measures:

- Long-term data
- Good quality rainfall runoff modelling
- Sustainable watershed management
- Readily available resource data and maps

GEOLOGY FAILURE

Geological instability can result in damage to civil works. Damage to dams can be particularly disastrous. Mitigation measures:

- Detailed investigations
- Catchment treatment
- Good design

POWER EVACUATION

If a good grid is not available, the generated power cannot be evacuated. A stable grid is required.

DELAYED PAYMENT BY STATE UTILITY

If payments are not received in a timely manner, it will be impossible to operate the scheme. Delayed payments severely affect the cash flow situation and hinder maintenance.

NATURAL CALAMITIES

Cloud bursts and earthquakes can cause major damage to civil works, resulting in associated problems for the population living downstream. Timely warning systems should be incorporated whenever an element of risk is assessed.

» Issues

Land acquisition problems

In many countries, land acquisition is a major socio-political issue. Legislative changes and reparations have achieved very little in the long run. As Michael Cernea[1] noted in his "impoverishment risk model", there are eight risks or dimensions of development-induced displacement. These eight risks are very immediate and basic in nature:

- Landlessness

[1] Impoverishment Risks, Risk Management, and Reconstruction: A Model of Population Displacement and Resettlement

- Joblessness
- Marginalisation
- Loss of access to common property resources
- Increased morbidity and morality
- Food insecurity
- Homelessness
- Social disarticulation

OBTAINING CLEARANCE FOR NEW PROJECTS FROM ENVIRONMENTAL AND FOREST DEPARTMENTS

Stringent laws on environmental and forest protection may cause major delays to the project and push back completion considerably. These issues have to be addressed and planned in the initial stages and should be factored into scheduling.

LONG GESTATION PERIOD

All the issues discussed above involve several studies such as an environmental impact study, a social impact study, etc. All of these analyses are time-consuming and must be included in planning for the initial stages.

SHORTAGE OF QUALIFIED LOCAL MANPOWER, LOCAL CONTRACTORS AND LOCAL QUALITY ASSURANCE

In many developing countries, qualified local technical personnel are not available. Machinery and equipment has to be imported. Project execution also suffers in the absence of local contractors.

NON-INVOLVEMENT OF LOCAL PEOPLE

Many a project has failed or taken a very long time to become functional because of non-involvement of local people. Local communities should be involved in the site assessment and development. They should benefit from the construction work, operation and maintenance, and the power supply to local villages and towns.

Projects that are not effective in actively engaging the local participation will experience difficulties in achieving their objectives.

REVIEW QUESTIONS

i. A hydropower scheme is to be deployed in Ikeji-Ile, Osun State. The gross head is 10 metres and the estimated average flow is 0.3 cubic metres per second. What is the theoretical power output expected from the scheme?

ii. What factors should be taken into consideration when considering the route that water takes as it exits the turbine?

iii. Which component is used to convey water to the turbine?

iv. How is a forebay tank different from a desilting tank?

v. What type of hydropower scheme is the power plant at Kainji?

vi. You are tasked to assess the potential of a site in Enugu LGA. Which parameters will you assess and measure? Describe the equipment and procedures you will use to collect credible results.

vii. List and discuss other environmental and social concerns that may arise while planning a micro hydropower scheme.

FURTHER READING

1. *Africa Energy Outlook 2014: A Focus on Energy prospects in Sub-Saharan Africa. Paris: World Energy Outlook Special Report* • IEA (2014): www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf (accessed Aug. 30, 2016)
2. *Climate Change: Impacts, Vulnerabilities and Adaptation in Developing* Countries • United Nations Framework Convention on Climate Change, Bonn, Germany – UNFCCC 2007 (www.unfccc.int/resource/docs/publications/impacts.pdf – accessed Aug. 30, 2016)
3. *Financing Renewable Energy in Developing Countries: Drivers and Barriers for Private Sector Finance in Sub-Saharan Africa* • Paris, UNEP Finance Initiative, 2012 (www.unepfi.org/fileadmin/documents/Financing_Renewable_Energy_in_subSaharan_Africa.pdf – accessed Aug. 30, 2016)
4. *Impoverishment Risks, Risk Management, and Reconstruction: A Model of Population Displacement and Resettlement* • M. Cernea; George Washington University, USA
5. *Layman's guidebook on how to develop a small hydro site* • C. Penche, European Small Hydropower Association (ESHA), 1998: www.seai.ie/Renewables/Hydro_Energy/EU_layman's_guide_to_small_hydro.pdf (accessed Aug. 30, 2016).
6. *Manuals and Guidelines for Micro-hydropower Development in Rural Electrification, Volume 1* • Japan International Cooperation Agency, 2009
7. *Micro-Hydropower Sourcebook: A Practical Guide to Design and Implementation in Developing Countries. ITDG Publishing* • I.R. Allen.,1986
8. *Mini Grid Design Manual. National Rural Electric Cooperative Association (NRECA)* • I.R. Allen.,1986
9. *Renewable Energy Resources (2nd edition)* • Tidwell, and Tony Weir, New York: Taylor & Francis, 2006
10. *Residential Pump Fundamentals. Goulds Pumps/ITT Industries* • Goulds Pumps (2001): www.kingpumps.com/PDFs/Goulds/bpump.pdf (accessed Aug. 30, 2016)
11. *Statistical Review of World Energy* • BP Global (2015): www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html (accessed Aug. 30, 2016)

3.3. WIND ENERGY (NON-FOCUS TOPIC)

Chapter focus

Wind energy is an important form of renewable energy. It offers advantages over solar energy due to its availability throughout the day. This module introduces the general concepts behind wind energy with a special focus on small wind turbines.

Learning outcomes

At the end of this chapter, the participant is able to

- Carry out simple wind resource assessments
- Explain the basics of energy production by wind energy
- Estimate available wind energy at different sites
- Select appropriate small wind turbines for off-grid applications

WIND RESOURCES AND ASSESSMENT

The use of wind energy is not a new phenomenon. Wind has been used for thousands of years for applications such as pumping water, milling grains, mechanical power and sailing. Today, however, it is the use of wind energy for electricity generation that is receiving the most attention. Modern windmills are normally referred to as "wind turbines" since their functions are similar to those of gas and steam turbines. They are also called wind energy conversion systems, and the systems used to generate electricity are termed wind generators.

» How is wind created?

As the Earth orbits the Sun, it receives light and heat. Most thermal energy from the Sun is received at the Equator and it gradually reduces in intensity towards either of the poles. Over the Earth's surface, these differences in temperature give rise to wind. In warmer regions, hot air rises and creates a low pressure layer near the Earth's surface. Colder, denser air moves in to replace it, creating a high-pressure area. Wind is ultimately the movement of air from areas of high pressure to low pressure.

Ideally, wind would flow from the Equator toward either pole if the Earth were not rotating. However, the Earth's rotation creates a force known as the Coriolis force. The Coriolis force can be described as a swirling pull on the winds caused by Earth's rotation. This causes a series of wind circulations in both the northern and southern latitudes as shown in Figure 3.127

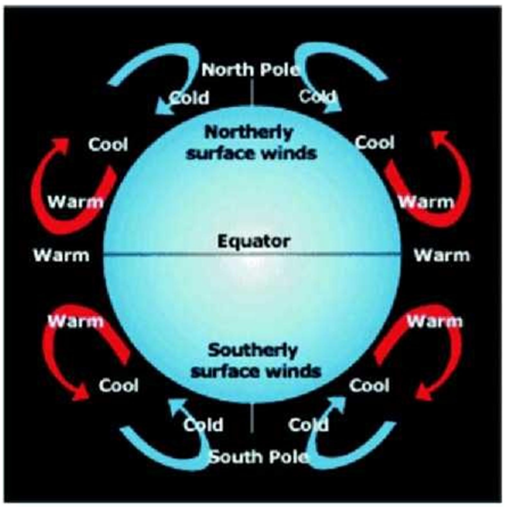


Figure 3.127: Global wind patterns due to the Coriolis force

Local winds are largely affected by the geographic terrain. The Earth has large flat plains (desert regions), areas covered with vegetation (rainforests), very uneven regions (mountain ranges) and very smooth regions (seas and oceans), all of which affect the wind near the surface to varying degrees. A sea breeze is created when hot air that is close to the land, which heats up faster than water, rises into the sky where it cools off. High in the sky, the cooled air then moves down towards the sea and presses the cold air from the sea towards the land.

BOUNDARY LAYER AND THE FREE ATMOSPHERE

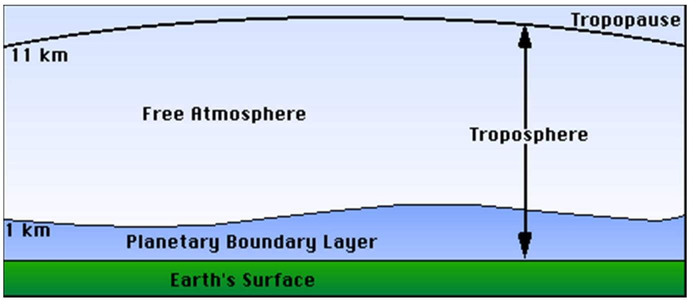


Figure 3.128: Boundary layer

The term jet stream is used to refer to the strongest, steadiest and most persistent winds which occur in bands at 10 kilometres above the Earth's surface. Modern wind turbines are, however, limited to the lowest 150 metres of Earth's atmosphere. At these heights, the wind is greatly affected by surface friction and wind speeds tend to be slower. The region below about 1 kilometre, where the wind is strongly influenced by the Earth's surface is known as the planetary boundary layer or atmospheric boundary layer. The exact height of this layer varies from a few hundred metres at night to up to 2 kilometres on the most convective days. The transfer of momentum, heat and moisture between the atmosphere and Earth's surface occurs within this layer.

The planetary boundary layer refers to the lower region of Earth's atmosphere where the wind speed is retarded by frictional forces on the Earth's surface. Generally, wind speed is nominally zero at ground level and increases steadily with height. This change in wind speed with height is known as wind shear. The lower layers of air tend to retard those above them until the shear forces are gradually reduced to zero. Above the boundary layer is the free atmosphere where wind is approximately geostrophic.

ROUGHNESS LENGTH

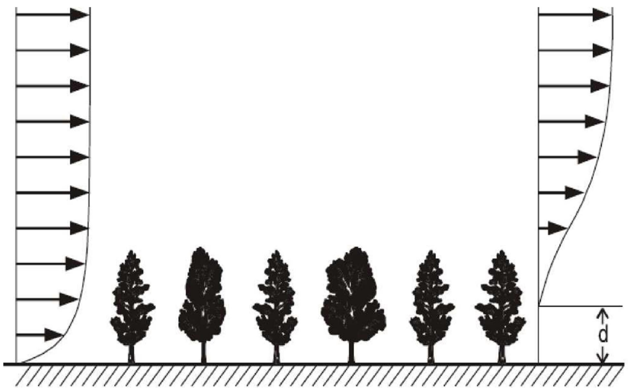


Figure 3.129: Wind shear due to roughness

In the first 100 to 200 metres above the ground, within the boundary layer, the variation of wind speed with height is greatly affected by the roughness length (Z_0). The roughness length is used to describe the roughness of the surface and has a magnitude usually in the order of a few centimetres over grass and plains to several meters over forests and towns. The roughness length is based on the size and distance between objects in a group. Hence, a field of short grass will have a smaller Z_0 than tall grass, whilst a city with skyscrapers will have a larger Z_0 than a small town.

Typical values for the roughness length for various types of terrain are outlined in the table below.

Table 3.20: Surface roughness values for different terrains

Terrain type	*Landscape description*	*Z_0 (m)*	*Wind shear exponent (α)*
Sea	Open sea, fetch at least 5 km	0.0005	0.1
Smooth	Mud flats, snow, little vegetation, no obstacles	0.005	0.1
Open	Flat terrain, grass, few isolated obstacles	0.03	0.15

Terrain type	Landscape description	Z_0 (m)	Wind shear exponent (α)
Roughly open	Low crops, occasional large obstacles	0.1	0.2
Rough	High crops, scattered obstacles	0.25	0.2
Very rough	Orchards, bushes, numerous obstacles	0.5	0.25
Closed	Regular large obstacles, suburban area, forest	1	0.25
Chaotic	City centre with both high and low buildings	>2	0.25

» *Wind resource estimation and assessment*

Of all the renewable energy sources, wind is the most unpredictable. To harness the power in the wind, engineers must be able to predict the availability and the characteristics of available wind. It is therefore important to assess a potential wind turbine site and estimate the available wind resource at that location. The key parameters to be measured are the wind speed and direction. In many instances, ambient air temperature and atmospheric pressure are also measured, because these two parameters affect the density of air, and hence the energy in the wind. Of the four parameters, wind speed is indisputably the most important.

WIND SPEED MEASUREMENT

The most dependable approach to site assessment is to measure the wind speed, ideally at the hub height of the proposed turbines so as to remove uncertainties in predicting wind shear. An additional measurement point lower on the mast is also useful as this provides greater certainty in data collection and allows wind shear at the site to be calculated, from which the surface roughness can then be estimated. A guyed, lattice or tubular mast is usually used, with the measuring instruments mounted sufficiently far from the mast itself (on booms or otherwise) so as not to be aerodynamically influenced by the mast. Instruments for measuring wind speed are detailed in the following.

Figure 3.130: A hemispherical cup anemometer as invented in 1846

- *Anemometers:* The most common instrument used to measure wind speed is an anemometer, a common weather station instrument. Its name is derived from the Greek *anemos*, meaning wind, and the word anemometer is used to describe any air speed measurement instrument used in meteorology or aerodynamics. Anemometers can be divided into two classes: those that measure the wind's speed, and those that measure the wind's pressure; but, as there is a close connection between pressure and speed, an anemometer designed for one will give information about both.

Figure 3.131: Vane anemometer

- *Cup anemometers:* These anemometers consist of hemispherical cups, each mounted on one end of horizontal arms and at equal angles to each other on a vertical shaft. The air flow past the cups in any horizontal direction turns the shaft in a manner proportional to the wind speed. Therefore, counting the turns of the shaft over a set time period, the average wind speed for a wide range of speeds can be measured.

- ***Vane anemometers:*** A vane anemometer may be described as a windmill or a propeller anemometer. Contrary to the hemispherical anemometer, where the axis of rotation is vertical, the axis on the vane anemometer is parallel to the direction of the wind and therefore horizontal. Furthermore, since the wind varies in direction and the axis has to follow its changes, a wind vane or some other contrivance to fulfil the same purpose must be employed. A vane anemometer thus combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction measurements from the same instrument.

Figure 3.132: Helicoid propeller anemometer incorporating a wind vane for orientation

ATMOSPHERIC REMOTE SENSING

With the increasing size of wind turbines comes the need to measure wind speeds at greater heights. The cost of installing a mast that is taller than 80 metres is significant and requires a planning permit. For these reasons, there is a growing interest in using ground-based remote sensing instruments for measuring wind speeds.

- ***Light detection and ranging (LIDAR):*** LIDAR can be used to increase the energy output from wind farms by accurately measuring wind speeds and wind turbulence. Atmospheric LIDAR remote sensing works by measuring backscatter from the atmosphere, and by measuring the scattered reflection off the ground (when the LIDAR is airborne) or another hard surface.
- ***Sonic detection and ranging (SODAR*):** SODAR is a meteorological instrument used as a wind profiler to measure the scattering of sound waves by atmospheric turbulence. SODAR systems are used to measure wind speed at various heights above the ground, as well as to measure the thermodynamic structure of the lower layer of the atmosphere. A SODAR sends out pulses of sound waves vertically into the atmosphere. These sound waves are scattered by turbulent eddies in the atmosphere and a returning sound wave detected by the SODAR will have a certain reduced intensity and exhibit a Doppler effect or shift. The degree of the shift determines the speed of the eddy and by using multiple beams in different directions it is possible to measure the direction of movement of the eddy. As the eddy moves with the mean speed of the wind, this gives a measure of the wind velocity. The intensity of the returning sound wave can be used to measure the turbulence intensity. Depending on the time delay between the pulse being emitted and the return measured, it is possible to measure the wind speed at different heights. The vertical range of SODARS is approximately 200 to 2,000 metres and is a function of frequency, power output, atmospheric stability, turbulence and, most importantly, the noise environment.

Figure 3.133: Wind monitoring using the Fulcrum3D SODAR

WIND DIRECTION MEASUREMENT

Because cup anemometers do not respond to changes in the direction of the horizontal component, a separate instrument is required to measure wind direction. This is normally done using a wind vane or windsock mounted on a vertical shaft free to rotate at multiple heights. A windsock is a conical textile tube (resembling a giant sock) designed to indicate wind direction and relative wind speed. Windsocks typically are found at airports and at chemical plants where there is risk of gaseous leakage. They are sometimes located alongside highways at windy locations.

Figure 3.134: Windsock with solar-powered data capture device

Naturally, the wind direction is the opposite of the direction in which the windsock is pointing. Wind speed is indicated by the windsock's angle relative to the mounting pole; in low winds, the windsock droops; in high winds it flies horizontally.

TEMPERATURE AND PRESSURE MEASUREMENT

Ambient temperature has conventionally been measured using a platinum resistance thermometer (PRT) or a thermocouple, although simple semiconductor devices can now be used with sufficient accuracy. Thermocouples are normally appropriately shielded from direct solar radiation in order to give an accurate air temperature reading. Suitable signal conditioning circuitry is supplied with proprietary instruments. The PRT or compact commercial pressure transducers are available for the measurement of atmospheric pressure. These instruments are normally supplied with appropriate signal conditioning.

To store the data measured by these instruments, data loggers are used. These loggers periodically store instrument readings. In some cases, information is transmitted electronically via the Internet; in others the logger is accessed physically.

WIND SPEED ESTIMATION

Wind speed is measured at standard heights in metrology, usually 10 metres above ground level. Wind speed does not increase in a linear fashion with height. The increase adheres to a pattern that can be described using a mathematical formula, known as the log law. To determine wind speed at a known distance above ground, a logarithmic law is employed.

$$U_2 = U_1 . \frac{ln\left(\frac{Z_2}{Z_0}\right)}{ln\left(\frac{Z_1}{Z_0}\right)}$$

Where:

- Z_0 = Roughness length
- Z_1 = Reference height
- Z_2 = Height at which wind speed is sought
- U_2 = Unknown wind speed at height Z_2
- U_1 = Reference wind speed at height Z_1

The power law is used as a substitute for the log law when surface roughness and stability information is not available. The power law is often used in wind power assessments where wind speeds at the height of a turbine must be estimated from near-surface wind observations, or where wind speed data at various heights must be adjusted to a standard height prior to use.

$$U_2 = U_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha}$$

Where:

Z_0 = Roughness length

Z_1 = Reference height

Z_2 = Height at which wind speed is sought

U_2 = Unknown wind speed at height Z_2

α = Wind shear exponent

Example: The mean wind speed measured at the local meteorological station (Enugu airport) is 3 m/s at a height of 10 m. Using (a) the log law and (b) the power law, what is the expected wind speed at a height of 70 m above the earth's surface?

Answer using the log law

⇒ *U_1 = 3 m/s, Z_1= 10 m, Z_2= 70 m, roughness length at an airport = 0.03 m*

$$U_2 = 3.\frac{ln\left(\frac{70}{0.03}\right)}{ln\left(\frac{10}{0.03}\right)} = 4m/s$$

Answer using the power law …

⇒ *The wind shear exponent at an airport = 0.15*

$$U_2 = 3\left(\frac{70}{10}\right)^{0.15} = 4.01m/s$$

THE VARIABLE NATURE OF WIND

The wind speed at a given location varies constantly. There are changes in the annual wind speed from year to year. These changes can be attributed to:

- Seasons
- Passing weather systems (synoptic)
- Changes on a daily basis (diurnal)
- Instantaneous changes (turbulence)

Changes in wind speed make it difficult to predict the overall energy capture from a site. Generally, the tropics have steady and moderate winds throughout the year; temperate latitudes have much more variation in wind speed, with high wind speeds occurring at a far greater frequency. Sites with higher wind speeds will generate more power. The Van der Hoven spectrum is used to represent the amount of variation in wind speed associated with a particular time scale. Table 3.21 provides a guideline for different wind speeds and their potential for electricity production.

Table 3.21: Suitability of wind speeds for power generation

Average wind speed in m/s	*Suitability*
Up to 4	Too low
5	Poor
6	Moderate
7	Good
8	Excellent

FREQUENCY DISTRIBUTION OF WIND SPEEDS

Wind speed is not a fixed value and is constantly changing. Hence, to make meaningful estimations for long-term energy capture, statistical methods are used. When gathering wind data, several site measurements are necessary to estimate mean wind speed. The information gathered is best represented using a histogram as seen in the figure below. A histogram illustrates the frequency of a particular wind speed within a given time span, usually over a year.

Figure 3.135 is based on wind speed measurements taken every 10 minutes at a particular site over one year.

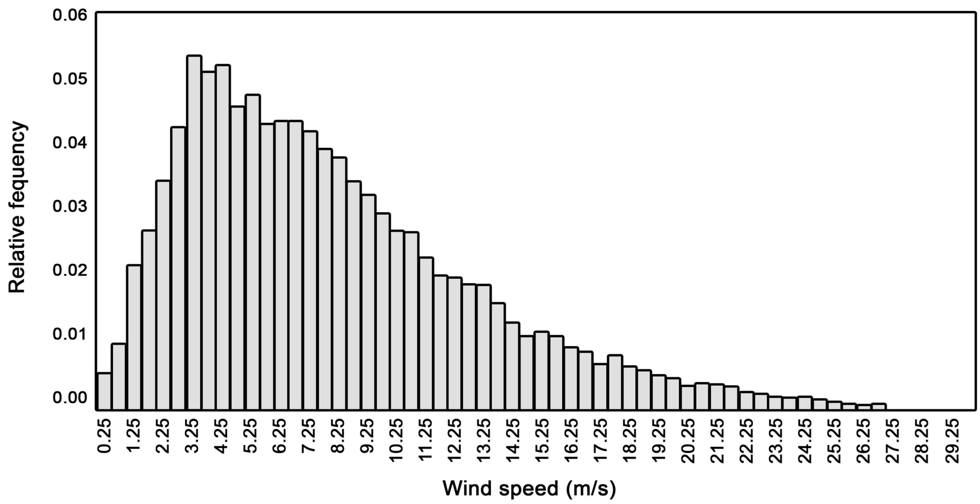


Figure 3.135: Histogram showing wind speeds

Each measurement has been sorted into narrow bands in a process known as binning. A bin width of 0.5 m/s was used. For example, a measured wind speed of 2.65 m/s was placed in a 2.5 to 3 m/s bin. The relative frequency is the number of measurements sorted into that particular bin. If such an assessment is made over one year (to accommodate all seasons), the bin can be viewed as a probability that a wind speed reading will be of a particular speed. This helps to attain a fair degree of certainty related to the available wind.

WEIBULL DISTRIBUTION

To calculate the energy capture from a given wind turbine at a given site and to estimate other useful figures such as the percentage of time that the wind speed falls within a certain range, it is convenient to identify a suitable probability distribution for wind speed. It has been found that the frequency distribution of wind speeds at most sites can be well represented by the two-parameter Weibull distribution function.

$$P(u) = \left(\frac{k}{C}\right) . \left(\frac{u}{C}\right)^{k-1} . exp^{\left[-\left(\frac{u}{C}\right)^{k}\right]}$$

Where k = Shape parameter

C = Scale parameter

P (u) = Probability of wind speed occurring

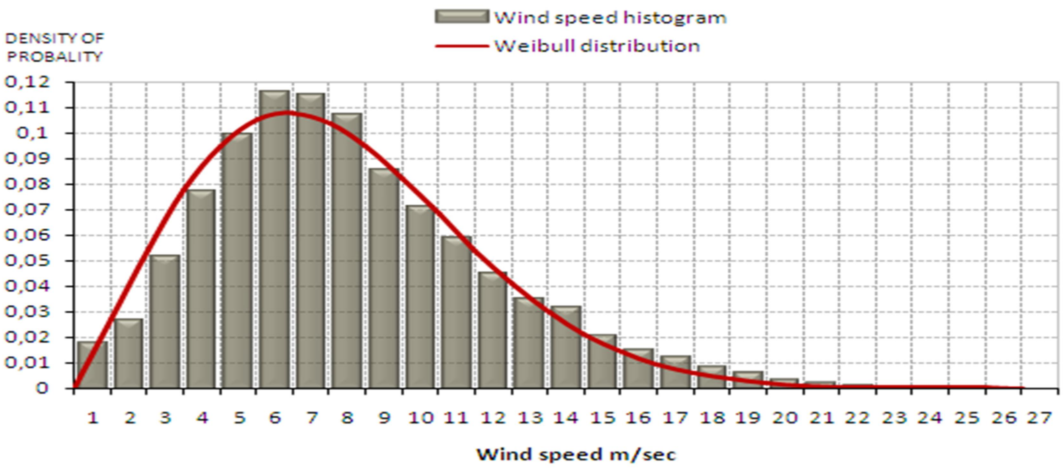


Figure 3.136: Example of a Weibull curve (in red) superimposed onto the pertaining histogram

The cumulative probability is obtained by integrating the function between zero and a defined wind speed *(v)*. This gives the probability *(Q)* that the wind is less than v as

$$Q(u < v) = 1 - exp^{\left[-\left(\frac{v}{c}\right)^k\right]}$$

The formula above is used to calculate the probability of the wind speed falling within a given range based on any two wind speed values.

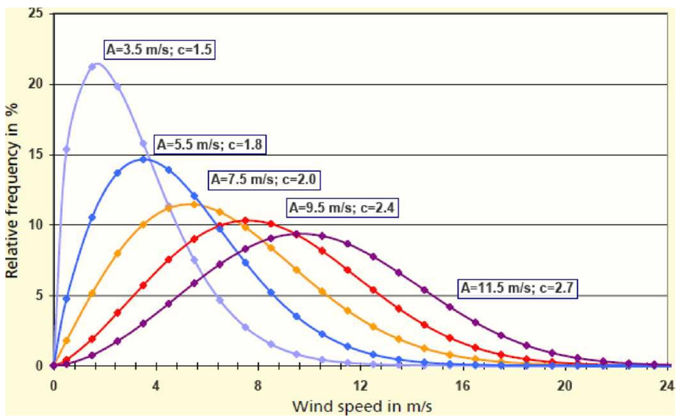


Figure 3.137: Weibull curves of different parameters

RAYLEIGH DISTRIBUTION

If the shape parameter *k* has a value of 2, the Weibull distribution converges with the well-known Rayleigh distribution. This is based on the assumption that wind is isotropic and uniformly distributed with no prevailing direction and that wind speed variations in orthogonal directions are normally distributed.

WIND ROSE

The wind rose is a graphical presentation for both the speed and direction of wind. It is usually used to describe the wind pattern over the span of a year but can also be used for shorter intervals, such as a day, week or month.

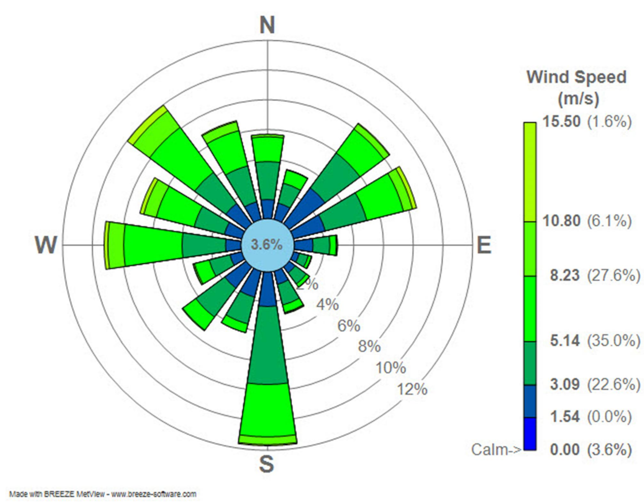


Figure 3.138: Example of a wind rose

Using the wind rose example above, the

following can be inferred:

- A summary of the average wind direction, average wind speed, and peak gust is given in the column on the right.
- The most important data is displayed by each "spoke". The spoke length indicates the frequency of wind coming from a particular direction. For the period in question, 12% of winds blew from south. Winds from the west accounted for 9% of all winds.
- Determining the wind speed frequency is slightly more difficult. Wind speeds are indicated by colour. If a spoke is mostly one colour, the winds from that direction mostly blew at the wind speed denoted by that colour. In the case shown here, 8% of the time, winds blowing from the south had a speed of 3.09 m/s. The circle in the centre indicates calm winds.
- Winds were calm 3.6% of the time, meaning there was no measurable wind or, in colloquial terms, there was "no wind".

ESTIMATING LONG-TERM WIND SPEED

Within the wind industry, techniques for assessing wind resources based on measured data have continued to evolve. Since it is impossible to measure future wind speeds, predictions must be made from past measurements. The basic assumption is that the wind speed distribution in the past will be the same as that in the future. Clearly, it is not feasible to measure the wind speed at the potential site for the expected lifetime of the wind farm (e.g. 15 or 20 years) prior to construction.

Methods of predicting future wind speed probability distributions that do not rely on very long-term wind speed measurement campaigns at the potential wind farm site can generally be classified as either statistical or physical in nature. Both types of methods are based on extrapolating long-term wind speed records from a single reference site or a network of reference sites to the potential wind farm site.

STATISTICAL METHODS

Statistical methods relating short-term measurements at the potential wind farm site to long-term measurements of wind speeds at a nearby reference site with the same wind climate are known as measure – correlate – predict (MCP) techniques. The final prediction from all statistical methods, including MCP, applies only to one particular location and height corresponding to the position of the anemometer.

Measure – correlate – predict: For all but very flat terrain, MCP is almost always more accurate than physical modelling methods. MCP can also offer a better gauge of the uncertainties in the predictions. These are some of the reasons why MCP is widely used in the wind industry. The aim of the MCP technique is to obtain an unbiased and reliable estimate of the "true" long-term wind resource at a potential wind farm site. The overall technique uses the following steps:

1. Collect wind data at the potential wind farm site for at least 12 months.
2. Identify a meteorological station for which high-quality, long-term records exist in the vicinity of the potential wind farm site. Ideally, it should be as close as possible and have a similar exposure.
3. Obtain a set of concurrent data from the two sites, i.e. obtain the wind data from the met station for the period during which data was collected in step 1.

4. Establish a suitable correlation between the concurrent data.
5. Obtain long-term data from the meteorological station for a historic period of ten to twenty years.
6. Apply the correlation identified in step 4 above to the historic data to predict what the wind resource would have been at the potential wind farm site over the historic period.

It is assumed that the weather patterns over the next twenty years will not vary significantly from those recorded over the last twenty years, so the predicted wind will provide a good estimate of the future wind resource at the site in question.

PHYSICAL METHODS

Physical methods are generally based on modelling the physical properties affecting the wind flow by comparing the potential wind farm site and a nearby reference site with the same wind climate. This form of estimation exceeds the scope of this handbook and will not be covered in any further detail.

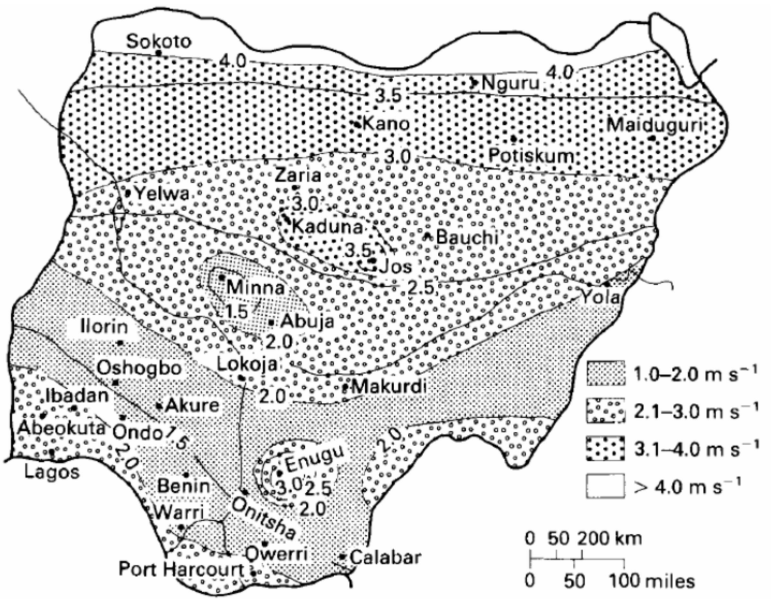


Figure 3.139: Wind speed distribution in Nigeria – *Courtesy: Ojosu and Salawu, 1990*

TECHNOLOGICAL HISTORY

It is widely believed that the birth of the windmill occurred over 2,000 years ago. Early windmills were designed with a vertical axis and used for pumping water and milling grain. The earliest known designs were developed in Persia (modern-day Iran) around 500–900 AD. The first apparent use of these constructions was to pump water; however, the mode of water transport is unknown. The first documented application of wind energy is milling grain. In this application, the grinding stone is connected to the vertical shaft and the mill machinery enclosed in a building, which was also equipped with a shield to

Figure 3.140: 7th century wind-powered flour mill, Afghanistan

reduce the decelerating effect of incoming wind on the side of the drag-type rotor.

In Europe, the earliest known windmill designs had a horizontal axis as well. In the 12th century, the Dutch set out to refine the early European designs. This was done by affixing the post mill to the top of a multi-storey tower. The new tower design had separate floors for various pre- and post-milling activities, including living quarters for the mill operator.

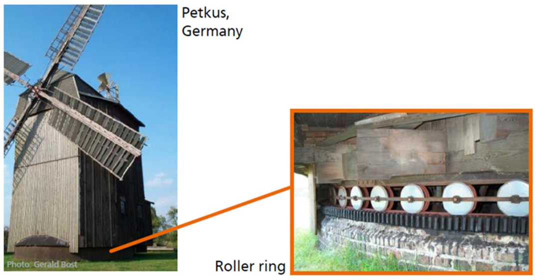


Figure 3.141: Revolving paltrok mill, 17th century, Germany

For over 500 years, windmill designers made gradual improvements to their creations. So much so that modern-day designers still rely on various historic improvements to wind sails for the performance of wind turbine blades. These advancements include:

- Placement of the blade spar at the quarter chord position (25% of the distance from the leading edge to the trailing edge)
- Centre of gravity placed at the same 1/4 chord position
- Nonlinear twist of the blade from root to tip.

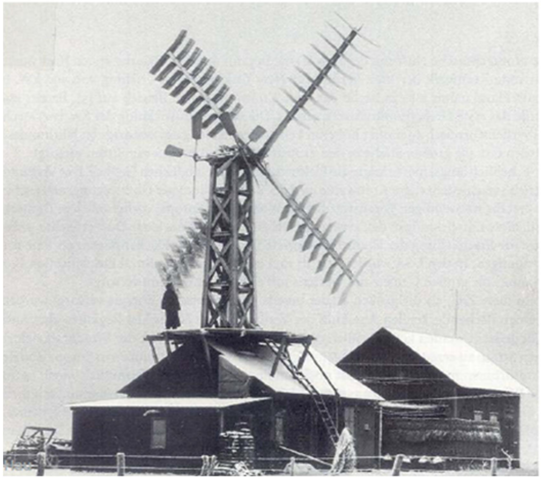


Figure 3.142: Four-blade rotor designed by Poul la Cour – *Courtesy: Paul Kuhn*

These mills were the "motor" of pre-industrial Europe. Their applications were diverse, ranging from the common waterwheel, irrigation, or drainage pumping using a scoop wheel (single or tandem), grain-grinding (again, using single or multiple stones), saw-milling of timber, and the processing of other commodities such as spices, cocoa, paints and dyes, and tobacco.

Figure 3.144: Halladay windmill – *Courtesy: Farm collector, www.farmcollector.com*

Figure 3.143: Dual-blade wind turbines of 3 MW in Brunsbüttel, Germany, 1983 (left) and 2 MW in Näsudden, Sweden, 1983

Over the centuries, small wind turbines in windmills have been used for water pumping applications. These systems were brought to maturity during the 19th century, beginning with the Halladay windmill in 1854 and continuing with the Aermotor and Dempster designs. Early windmills had four paddle-like wooden blades. These designs were followed by mills with thin wooden slats nailed to wooden rims. The majority of mills were designed with tails to orient them in the wind. In the late 19th century, the successful "American" multi-blade windmill design became the first large windmills to generate electricity.

In 1891, Poul la Cour, a Danish inventor, developed an electrical output machine that incorporated aerodynamic principles used in European tower mills. It had a higher drive train speed which was practical for electricity generation.

Figure 3.145: Darrieus rotor, Cap-Chat, Quebec, Canada, 1988

Over the next few years, engineers and inventors experimented with various designs for utility-scale wind energy converters but failed to produce a practical solution. The largest of these was the 1.25 MW Putnam-Smith machine installed in the USA. The Putnam-Smith machine was a horizontal axis turbine with a 53.3-metre rotor diameter operating at 28 revolutions per minute. The blades were made of steel and each weighed 16 tonnes.

During this time, various designs of the vertical axis wind turbine (VAWT) were also tested but found to be less efficient than the horizontal axis wind turbines. VAWTs are still in production today, however mostly as small wind turbines.

DESIGN, COMPONENTS AND CONTROL

» Wind turbine design

As mentioned earlier in this handbook, the horizontal axis wind turbine (HAWT) is the most commonly employed design for a wind turbine today. Wind turbines vary in size from generating a few hundred watts to megawatts of power. The general layout is shown below in Figure 3.146

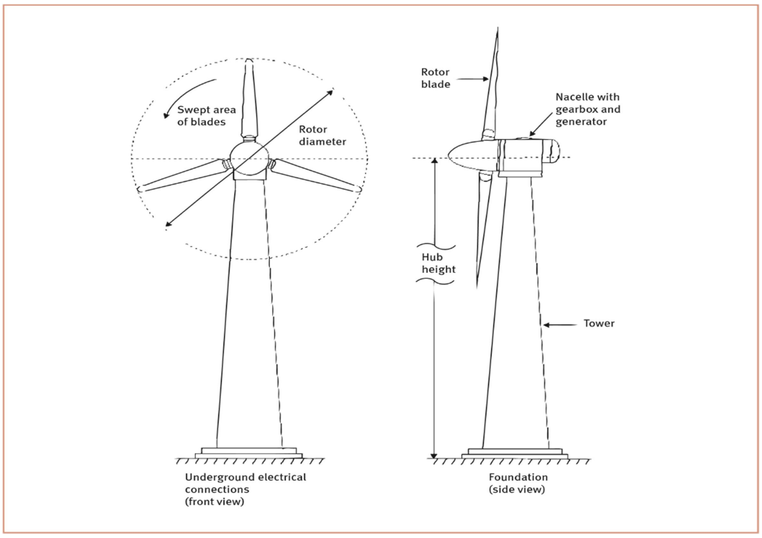


Figure 3.146: HAWT layout – *Source: Canada Centre for Mineral and Energy Technology, 1999*

The main components of a wind turbine for electricity generation are the rotor, the transmission system, the generator, the yaw and control mechanism and the tower. Figure 3.147 shows a section of the nacelle of a typical large wind turbine.

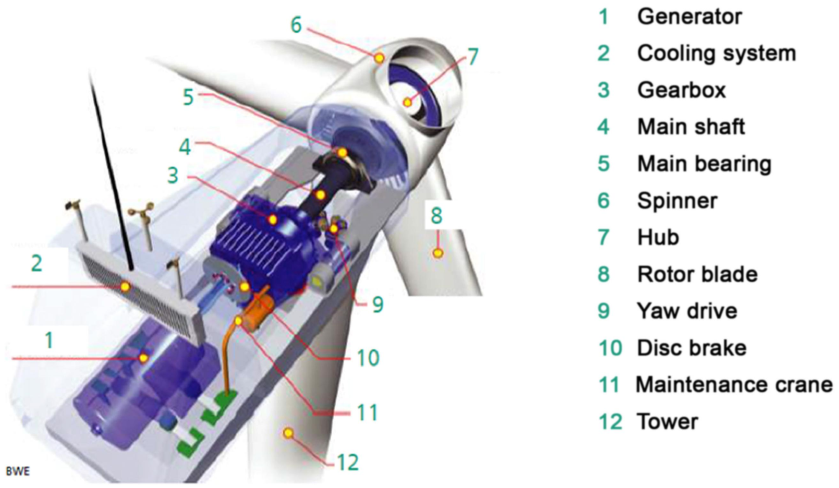


Figure 3.147: Main components of a wind turbine

Table 3.22: Components and functions of a wind turbine

Component	*Function*
Generator	Converts the mechanical energy of the input shaft to electrical energy
Gear box	Converts the low rpms of the rotor blades to rpms that are compatible with the generator, which requires much higher rotational speeds for parity with grid frequency
Main shaft	Transfers the primary torque from the rotor assembly to the gear train
Hub	Secures the rotor blades
Rotor blade	Aerofoil made of composite material which produces torque from the wind
Yaw drive	Controls the turning of the turbine nacelle into the wind. This helps align the rotor axis with the wind and maximise the kinetic energy of wind that can be extracted.
Tower	Holds the wind turbine erect and in place
Nacelle	Houses all the above-listed equipment, with the exception of the tower, blades and hub

» *Horizontal axis wind turbine*

SOLIDITY

Solidity in a wind turbine refers to the portion of area that the turbine blades sweep through (swept area) that is occupied by the turbine blades. A turbine in which most of the swept area is covered by the blades is called a high-solidity turbine. A low-

Figure 3.148: High-solidity turbine (left) and low-solidity turbine (right)
– Courtesy: Wikipedia

solidity turbine has blades that cover a minimal area swept by the turbine.

OPERATING CHARACTERISTICS OF WIND TURBINES

Some important operating characteristics of a wind turbine include the cut-in speed, rated speed, cut-out speeds, power output and capacity factor. These and other characteristics are explained in the following.

Cut-in wind speed: There is a minimum speed at which a wind turbine can reliably produce useable power. This is known as the cut-in speed, which is generally around 5 metres per second.

Rated wind speed: Most wind turbines are designed to generate maximum power at a particular wind speed. This is known as rated power and the minimum wind speed at which it is achieved is the rated wind speed. The rated wind speed is chosen to fit the local site and wind regime and is often 1.5 times the mean wind speed of the site.

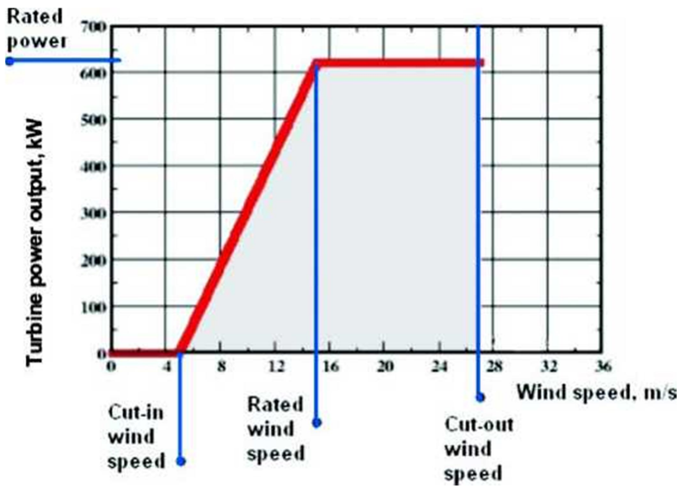


Figure 3.149: Idealised power curve for a wind turbine

Cut-out wind speed (furling speed): At a certain point beyond the rated speed, the wind turbine shuts down and ceases to operate to prevent damage to itself. Cut-out speeds vary by manufacturer from about 20 to 30 metres per second. The wind speed at which the turbine shuts down is called the cut-out speed, also known as furling speed.

Betz limit: It is impossible for a wind turbine to harness all energy in the wind. If it would, the wind would halt behind the turbine, blocking oncoming wind. It is logical that the wind, after having swept across the turbine, must depart. For this it needs energy. However, the wind turbine extracts energy by slowing down the wind. The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is about 59%. This value is known as the Betz limit.

Rotor efficiency: The ability of a turbine rotor to extract the wind's power depends upon its efficiency. Thus to express the power output of the turbine, a non-dimensional coefficient of performance of the blades (C_P) is included. The performance coefficient of the blades (C_P) varies with speed and generally falls between 0.33 and 0.59. This performance coefficient refers to how efficiently a wind turbine converts energy in the wind. It is represented by the following equation.

$$C_p = \frac{Electricity\ produced\ by\ the\ wind\ turbine}{Total\ energy\ available\ in\ the\ wind}$$

POWER AVAILABLE FROM THE WIND TURBINE

Power extracted by wind turbine is proportional to the cross-sectional area of the wind intercepted by the wind turbine and the cube of the wind speed. The maximum amount of power that can be extracted from the wind is determined by the following formula:

Kinetic energy from wind = mass * velocity^2

Knowing that

Mass = ϱ Av

Hence, Power (P) $= \mathrm{P} = \mathrm{C_p}\frac{\rho A v^3}{2}\eta_g\eta_b$

Where P = Power produced by generator (kW)

ϱ = Density of air (kg/m^3)

A = Area swept by rotor (m^2)

V = Wind speed (m/s)

C_p = Coefficient of performance

η_g = Generator efficiency

η_b = Gearbox efficiency

Power generated is highly dependent upon wind speed. Doubling the wind speed increases the power by eight times, but doubling the turbine area only doubles the power. Thus, optimising the siting of wind turbines in the highest wind speed areas has significant benefits and is critical for achieving the best economic performance.

Example: Consider a wind turbine with a rotor measuring 6 metres in diameter, a coefficient of performance of 0.30, generator efficiency of 0.8, gearbox efficiency of 0.90, and wind speed of 11 metres per second. What is the expected power output in watts?

⇒ $Area\ (A) = \frac{\pi D^2}{4} = \frac{\pi 6^2}{4} = 28.28m^2$

⇒ $Power\ (P) = C_p\frac{\rho A v^3}{2}\eta_g\eta_b = \frac{1.2*28.28*11^3 0.3*0.8*0.9}{2} = 4.88\ kW$

CAPACITY FACTOR

The capacity factor of a wind turbine is the turbine's actual energy output during a given time period, usually one year, compared to its theoretical maximum energy output. Typical capacity factors are 20 to 40% with values at the upper end of the range occurring in particularly favourable sites.

The capacity factor (CF) is calculated as thus

$$CF = \frac{Measured\ energy\ produced}{8760\ *\ Name\ plate\ rating\ of\ wind\ turbine}$$

Example: A 2.5 MW wind turbine could produce a theoretical maximum energy of 21,900,000 kWh per year. Due to the variability of the wind, the unit's actual production amounts to 5,000,000 kWh per year. What is the capacity factor of the wind turbine?

⇒ *CF = 5,000,000 / (2.5 * 1,000 * 8,760) = 22.8%*

Example: How much power can be extracted from a Darrieus wind turbine given that its height is 10 metres and diameter 6 metres?

a) Assume that the average wind speed at the location is 2 m/s.

b) What is the increase in power if the wind speed doubles?

⇒ $Area\ swept\ by\ the\ turbine\ blades\ (A) = 0.65.D.H = 0.65 * 10 * 6 = 39\ m^2$

$$Power\ (P) = \frac{\rho A v^3}{2} = \frac{1 * 39 * 2^3}{2} = 156\ W$$

⇒ $Power\ (P) = \frac{\rho A v^3}{2} = \frac{1*39*4^3}{2} = 1{,}248\ W$ *(Increase is by a factor of 8)*

Example: Field tests show that the turbine in the example above generates 34 kW at a wind speed of 2 m/s. What is the efficiency of the wind turbine?

$$C_p = \frac{Electricity\ produced\ by\ the\ wind\ turbine}{Total\ energy\ available\ in\ the\ wind} = \frac{34}{156} = 0.22$$

Number of blades: Theoretically, the lower the number of blades, the higher the efficiency of a turbine. Wind turbines used for electricity generation usually have dual-blade or triple-blade rotors. Nevertheless, small wind turbines (SWTs) for water pumping applications, which require high torques and low rotor speeds, normally use more than three blades as they operate at lower wind speeds. Experiments have also been conducted with single-blade turbines, fitted with a counterweight to prevent mechanical imbalances. Yet, the mechanical strain exerted on the system resulted in increased wear and tear on the hub and such designs have not made it into commercial production.

Table 3.23: Comparison of the two main designs

	Advantages	***Disadvantages***
Two blades	• Low cost and weight • High rotor speed reduces cost of gearbox • Cyclic loads reduced with tether • Ease of installation	• High cost of tether mechanism • Complexity of tether mechanism • Fixed hub experiences high cyclic loads • More aerodynamic noise from blades
Three blades	• Produces 5% more energy • Reduced cyclic loads • Visually more pleasing • Quieter operation	• More expensive and heavier • More complex to install

SMALL WIND TURBINES

» *Characteristics and design concept*

SMALL WIND TURBINES (SWT)

Small wind turbines exist in a variety of designs and sizes, including designs with horizontal or vertical axes as well as Darrieus and Savonius rotors. A noteworthy website[1] identifies 407 different turbines produced by 192 manufacturers worldwide.

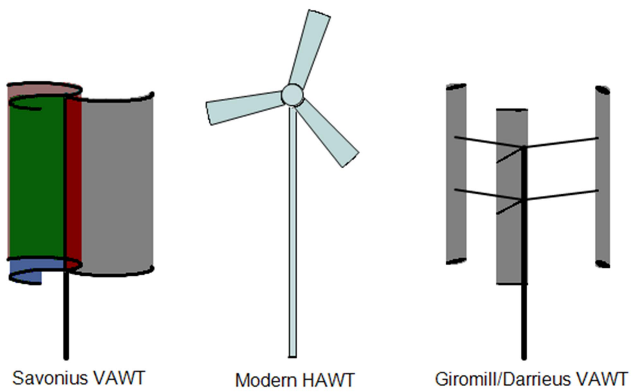


Figure 3.150: Various small wind turbine designs

ROTOR TYPES

The rotor is arguably the most important turbine component. It is the interface that allows the extraction of power from the wind. For different small wind turbines, the area swept by the rotor is calculated as shown in the figure below.

[1] See www.allsmallwindturbines.com

TOWER TYPES

Towers for SWTs can be made of a variety of materials. Steel and concrete are the most common. There are four main types of towers used to deploy small wind turbines.

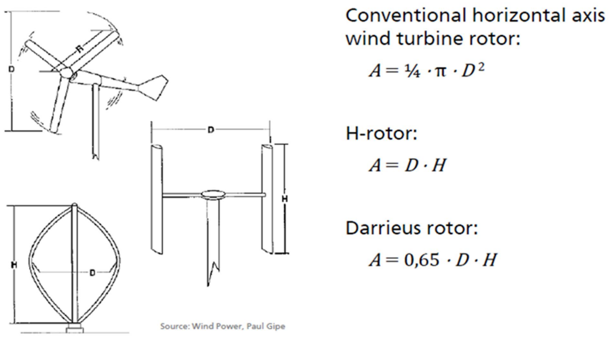


Figure 3.151: Rotor types in wind turbines

Monopole tower: These towers are mostly made of steel. Depending on the cost of concrete and other factors such as turbine weight, height, and installation location, concrete poles may also be used. The monopole tower is also called the free-standing tower. It consists of a steel pipe with a free-standing design.

Lattice tower: Mostly made of steel, these towers have a tapered, three-legged structure. The tower's footprint will vary depending on the tower height and turbine size.

Guyed tower: A guyed tower is made using a narrow steel pipe and supported by guy wires. It is usually used for 500 W to 5 kW wind turbines. The height of a guyed tower normally ranges from 6 to 18 metres.

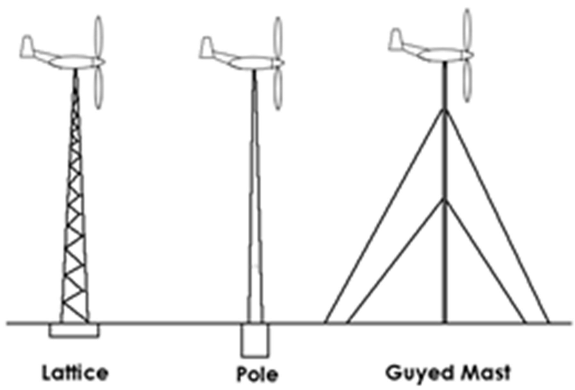


Figure 3.152: Different tower types

Tilt-up tower: Motorised tilt-up towers have all the aesthetic qualities of a monopole plus the convenience of raising and lowering when needed. A small motor is used to raise and lower the tower; the tower can also be operated with a hand crank. This type of tower is perfect for coastal or severe weather locations. The height of this tower usually ranges from 12 to 30 metres.

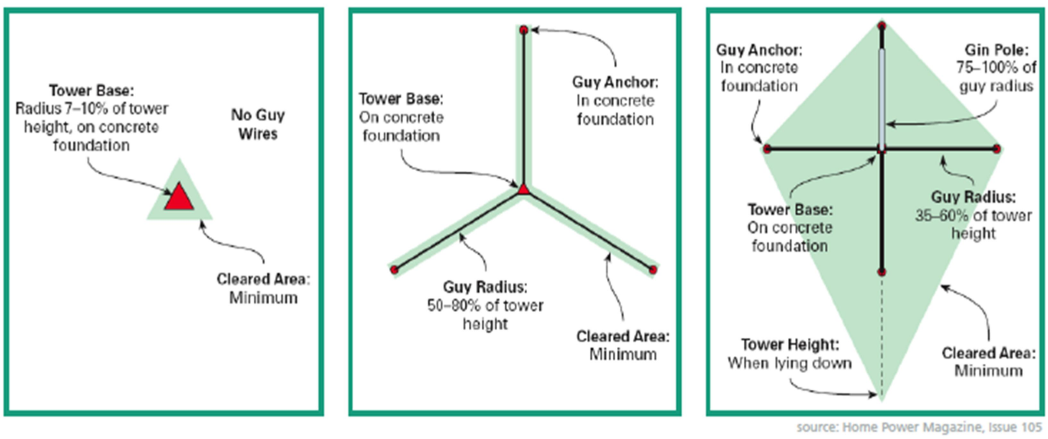


Figure 3.153: Physical footprints of different tower types

Table 3.24: Comparison of different tower types

Tower type	*Advantages*	*Disadvantages*
Monopole	• Elegant design • Less vibration • High reliability	• Higher installation costs than guyed towers • Crane required for maintenance
Lattice	• Easy fabrication • Easy installation	• Low cost compared to other designs
Guyed mast	• Most inexpensive solution • Easy installation	• Not easy climbable for inspections or repairs • Requires more land than monopole tower
Tilt-up	• Easy maintenance • Crane not required	• Highest cost among all options

UPWIND VERSUS DOWNWIND

SWTs can operate either upwind or downwind of the tower, depending on the manufacturer's design. Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its support mast. Turbine blades are constructed in a rigid design to prevent the blades from being pushed into the tower by high winds. Ample spacing is also provided between the tower and the blades, which are sometimes tilted slightly into the wind.

Downwind turbines continue to be built despite the problem of turbulence (mast wake), because they do not require a mechanism for keeping them in line with the wind and because in high winds the blades can be allowed to bend, which reduces their swept area and wind resistance. But the cyclical (repetitive) turbulence infringing on every rotation leads to additional material fatigue and failures. Most HAWTs are therefore designed as upwind turbines.

Table 3.25: Comparison of upwind and downwind wind turbines

	Advantages	*Disadvantages*
Upwind	• Small tower shadow • Reduced aerodynamic noise • Aerodynamic loads can offset blade bending moment caused by weight	• Coning can cause tower clearance problems • Tilting of axis is used to enhance clearance
Downwind	• Blade coning aids tower clearance • Free yawing may be adopted	• Aerodynamic loads augment bending moment caused by weight at tower top • Large tower shadow produces aerodynamic noise and extra fatigue loading

» *Application of small wind turbines*

GRID-CONNECTED WIND TURBINES

Grid-connected wind turbines have made a considerable impact in industrialised countries and in some developing countries like Argentina, China and India. They have mainly been adopted in large-scale installations either on land (onshore) or in the sea on the continental shelf (offshore). In developed countries, smaller machines are now being grid-connected,

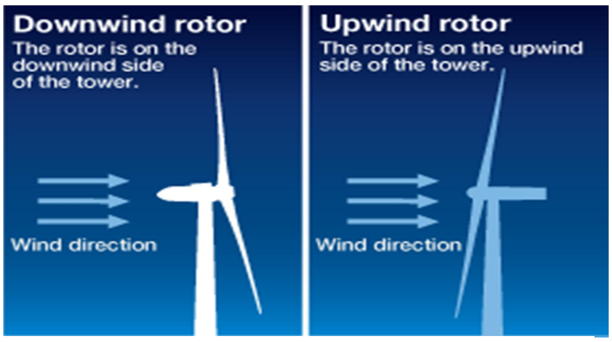


Figure 3.154: Airflow for upwind and downwind turbines – *Courtesy: Hitatchi Ltd, www.hitachi.com*

as well. These turbines are usually installed to supply power to a private owner who wishes to supplement power supplied by the electricity grid. This principle can be used in developing countries to contribute to a more decentralised grid network and/or to support a weak grid.

Wind turbines do, however, generate electricity intermittently because wind is not in steady supply. Because wind turbines do not produce power constantly and at their rated power (which is only achieved at higher wind speeds), their capacity factors (i.e. actual annual energy output divided by the theoretical maximum output) typically range between 20 and 30%.

Figure 3.155: Grid-connected small wind turbines

STAND-ALONE WIND TURBINES

Battery charging - the most common type of stand-alone small wind electric system involves the use of a wind generator to maintain an adequate level of charge in an electrical storage battery. The battery in turn can provide electricity on demand for electrical applications such as lighting, radios, refrigeration, telecommunications, etc., irrespective of whether or not the wind is blowing. A controller is also used to ensure that the batteries are not damaged by overcharging (when surplus energy is dissipated through a dump load) or excessive discharge, usually by sensing low voltage. Loads connected to the battery can either be DC or AC (via an inverter).

Wind turbines for water pumping - wind turbines are typically used as a water supply system (livestock or human settlements), for small-scale irrigation or for pumping seawater in sea salt production. SWTs used to supply water must be ultra-reliable and require low-maintenance, able to operate largely unattended (with automatic devices to prevent over speeding in storms) and pump water generally from depths of 10 to 100 metres or more. A typical SWT used for this purpose is expected to run for over 20 years with only annual maintenance work and without any major replacements. The latter is a very demanding technical requirement, since it means that a wind pump must perform for over 80,000 operating hours without any significant wear and tear, i.e. four to ten times the operating life of most small diesel engines or about 20 times the operating life of a small engine pump.

Irrigation duties, on the other hand, are seasonal and involve pumping much larger volumes of water over a low head. The intrinsic value of water used for irrigation is low when compared with drinking water. Therefore, any wind pump developed for irrigation must be as inexpensive as possible and this requirement tends to override most other considerations. Since the farmer and other workers are generally present during irrigation, it is not as critical to have a machine capable of running unattended. Windmills used for irrigation in the past have thus tended to be indigenous designs that are often improvised or built by the farmer as a method of low-cost mechanisation.

Rural electrification **-** worldwide, it is estimated that at least 1.3 billion people lack access to electricity. SWTs can be employed to provide electricity to remote communities where the wind resource is adequate. In the context of rural electrification, SWTs can help in combatting rising fuel prices and improving the socio-economic situation of rural dwellers with an environmentally friendly solution. On the other hand, maintenance requirements and high upfront costs generally impede their application.

Figure 3.156: Examples of SWTs for rural electrification

Remote power supply **-** equipment such as telecommunications base transceiver stations which could be located in remote areas are often powered by diesel generators. SWTs provide an environmentally friendly solution in areas with ample wind to provide the needed power for these installations.

» *Planning to install a wind turbine*

When siting a SWT, various factors are taken into consideration. These include:

Figure 3.157: Remote power supply for meteorological platform at sea (left), traffic signal (right)

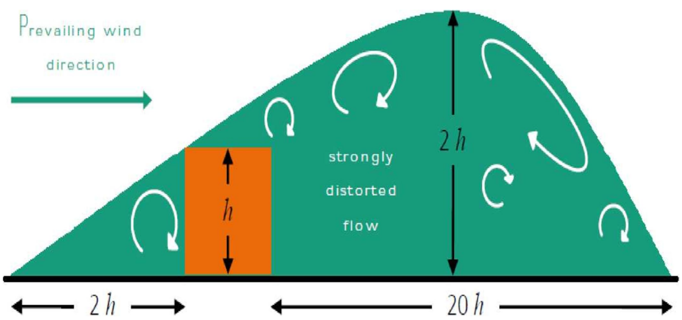


Figure 3.158: Turbulence generated by structures on the windward side

- Availability of wind resource: Without a sufficient wind resource, SWTs are not technologically or financially prudent.
- Proximity to location of energy consumption: SWTs should be located as close to the energy consumption location as possible to reduce costs of installation.
- Environmental and social impacts: Impacts such as noise pollution caused by the rotation of the turbine are to be considered, along with the visual effect of the wind turbine.
- Location of obstacles: The local conditions at a proposed SWT installation site are greatly affected by obstacles such as trees and houses.

Figure 3.158 show the turbulence generated by a structure of a height h located in the direction of prevailing wind. Wind turbines should be sited at an appropriate distance:

- 2 × h before the obstacle or
- 20 × h after the obstacle or
- 2 × h higher than the obstacle if within 20 × h.

ENERGY YIELD ESTIMATION

Before installing an SWT, it is imperative to estimate the amount of energy that can be produced based on available wind resources. Manufacturers of SWTs include energy yield graphs in the product data sheets. Applicable figures can then be used for planning and making the necessary cost comparisons to determine the most practicable form of energy generation. Two sample specifications are compared in the table below.

Table 3.26: Examples of SWT specifications

	Skystream 3.7	*Eoltec Scirocco 5.6*
Rated power	2.1 kW	6.1 kW
Rotor diameter	3.72 m	5.6 m
Swept area	10.87 m^2	24.64 m^2
Number of blades	3	2
Cut-in wind speed	3 m/s	3 m/s

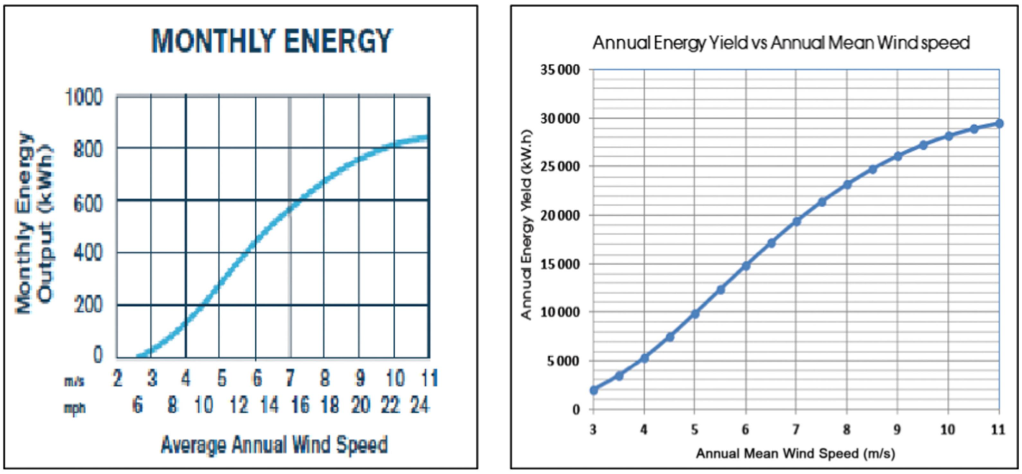


Figure 3.159: Energy yield graphs for Skystream 3.7 (left), Eoltec Scirocco 5.6 (right)

Example: At a wind speed of 4.5 m/s, the expected monthly energy produced by the SWT according to the energy production graphs above is:

⇒ *200 kWh for the Skystream 3.7*

⇒ *458 kWh for the Eoltec Scirocco 5.6*

Table 3.27: Strengths and weaknesses of wind energy systems

Strengths	*Weaknesses*
• Technology is relatively simple and robust with lifetimes of over 15 years without major new investments. • Automatic operation with low maintenance requirements. • No fuel required (no additional costs for fuel or delivery logistics). • Technology can be adapted for complete or partial manufacture (e.g. the tower) in developing countries. • Low environmental impact compared with conventional energy sources. • Mature technology in industrialised countries.	• Site-dependent technology (requires a suitable site). • Requires storage/backup due to variable power production. • Potential market needs to be large enough to support expertise/equipment required for implementation. • High capital/initial investment costs can impede development (especially in developing countries). • Cranage and transport access problems for installation of larger systems in remote areas.

REVIEW QUESTIONS

i. What is roughness length? How does it affect wind speed?
ii. List and describe five instruments used to measure wind speed.
iii. What is a wind rose?
iv. Explain a histogram. How is it created?
v. What is a line connecting points of equal wind speed called?
vi. What kind of wind turbine is used for pumping water? Low or high solidity?

FURTHER READING

1. *A survey of wind energy potential in Nigeria* • Ojosu, J. O. and Salawu, R. I. Solar & Wind Technology. 7(2–3): 155–167. (1990)
2. *Wind and Solar Power Systems: Design, Analysis and Operation (2nd edition)* • M.R. Patel (2006): M.R. Patel, R. Boca, FL: Taylor & Francis
3. *Renewable Energy Resources (2nd edition)* • J. Tidwell and T. Weir New York: Taylor & Francis (2006)

3.4. BIOMASS (NON-FOCUS TOPIC)

About this chapter

Biomass energy is the most common form of energy used in Nigeria today. This module provides vital information on sources and technologies that are used to convert biomass energy sources to useful electrical energy.

Learning outcomes

At the end of this chapter, the participant is able to

- Appreciate the importance of biomass as an energy source
- Outline and describe different forms of bioenergy
- Understand the role of bioenergy in Nigeria

CARBON CYCLE, CLIMATE CHANGE AND BIOMASS

Bioenergy, or biomass energy, is mainly renewable energy from biological sources, whereas biomass is stored sunlight in the form of chemical energy as it is found in living material like plants, agricultural waste or manure. Generally, it is material derived from recently living organisms. Biomass always contains the element carbon, which is part of the global carbon cycle. The carbon cycle is the base of all life on Earth.

Biomass can be converted by chemical, physical or biological processes into fuel (gas, alcohol, and biodiesel), heat or electricity. The use of biomass energy has the potential to greatly reduce our greenhouse gas emissions. Biomass generates about the same amount of carbon dioxide as fossil fuels, but every time a new plant grows, carbon dioxide is actually removed from the atmosphere. The net emission of carbon dioxide will be zero as long as plants continue to be replenished for biomass energy purposes.

The crops cultivated for the specific use of generating energy are called *energy crops.* These energy crops, also called *biomass feedstocks*, are usually fast-growing trees and grasses. The cultivation use of biomass feedstocks can also help increase profits for the agricultural industry.

Note: Biomass is any organic, i.e. decomposable, matter derived from plants or animals available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops, municipal organic wastes as well as manure. Bioenergy is energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquids and gases. Traditional biomass use refers to the use of wood, charcoal, agricultural residues and animal dung for cooking and heating in the residential sector. It tends to have a very low conversion efficiency (10% to 20%) and an often unsustainable supply.

THE CARBON CYCLE

The carbon cycle is the biogeochemical cycle by which carbon is exchanged between the biosphere, geosphere, hydrosphere, and atmosphere of the Earth. Carbon appears not only in the form of carbon dioxide, it also includes all carbon fixed to all kinds of biological material. The carbon cycle describes the movement of carbon as it is recycled and reused throughout the biosphere.

The global carbon budget is the balance of the exchanges (incomes and losses) of carbon between the carbon reservoirs or between one specific loop (e.g. atmosphere to biosphere) of the carbon cycle. It describes carbon dioxide sources (generation) and sinks (fixation), for instance emissions from combustion processes as a carbon dioxide source and forests as a carbon dioxide sink.

Carbon-based molecules are crucial building blocks for life on Earth, because carbon is the main component in all biological compounds. Carbon is also a major component of many minerals. Carbon dioxide (CO_2) is partly responsible for the greenhouse effect and is the most abundant greenhouse gas emitted by human activity.

THE ATMOSPHERE

Carbon in the Earth's atmosphere exists in two main forms: carbon dioxide and methane. Both gases absorb and retain heat in the atmosphere and are each in part responsible for the greenhouse effect. Methane has a more powerful greenhouse effect per volume as compared to carbon dioxide, but it exists in much lower concentrations and is more short-lived than carbon dioxide, making carbon dioxide the more important greenhouse gas of the two.

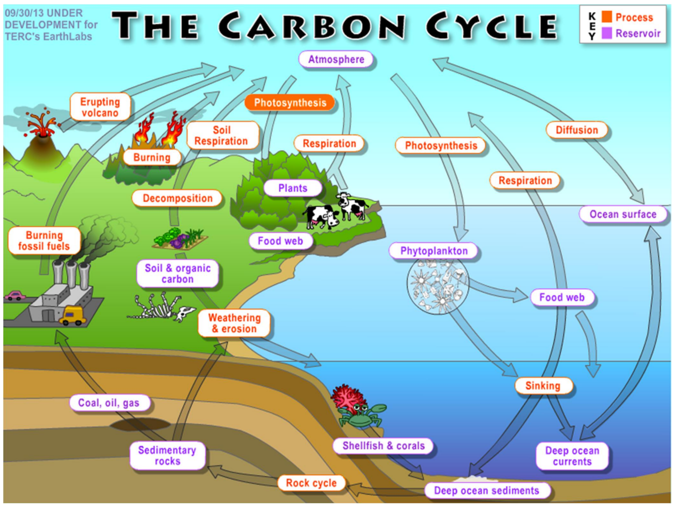


Figure 3.160: Global carbon cycle – *Courtesy: The Science Education Resource Centre at Carleton College Information, http://serc.carleton.edu/earthlabs/carbon/lab_2.html*

Carbon dioxide leaves the atmosphere through photosynthesis (as it is transformed into biological material like plants), thus entering the terrestrial and oceanic biospheres. Carbon dioxide also dissolves directly from the atmosphere into bodies of water (oceans, lakes, etc.), as well as dissolving in precipitation as raindrops fall through the atmosphere. When dissolved in water, carbon dioxide reacts with water molecules and forms carbonic acid, which contributes to ocean acidity. It can then be absorbed by rocks through weathering.

THE TERRESTRIAL BIOSPHERE

The terrestrial biosphere includes the organic carbon in all land-dwelling organisms, both alive and dead, as well as carbon stored in soils. About 500 gigatonnes (GT) of carbon are stored above ground in plants and other living organisms, while soil holds approximately 1,500 GT of carbon. Most carbon in the terrestrial biosphere is organic carbon, while about a third of soil carbon is stored in inorganic forms, such as calcium carbonate (limestone). Organic carbon is a major component of all organisms living on Earth.

Carbon leaves the terrestrial biosphere in several ways and on different time scales. Combustion releases it rapidly into the atmosphere. It can also be exported into the oceans through rivers or remain sequestered in soils in the form of inert carbon.

OCEANS

Oceans contain the greatest quantity of actively cycled carbon in this world and are second only to the lithosphere in the amount of carbon they store. The surface layer of the ocean holds large amounts of dissolved organic carbon that is exchanged rapidly with the atmosphere. The ocean's deep layer contains approximately 15% more dissolved inorganic carbon (DIC) than the surface layer.

The lithosphere is the solid outer section of the Earth, which includes the Earth's crust (the "skin" of rock), as well as the underlying cool, dense, and rigid top layer of the upper mantle.

Carbon enters the ocean mainly through the dissolution of atmospheric carbon dioxide, which is converted into carbonate. It can also enter the oceans through rivers as dissolved organic carbon. It is converted by organisms into organic carbon through photosynthesis and can either be exchanged throughout the food chain or precipitated into the ocean's deeper, more carbon-rich layers as dead soft tissue or in shells as calcium carbonate.

GEOLOGICAL CARBON CYCLE

These carbon stores of our planet's mantle interact with the other components through geological processes. The geologic component of the carbon cycle operates slowly in comparison to the other parts of the global carbon cycle. It is one of the most important determinants of the amount of carbon in the atmosphere and thus of global temperatures.

Carbon can leave the geosphere in several ways. Carbon dioxide is released during the metamorphosis of carbonate rocks when they are subducted into the Earth's mantle. This carbon dioxide can be released into the oceans and atmosphere through volcanoes and hotspots. Carbon dioxide is removed by humans through the direct extraction of fossil fuels. After extraction, fossil fuels are burned to release energy, emitting carbon into the atmosphere.

The exchanges between carbon deposits are a result of different processes which are chemical, physical, geological, and biological in nature.

SEDIMENTS

Most carbon is stored inertly in the Earth's lithosphere. Much of the carbon stored in the Earth's mantle was deposited there when the Earth was formed. Some of it was deposited in the form of organic carbon from the biosphere. Of the carbon stored in the geosphere, about 80% is contained in limestone and its derivatives, which form from the sedimentation of calcium carbonate contained in the shells of marine organisms. The remaining 20% is stored as kerogens formed through the sedimentation and burial of terrestrial organisms under high heat and pressure. Organic carbon stored in the geosphere can remain there for millions of years.

» *Plants and biomass*

FORMATION OF BIOMASS: PHOTOSYNTHESIS

Photosynthesis is a process by which certain organisms, mostly plants, convert light energy into chemical energy that can later be released to fuel the organisms' activities. This chemical energy is stored in carbohydrate molecules, such as sugars, which are synthesised from carbon dioxide and water.

In most cases, oxygen is also released as a waste product. Photosynthesis maintains atmospheric oxygen levels and supplies all of the organic compounds and most of the energy necessary for life on Earth.

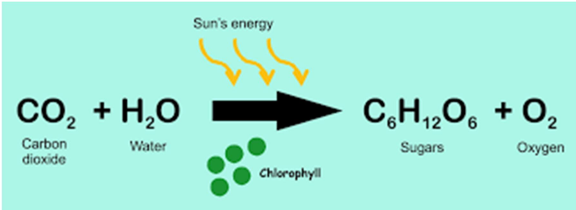


Figure 3.161: Chemical equation of photosynthesis

Photosynthesis is performed differently by different species. The process always begins when energy from light is absorbed by proteins called reaction centres that contain green chlorophyll pigments. In these light-dependent reactions, some energy is used to strip electrons from suitable substances such as water, producing oxygen gas.

In plants, algae, and cyanobacteria, sugars are produced by a subsequent sequence of light-independent reactions. Atmospheric carbon dioxide is thereby incorporated into already existing organic carbon compounds; the resulting compounds are then reduced and removed to form further carbohydrates such as glucose.

Today, the average rate of energy capture by photosynthesis globally is approximately 130 terawatts, which is about six times larger than the current power consumption of human civilisation. Photosynthetic organisms also convert around 100 to 115 thousand million metric tonnes of carbon into biomass per year.

BIOMASS CONVERSION TECHNOLOGIES

As stated earlier, biomass is biological material derived from living or recently deceased organisms. It most often refers to plants or plant-derived materials which are specifically called lignocellulose biomass. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel.

Direct combustion: Burning of material by direct heat.

Gasification: Biomass can be used to produce methane through heating or anaerobic digestion. The result is a synthetic gas (syngas), which consists of a mixture of carbon monoxide and hydrogen.

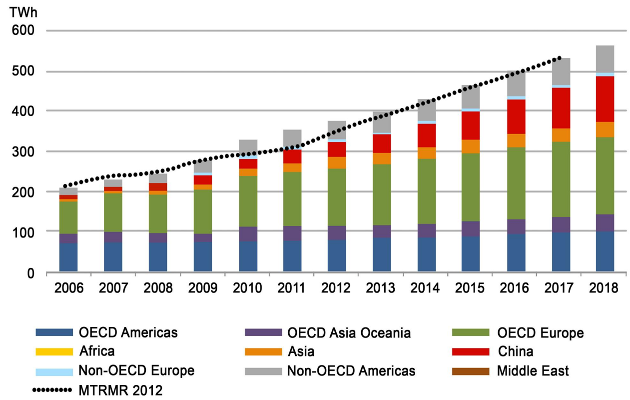


Figure 3.162: Growth rates of biomass use – *Courtesy: International Energy Agency*

Pyrolysis: Thermal degradation of biomass at high temperatures in the absence of oxygen. Biomass is heated up to a level between 400 and 750°C. No oxygen is introduced to support combustion, thus resulting in the creation of gas, fuel oil and charcoal.

Anaerobic digestion: Conversion of organic matter to natural gas (methane), carbon dioxide and other trace gases. Biomass is mixed with bacteria which break down the organic matter in the absence of oxygen. Biomass such as sewage, manure, or food processing waste is transferred to sludge and fed into a digester tank without air.

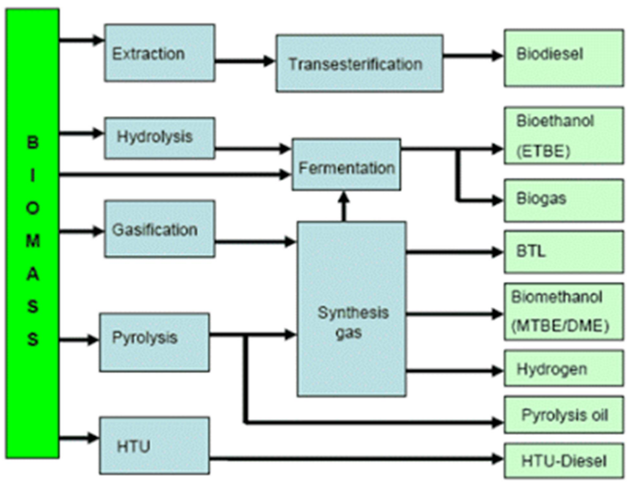


Figure 3.163: Biomass conversion technologies – *Courtesy: Zero Emission Resource Organisation and World Bank*

Landfill gas: Gas generated by the decay (anaerobic digestion) of buried garbage in landfills. When organic waste decomposes, it generates gas which initially consists of approximately

70% methane, the major component of natural gas, with a decreasing methane concentration over time.

Biofuels: Fuel alcohol can be produced by aerobic fermentation of starch to sugar. This is done by fermenting the sugar to alcohol, then separating the alcohol water mixture by distillation. Typical biofuel feedstock includes plants such as wheat, barley and potatoes, as well as waste paper, sawdust, and straw-containing sugar. On the other hand, biodiesel also refers to a vegetable oil, or animal fat-based diesel fuel consisting of long-chain alkylesters. It is typically made by a chemical reaction between lipids (e.g. vegetable oil, soybean oil, animal fat) and alcohol-producing fatty acid esters. Biodiesel is meant to be used in standard diesel engines and is thus distinct from the vegetable and waste oils used to fuel converted diesel engines. Biodiesel can be used alone or blended in varying proportions with conventional diesel.

» *Combustion*

Thanks to its low cost and high reliability, combustion is the simplest, most developed and most frequently applied process used to convert biomass to energy for solid biomass fuels. Biomass energy is used to generate heat and electricity through direct combustion, ranging in scale from very small domestic boilers to multi-megawatt power plants. For combustion to occur, the following conditions, called the *three T's* of complete combustion, must be satisfied: (1) Temperature high enough to ignite and maintain ignition of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time sufficient for complete combustion. Direct combustion of biomass is used from the household level up to power plants, depending on how much material is available as well as on existing technologies. Not all heat in the fuel is converted to heat and absorbed by the steam generation equipment. The main challenge in combustion efficiency is thus eliminating the occurrence of unburned carbon (in the ash or incompletely burned gas), which forms carbon monoxide (CO) instead of carbon dioxide (CO_2). Different biomass combustion systems have been developed for industrial purposes. These systems fall into three basic categories: fixed bed combustion, dust combustion, and fluidised bed combustion.

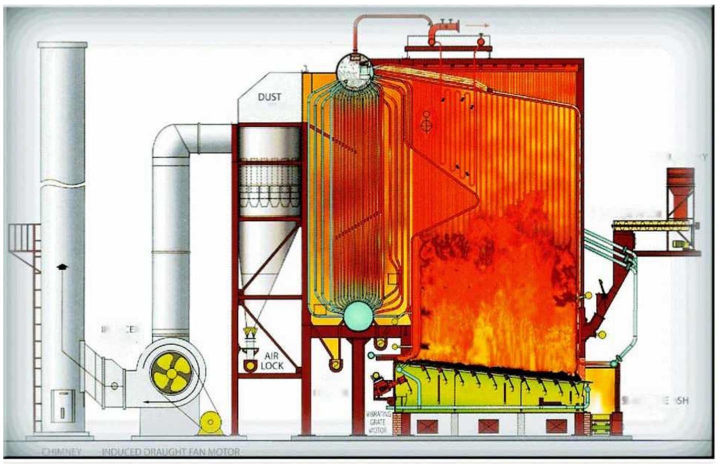


Figure 3.166: Large-scale fixed bed combustion stoke burner – *Courtesy: Bureau of Energy Efficiency, India*

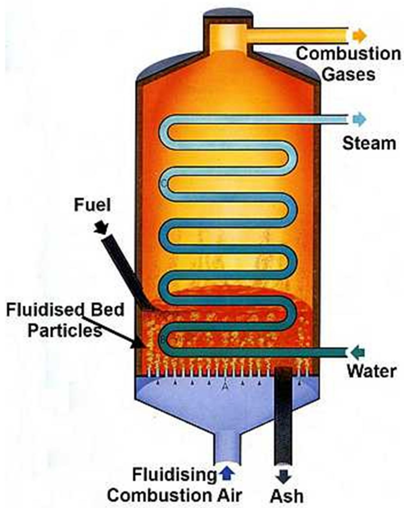


Figure 3.164: Fluidised bed reactor – *Source: Wikipedia*

FIXED BED COMBUSTION

Fixed bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, where drying, gasification, and charcoal combustion take place in consecutive stages. The combustible gases are burned in a separate combustion zone using secondary air.

DUST COMBUSTION

Dust combustion mostly relies on grate burners, which can be subdivided into pile and stoke burners. Pile burners are the simplest form of burner with the fuel (biomass) lying in a pile or on a fixed bed or grate through which combustion air flows and ash falls. On the other hand, stoke burners facilitate the movement of the fuel on the grate and the removal of ash, resulting in increased combustion efficiencies, high burning rates and relatively high temperatures. For both systems, primary air passes through a fixed bed, where drying, gasification, and charcoal combustion take place in consecutive stages. The combustible gases are burned in a separate combustion zone using secondary air. Grate furnaces are appropriate for burning biomass fuels with high moisture and ash content as well as different particle sizes. The design and control of the grate are aimed at guaranteeing smooth transportation and even distribution of the fuel and a homogeneous primary air supply over the whole grate surface. An irregular air supply may cause slagging, and higher amounts of fly ash, and may increase the oxygen needed for complete combustion. Load changes can be achieved more easily and quickly than in grate furnaces because there is better control of the fuel supply.

FLUIDISED BED COMBUSTION

In a fluidised bed, biomass fuel is burned in a self-mixing suspension of gas and solid bed material (usually silica sand and dolomite) in which air for combustion enters from below. Depending on the fluidisation velocity, bubbling and circulating fluidised bed combustion can be distinguished. The intense heat transfer and mixing provide good conditions for complete combustion with low excess air demand. The low excess air requirement reduces the flue gas volume flow and increases combustion efficiency. Fluidised bed combustion plants are of special interest for large-scale applications (normally exceeding 30 MWth). For smaller plants, fixed bed systems are usually more cost-effective. One disadvantage is the high dust loads in the flue gas, which make efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new bed material.

» *Gasification of biomass*

Biomass contains carbon, hydrogen and oxygen molecules. Complete combustion would produce carbon dioxide (CO_2) and water vapour (H_2O) whereas combustion under controlled conditions, i.e. partial combustion, produces carbon monoxide (CO) and hydrogen, which are combustible gases. These gases are produced by the reaction of water vapour and carbon dioxide as they pass through a glowing layer of charcoal. Combustion also produces non-useful products like tar and dust.

The key to gasifier design is to create conditions such that (a) biomass is reduced to charcoal and, (b) charcoal is converted at a suitable temperature to produce CO and H_2.

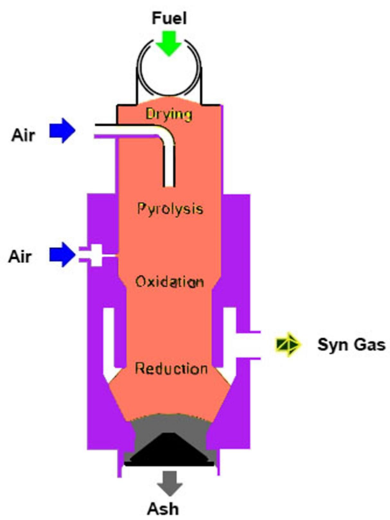


Figure 3.167: Stages inside the gasifier

A gasification system consists of four main stages:

- Supply of feedstock to gasifier
- Gasifier reactions where gasification takes place
- Cleaning of resultant gas
- Utilisation of cleaned gas

Biomass gasifiers are thermochemical converters (reactors) where various physical and chemical reactions take place. Biomass passes through various zones: drying zone, distillation zone, pyrolysis zone, combustion zone and reduction zone. Once the biomass has passed through all the above zones, it gets converted into a high-quality combustible producer gas. Biogas produced through gasification is called producer gas, which has a relatively low calorific value ranging from 1,000 to 1,200 kCal/Nm^3. The conversion efficiency of the gasification process ranges from 60 to 70%. It can be used for combustion in a reciprocating engine.

» *Anaerobic digestion*

Anaerobic digestion is the use of biological processes, in the absence of oxygen, for the breakdown of organic matter and the stabilisation of these materials by conversion to methane and carbon dioxide gases and a nearly stable residue. The process is based on biological digestion/anaerobic digestion of biomass. It is the only process that provides the additional advantage of high-grade manure as a by-product. The raw materials for the anaerobic process can include manure, sewage sludge, municipal solid waste, fruit and vegetable waste, food waste, distillery wastes and other biodegradable wastes. Bio-methane can completely replace natural gas in applications such as boilers, furnaces, internal combustion engines, etc.

Biomass offers higher energy efficiency in the form of biogas than by direct burning. At the beginning of the process, when organic matter is broken down by specific bacteria in the absence of air and at slightly elevated temperatures (35 to 40°C), biogas typically consists of 60 to 70% methane and 30 to 40% carbon dioxide. Also known as anaerobic digestion or fermentation, the biogas process provides a clean fuel that can be produced on a scale varying from a small household system to a large commercial plant of several thousand cubic metres. Biogas can be used for electricity generation or purified for use as a vehicle fuel.

In assessing the economic viability of biogas programmes, it is useful to distinguish between four main areas of application, namely:

- Individual household units
- Community plants
- Large-scale commercial animal rearing operations
- Municipal or industrial projects

In each of these cases, the economic feasibility of individual facilities depends largely on whether output in the forms of gas (for cooking, lighting, electricity and power) and slurry (for use as fertiliser/soil conditioner, fishpond or animal feed) can substitute for the costly fuels, fertilisers or feeds which were previously purchased.

Biogas technology is receiving increased attention due to its potential to bring an economically viable solution to the following problems:

- Dependence on imported energy

- Deforestation, leading to soil erosion and a drop in agricultural productivity
- Providing inexpensive fertilisers to increase food production
- Disposal of wastes, which cause severe pollution and public health problems

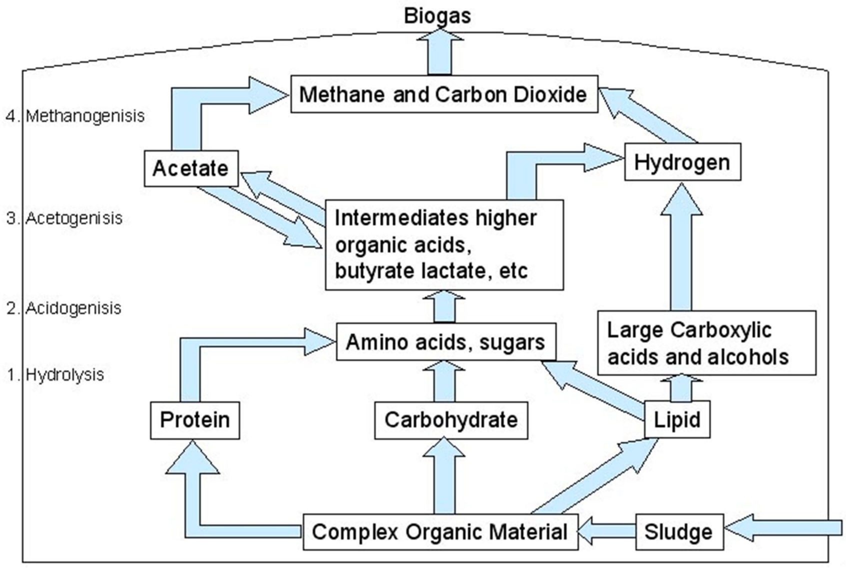


Figure 3.168: Biochemical steps in anaerobic digestion

Anaerobic digestion is a four-stage process that occurs as specific bacteria feed on certain organic materials. In the first stage (hydrolysis), acidic bacteria dismantle the complex organic molecules into smaller molecules. In the second stage (acidogenesis), these molecules further break down into organic acids, carbon dioxide and ammonia. A second type of bacteria (methanogenic bacteria) starts to convert these molecules into acetates (acetogenesis) and hydrogen in the third stage, and finally to methane in the fourth stage (methanogenesis). Methane-producing bacteria are particularly influenced by ambient conditions, which can slow or halt the process in the final stage completely or change the composition of resulting gases if conditions are not favourable. Anaerobic processes can be used for the degradation of very different materials like carbohydrates, fat and protein as they occur in organic waste.

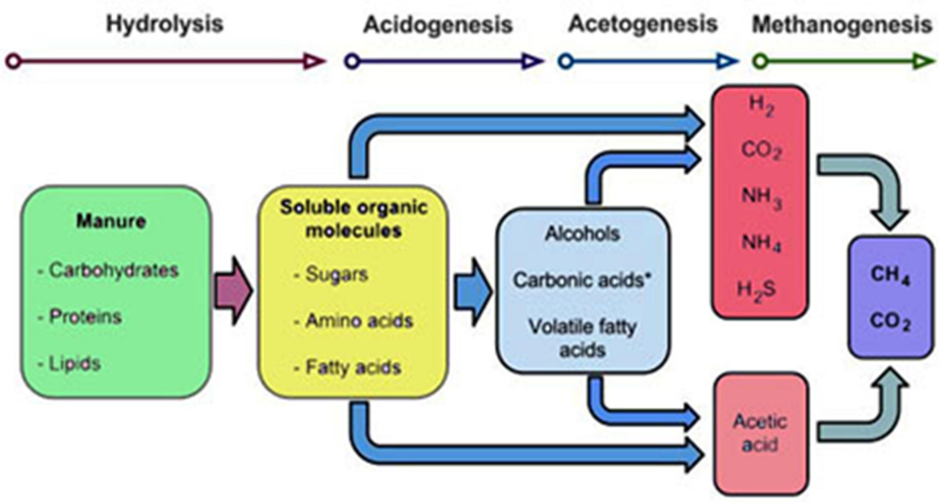


Figure 3.169: Principle and components of anaerobic digestion

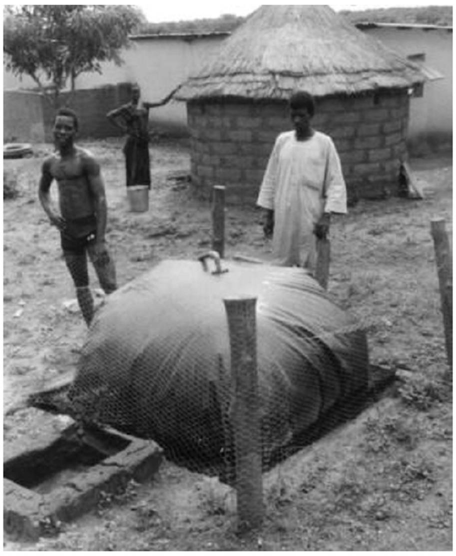


Figure 3.171: Simple biogas plant in Tanzania

Figure 3.170: Industrial-scale biogas plant in Germany – *Courtesy: Wikipedia*

PRODUCTS OF ANAEROBIC DIGESTION

The three principal products of anaerobic digestion are biogas, digestate, and waste-water.

Biogas - The gaseous output of anaerobic digestion consists of the gases listed in the table below. To extract the relevant methane gas, the output gas is scrubbed to remove impurities.

Table 3.28: Ratio of biogas output from anaerobic digestion

Typical composition of biogas	
Methane (CH_4)	50–75%
Carbon dioxide(CO_2)	25–50%
Nitrogen(N_2)	1–10%
Hydrogen(H_2)	0–1%
Hydrogen sulfide (H_2S)	0–3%
Oxygen(O_2)	0–20%

Digestate **-** refers to the solid remnants of the original input material that the microbes cannot convert. It also consists of the mineralised remains of the dead bacteria from within the digesters. Digestate can be fibrous or liquid or a combination of the two. In two-stage systems, different forms of digestate come from different digestion tanks. In single-stage digestion systems, the two fractions will be combined and, if desired, separated by further processing.

Figure 3.172: Digestate

Wastewater **-** the final output from anaerobic digestion systems is water, which originates from the moisture content of the original treated waste and water produced during the microbial reactions. This water may be released from the dewatering of the digestate or may be implicitly separated from the digestate.

USES OF BIOGAS

Biogas is a lean gas that can, in principle, be used like other fuel gases for household and industrial purposes. Common domestic appliances that use biogas include:

- Gas cookers/stoves: Biogas cookers and stoves for domestic use must meet certain requirements especially if they are to be used in rural areas. Amongst these requirements are simple and easy operation, suitability for pots of various sizes, easy cleaning, acceptable cost, easy repair and good burning properties, i.e. stable flame, high efficiency.
- Biogas lamps: Commonly used in rural areas without electricity where lighting is a basic need as well as a status symbol. Biogas lamps are not very energy-efficient, and they grow very hot during operation. The bright light of a biogas lamp is the result of incandescence, i.e. the intense heat-induced luminosity of special metals.

BENEFITS OF BIOGAS PLANTS

Figure 3.174: Biogas lamp, Thailand.

Figure 3.173: Cooking range operating with biogas.

- Like natural gas, biogas has a wide variety of uses, but, as it is derived from biomass, it is a renewable energy source. There are many other benefits to be derived from the process of converting substrates in a biogas plant.
- The economic pressure on conventional agricultural products has continued to rise. Many farmers have been forced to give up their occupation, since their land could not produce sufficient yield. However, the production of biogas is subsidised in many countries, giving the farmer an additional income. For the farmer, biogas production does not mean a major reorientation in activities, because microorganisms for methanation require similar care to that needed for livestock in the stable.
- Biogas production from maize or grass could help maintain and groom the existing layout of small farms.
- While unneeded plants and other biomass sources are often left to decompose, bioenergy production can recover this potential energy.
- Substantial reduction in the disposal costs of organic wastes, even including meaningful re-use (e.g. as fertilisers), due to the significant quantity reduction of biomass to make biogas.
- If plants are used as co-substrates for biogas production and the residues are recycled to fertilise fields, no mineral fertiliser needs to be purchased. A cycle of nutrients is reached, nitrate leaching is reduced and plant compatibility and plant health are improved.
- $C0_2$ neutral energy production (especially electrical power and heat) is achieved, thus effectively supporting climate protection.
- Reduction of landfill area and the protection of groundwater: Organic waste materials can be reduced to 4% of their original mass as sludge when the residue is

squeezed off and the waste water from the biogas plant is recycled into the waste water treatment plant.

» ***Energy farming for biomass production***

Energy farming is a concept whereby farmers grow and harvest energy crops for the sole purpose of converting them into fuels. The conversion processes could involve combustion, pyrolysis, esterification or in certain cases anaerobic digestion. Energy crops are woody or herbaceous plants that are cultivated for the sole purpose of being converted into energy. These plants are usually low-cost and low-maintenance plants. Once harvested, they can be converted into biofuels or combusted. Common energy crops include maize (or corn), giant Miscanthus (elephant grass) and Jatropha.

Agriculture is not an exact science as there are many variables involved from the initial planning to the harvest. When modelling a biomass system, it is possible to estimate the amount of land required to yield a certain amount of energy.

Example: Calculate the area of short-rotation giant Miscanthus needed to produce an annual thermal energy output of 900 GJ for agro-processing businesses in Makurdi.

Yield	14 t/ha/a (wet)
Equivalent	11.9 t/ha/a (dry)
Boiler thermal efficiency	78%
Calorific content of dry wood	17 MJ/kg

$$\Rightarrow \quad Annual\ energy\ output\ required = 900\ GJ$$

$$\Rightarrow \quad Total\ energy\ needed = \frac{Energy\ requirement}{Boiler\ efficiency} = \frac{900 \times 10^{12} J}{78\%} = 1.154 \times 10^{13} GJ$$

$$\Rightarrow \quad Amount\ of\ wood\ required = \frac{Total\ energy\ needed}{Calorific\ content} \frac{1.154 \times 10^{13} J}{17 \times 10^{6} \frac{J}{kg}} = 678.73\ t$$

$$\Rightarrow \quad Farmland\ required = \frac{Wood\ required}{Dry\ mass\ equivalent} \frac{678.73\ t}{11.9\ t/Ha} = 53.44\ ha$$

BIOMASS ENERGY IN NIGERIA

Wood remains the largest bioenergy source today. Examples include forest residues (dead trees, branches and tree stumps), yard clippings, wood chips and even municipal solid waste. In terms of scope, biomass includes all plants or animal matter that can be converted into fibres or other industrial chemicals, including biofuels. Industrial biomass can be grown from numerous types of plants, including miscanthus, switchgrass, hemp, corn, poplar, willow, sorghum, sugarcane, bamboo, and a variety of tree species, ranging from eucalyptus to oil palm (palm oil).

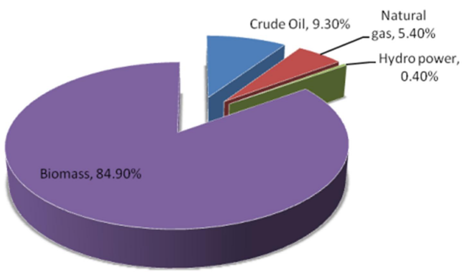


Figure 3.175: Energy consumption in Nigeria, 2009 – *Courtesy: IEA, 2012*

The advantages of using biomass for energy include:

- Providing access to energy and reducing fossil fuel consumption
- Rural development through employment and increased livelihood and market opportunities

- Rural infrastructural development as biomass energy can attract and increase investments in rural infrastructure such as potable water facilities, roads, electricity, hospitals as well as markets.
- Technological developments such as bioenergy could be used to bridge the gap between current fossil fuel technologies and future technologies.

» *Barriers to the development of biomass energy and production benefits*

There are six issues that stakeholders in biomass energy development need to consider:

- Are biomass resources available or can they be produced sustainably?
- Which technologies will deliver environmentally acceptable products and services?
- What will be the effects of increasing the use of biomass on environmental and socio-economic systems?
- What markets are readily available or need to be established?
- What investments are going to be required to establish the biomass industry?
- What risks are associated with investing in the biomass sector?

These questions can be broadly classified into[1]:

- Economic and policy barriers: High costs associated with energy produced from biomass and its associated technologies compared to conventional energy pose a challenge, especially for application in rural areas dominated by low-income residents. At the policy level, inconsistent and unclear market policies and incentives (subsidies) have limited the progress of biomass energy in Nigeria.
- Technological and human capacity barriers: Low rates of technology transfer (design, installation and maintenance) and lack of promotion of local content (manufacturing) for biomass technologies such as biogas digesters and gasification have resulted in limited access to the benefits of biomass energy in Nigeria.
- Social and environmental barriers: Fears of pollution due to agro-based industries are prevalent.
- Land ownership structure: The current system of communal land ownership with a pocket of private ownership poses a hindrance to large-scale farming practices, which can in turn affect the availability of raw material for bioenergy production.

REVIEW QUESTIONS

i. What is energy farming?

ii. Discuss the advantages and disadvantages of energy farming.

iii. Describe the process by which biomass is converted to energy.

iv. How much money can be earned by selling thermal energy to agro-allied businesses in Jigawa state through the direct combustion of Miscanthus (moisture content 80%). Assume that businesses pay NGN 30 per kJ of energy. The available arable land is 100 ha.

v. Discuss other barriers to the use of biomass as a source of energy in Nigeria.

[1] See Simonyan and Fasina (2013).

FURTHER READING

1. *Energy from Field Energy Crops – A Handbook for Energy Producers* • Jyväskylä Innovation Oy & MTT Agrifood Research Finland (2009) https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/encrop_international_handbook_for_energy_producers.pdf (accessed Aug. 30, 2016)

2. *Biomass Resources and Bioenergy Potentials in Nigeria* • Simonyan, K. J., and O. Fasina; African Journal of Agricultural Research 8(40): 4975–4989. (2013) www.academicjournals.org/article/article1381916826_Simonyan and Fasina.pdf (accessed Aug. 30, 2016)

3. *Renewable Energy Resources (2nd edition)* • J. Tidwell, and T. Weir; New York: Taylor & Francis. (2006)

4. ELECTRIC POWER DISTRIBUTION

About this module

In real-life situations, renewable energy is rarely used as a sole energy source for off-grid systems. Most renewable energy-based mini-grids are hybrids of two generating sources. This section introduces hybrid systems for powering mini-grids, and equips participants with the skills to design them.

Learning outcomes

At the end of this module, the participant is able to

- Design a mini-grid for a remote village
- Carry out commissioning tasks for an installed mini-grid
- Advise potential clients on mini-grids
- Develop operation and maintenance schedules for RE projects

INTRODUCTION

The modern electricity grid is gradually evolving away from the traditional centralised grid (i.e. consumers connected to the national grid) and towards a distributed grid system that utilises local sources of generation. Hybrid electric mini-grids that rely on renewable energy (RE) resources like wind, solar, micro hydropower, or biomass for on-site generation are gaining in popularity as they become more economically viable. RE generators are commonly used in addition to diesel generators to reduce fuel expenditures. Diesel is often relegated to back-up use to avoid an oversized battery bank.

For communities and remote facilities in Nigeria that do not have access to the national grid, the technical extension of the national grid often is not practical, thus the use of localised electricity systems with mini-grids is often the only realistic alternative. In this case, local communities can leapfrog technology development and operate small and completely independent modern power grids that are commonly referred to as mini or micro-grids.

Reliable, high-quality and affordable full-time (24-hour) electricity is essential to support critical community services, enterprise development and growth, and residential power needs. Schools, clinics, community centres, government facilities, and industry all operate primarily or exclusively during daylight hours. Yet few off-grid rural Nigerian communities have daytime power services. When diesel power generation is available, it is almost always used for night-time operation for residential lighting and entertainment.

Modern mini-grids are often supplied by a mix of energy sources such as solar or wind, often using diesel gen-sets as a dispatchable back-up in a hybrid configuration. Mixing technologies that use different energy sources provides operational, economic, and reliability advantages as compared to single technologies. The advantage of using mostly renewable energy technologies is that the fuel is clean and free, and thus not subject to price or supply volatility. However, capital costs for renewable energy technologies are higher to capture the free energy, and availability depends on the particular RE resource available at the location.

The electric grids of the future are becoming more decentralised, interconnected, and reliable, often incorporating mini-grids. Mini-grids are independent small- to medium-scale electricity generation systems serving a fixed customer base via a stand-alone electrical distribution grid. Mini-grids are electricity distribution systems containing loads and distributed energy resources such as distributed generators, energy storage, and controllable loads. Different technology options can be combined to form a hybrid mini-grid that benefits consumers and facility owners through lower bills, improved power quality and performance, as well as better reliability while reducing operating costs. The next section deals with hybrid systems powering mini-grids; the planning of mini-grids themselves is dealt with in section 4.2.

4.1. THE NATIONAL GRID

OVERVIEW

Electricity generation in Nigeria began in 1896. The Nigeria Electricity Supply Company (NESCO) commenced operations as an electric utility company in 1929 with the construction of a hydroelectric power station at Kurra near Jos. The Electricity Corporation of Nigeria (ECN) was established in 1951, while the first 132 kV line was constructed in 1962, linking Ijora Power Station to Ibadan Power Station. The Niger Dams Authority (NDA) was established in 1962 with a mandate to develop the hydropower potentials of the country. However, ECN and NDA were merged in 1972 to form the National Electric Power Authority (NEPA). In 1998, NEPA ceased to have an exclusive monopoly over electricity generation, transmission, distribution and sales. The name NEPA was changed to Power Holding Company of Nigeria in 2005 in the process of privatising power generation and distribution in accordance with the Power Sector Reform Act of 2005.

» *Current situation/structure*

As of 2016, there are 23 grid-connected power generating plants in operation in the Nigerian electricity supply industry (NESI) with a total installed capacity of10,396 MW and available capacity of 6,056 MW. Most generation is thermal based, with an installed capacity of 8,457 MW (81% of the total) and an available capacity of 4,996 MW (83% of the total). Hydropower from three major plants (Kainji, Jebba and Shiroro) accounts for 1,938 MW of total installed capacity with an available capacity of 1,060 MW.

Generally speaking, the national grid consists of the following core entities:

- 23 competing, privatised generation companies (GENCOs)
- 11 privatised distribution and retail sales (marketing) companies (DISCOs)
- The Transmission Company of Nigeria (TCN), responsible for the transmission and dispatch of electricity from the GENCOs to the DISCOs

TRANSMISSION COMPANY OF NIGERIA

The Transmission Company of Nigeria (TCN) is a successor company of PHCN, following the unbundling of the sector, and is currently being managed by a Canadian management contractor, Manitoba Hydro International. TCN is also referred to as a transmission service provider (TSP). Currently, the Nigerian electricity transmission system is made up of about 5,524 kilometres of 330 kV lines and 6,801 kilometres of 132 kV lines. TCN is composed of two major departments: System Operation (SO), responsible for system planning, administration and grid discipline, and Market Operation (MO), concerned with the electricity wholesale market.

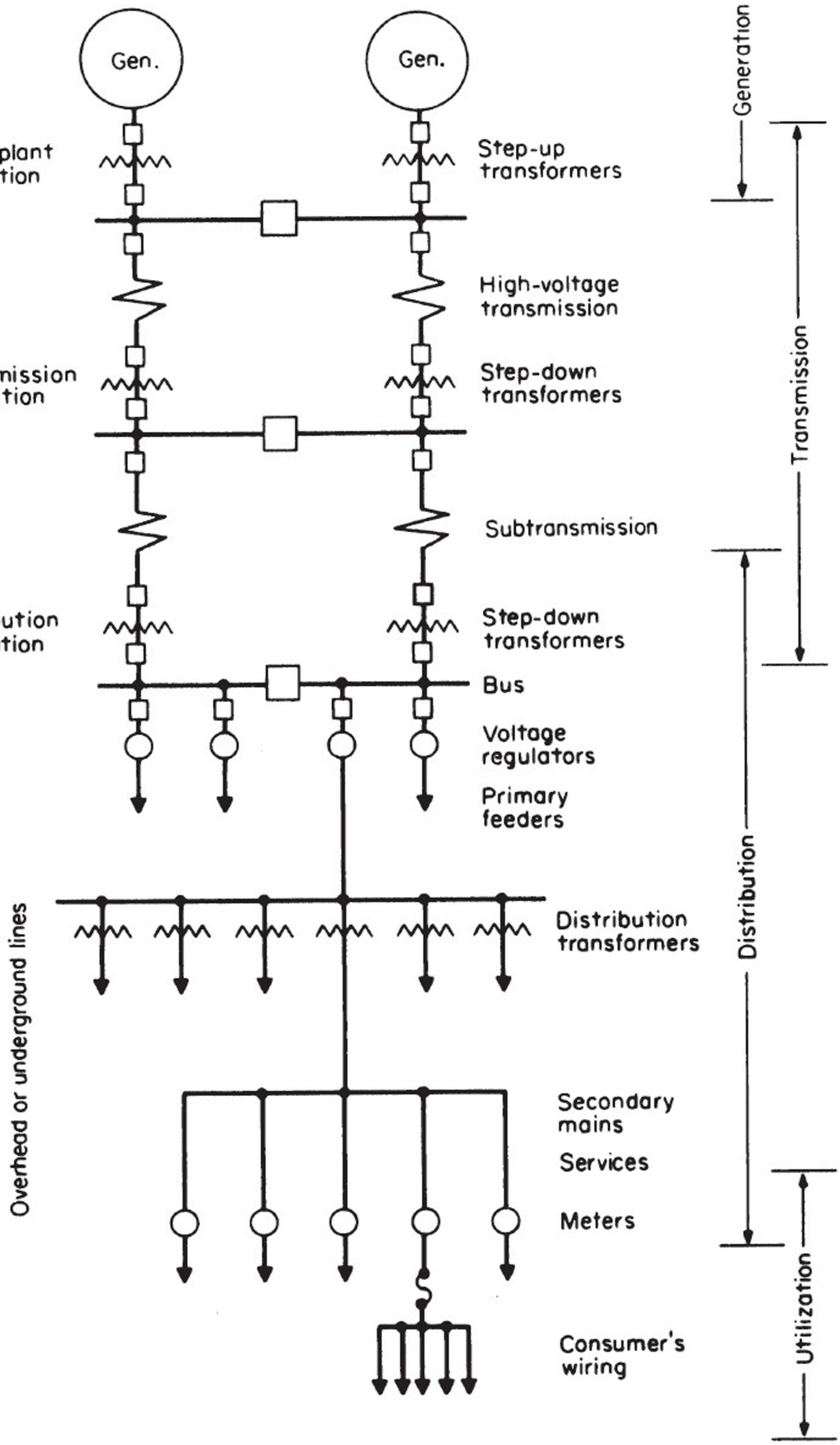


Figure 4.1: Single-line diagram of the Nigerian power sector on the national grid

DISTRIBUTION COMPANIES

There are 11 electricity distribution companies (DISCOs) in Nigeria.

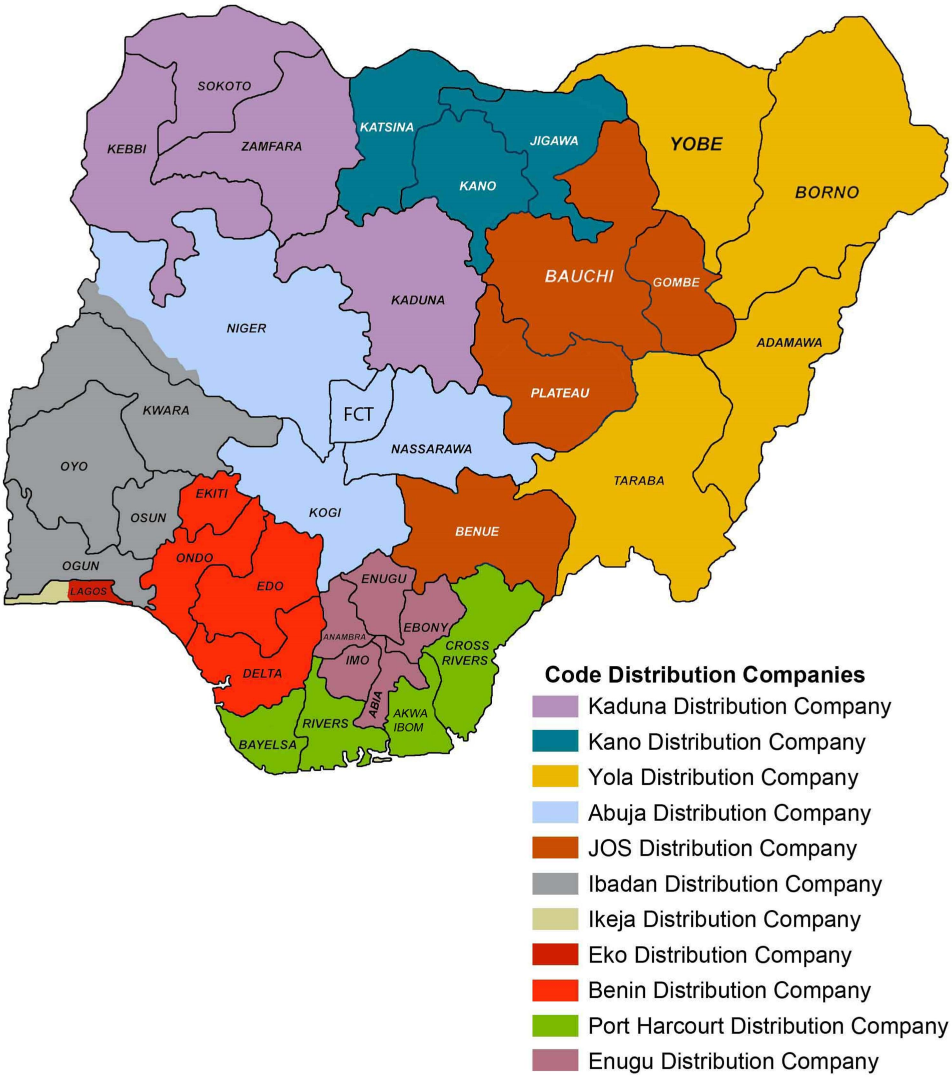


Figure 4.2: Regional coverage area of DISCOs

Table 4.1: Load allocation by DISCO in 2013

	DISCO	*Load allocation*
1	Abuja	11.5%
2	Benin	9.0%
3	Eko	11.0%
4	Enugu	9.0%
5	Ibadan	13.0%
6	Ikeja	15.0%
7	Jos	5.5%
8	Kaduna	8.0%
9	Kano	8.0%
10	Port Harcourt	6.5%
11	Yola	11.0%

GRID PARAMETERS

The grid code specifies the following parameters for the grid system performance characteristics:

- Nominal frequency: 50 Hz ±0.5% and ±2.5% under system stress
- High voltage: 132 kV, 330 kV
- Medium voltage: 11 kV, 33 kV and 66 kV
- Low voltage: 415 V (3-phase) and 220–230 V (1-phase)

4.2. MINI-GRIDS

INTRODUCTION

The purpose of this training module on electrical distribution systems is to provide a basic understanding of the elements of distribution system design as applied to mini-grid systems. Participants are encouraged to use the listed references along with other materials and expert advice while furthering their study on this topic.

A number of references were used in preparing this module. The authors especially like to thank the World Bank Group, who authorised the use of this material subject to the terms and conditions on its website[1], for its permission to use the Energy Sector Management Programme's *ESMAP Technical Paper 007 Mini-Grid Design Manual 21364* from 2000. Our further thanks go to the US National Rural Electric Cooperative Association for permission to use materials from the *Simplified Staking Manual for Overhead Distribution Lines (4th ed.)*. Finally, we are indebted to our colleague and friend Ing. Oscar Salinas, who sadly recently passed, for his excellent work on the *Bamyan Small Hydro Project: Distribution Design Report* published by NRECA International Ltd. with funding support from the US Agency for International Development's Afghanistan Clean Energy Program; excerpts of which are used herein.

» Design considerations

The process of designing an electric distribution system often begins by (a) defining the geographic scope of the project, (b) identifying the population that will be served by the project, and (c) estimating the expected energy consumption by the served population.

Given that electric power systems grow in conjunction with economic expansion, not only is it necessary to estimate the existing demand, it is also necessary to assess changing demand requirements over the expected lifetime of the power system.

Upon defining the likely geographic scope of the project, and after completing an initial estimate of energy consumption and power demand, the design phase for the electric distribution system can commence. The design process is normally performed in two stages.

- The first stage – the preliminary design – consists of identifying preliminary line alignments for the purpose of performing load flow and voltage drop calculations. Given that load flow analyses are a function of maximum system demand, the geographic configuration of the distribution system, and the attributes of the power system employed (voltage level, conductor impedance and power factor), the distribution system must be laid out and system attributes assigned to model the system performance. Once the model is defined, the conductor size can be evaluated on the basis

[1] www.worldbank.org/terms

of the load allocated over the geographic scope of the distribution system. Variations in line routing, single-phase versus three-phase service, and load can be modelled once the base case model has been completed.

- The final design process occurs when design crews perform a final survey of the distribution system alignments, defining the pole locations, the pole top structures, the guy requirements, and the final structural (as opposed to electrical) design features of the distribution system.

» *Load assessment*

The process of estimating the system demand is a function of identifying the geographic load centres, estimating the number of likely consumers in those load centres, and estimating the energy demand for each consumer. In any given project, there is most often a significant variation in load between the population of residential consumers, the population of commercial consumers, and the smaller population of industrial consumers – should there be any small or medium industries in the service territory.

A survey should be conducted of each household, including a number of interviews with home owners in villages. Besides household demographics, the interviews should include discussions of energy use. Some families may already have electric service either by solar home systems, gen-sets or micro hydropower schemes. The household energy and commercial surveys will provide information that should allow for a complete evaluation of energy consumption and power demand. It is important to weigh the results of the survey to determine the projected demand. Household energy use in remote rural villages like those in Nigeria is typically about 30 kWh per month (1 kWh per day) for lighting and television, but will vary depending on actual loads.

Quantity of Consumers		Bamyan Urban	Bamyan Rural
Small Residential, Class 1		300	2,688
Large Residential, Class 2		128	1
Commercial, small		670	30
Commercial, large		123	0
NGO or other large loads		81	1
Institutional, other government		47	4
Street lights		130	0
Total (without streetlights)		**1,479**	**2,724**
Monthly Specific Consumption		**Bamyan Urban**	**Bamyan Rural**
Residential, Class 1	kWh	40	40
Residential, Class 2	kWh	200	200
Commercial, small	kWh	75	75
Commercial, large	kWh	400	
NGO or large loads	kWh	500	500
Institutional, other government	kWh	250	250
Street lights	kWh	30	
Monthly Consumption by Sector		**Bamyan Total**	
Residential, Class 1	kWh	119,520	
Residential, Class 2	kWh	25,800	
All Commercial, NGO's, Gov.	kWh	155,975	
Street lights	kWh	3,954	
Total Monthly Sales	**kWh**	**305,249**	
Total Annual Sales	kWh	3,622,989	
Losses, kWh	12%	499,499	
Total Annual Generation	**kWh**	**4,162,488**	
Demand at Topchi Small Hydro Plant	**kW**	**1,235**	

Figure 4.3: Typical load analysis for mini-grid project – *Courtesy: Bamyan, Small Hydro Project: Distribution Design Report developed by NRECA International Ltd.*

In the case of commercial consumers, it is often expedient to break down these consumers into distinct groups, for example, small shops, larger shops, hotels, restaurants, fabrication shops (metal and wood-working), and small businesses (banks, NGOs, and other offices). Differences in monthly energy consumption can vary greatly dependent on the nature of the business, so care should be taken in the load estimation process. Lastly, some significant load centres may require individual energy surveys to gain a better understanding of monthly energy requirements. Energy efficiency and demand-side management interventions should be thoroughly investigated and implemented to keep energy usage as low as practicable.

MINI-GRID DISTRIBUTION

Once you have completed the geographic survey and the load estimation for the mini-grid, an engineering model can be developed to facilitate the design of the distribution system. It is a good idea to use the national distribution voltage standard to assure that parts can easily be obtained, and if a national grid extension is ever brought to the mini-grid area, the distribution system used for a stand-alone mini-grid will be completely compatible with national infrastructure and any future expansions. Overhead distribution line construction is most commonly used for mini-grids. However, underground construction may be used in sensitive areas (archaeological sites, nature preserves, etc.).

Many electrical distribution systems are designed using dedicated design software such as Milsoft Utility Solutions' *Milsoft Engineering Analysis (EA) WindMil®*product. This model can create an electrical circuit diagram of the proposed design that can then be optimised to select the distribution system voltage and configuration, conductor sizing, calculation of line losses, and a number of other key design parameters. Several global information system (GIS) mapping products such as ESRI's ArcGIS model can be used to create spatially oriented drawings of the design showing the distribution grid in relation to other geographic features such as roads, trails, rivers as well as house locations. An example of the level of system modelling and optimisation that can be achieved using computer-based tools is shown in Figure 4.4

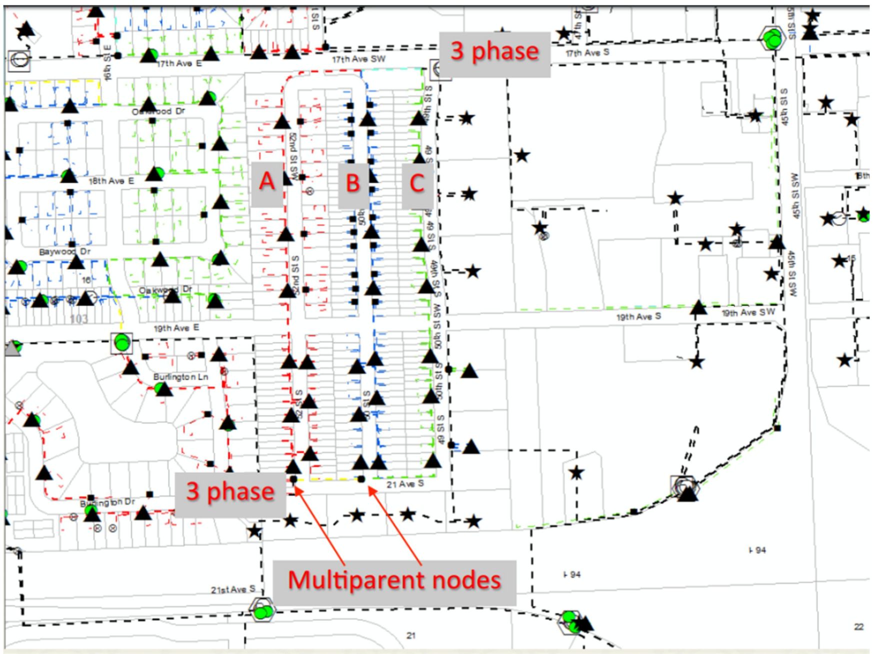


Figure 4.4: Distribution system analysis software – *Courtesy: Complex Staking and Modelling for Field Engineering and WindMilMap – Nick Ludowese, 2015*

» *Voltage selection*

Voltage selection is an iterative process based primarily on the amount of power to be transmitted and the line distance from the power source to the load. A higher power requirement for a longer distance will result in a higher voltage selection than a lower power requirement over a shorter distance. Distributions grids are always operated on AC as the low voltage typical for off-grid DC systems would incur voltage drops of an order that is prohibitive. Nigeria currently uses 11 kV and 33 kV three-phase configurations for distribution with 415 V low-voltage three-phase circuits for secondary distribution within the load centres.[1]

The process of selecting the voltage is iterative because the other component of the power flow equation is the conductor size. A bit of electrical theory will help explain this process:

- Power is a measure of work performed and is measured in watts.
- Voltage is the force that pushes current through an electrical circuit measured in volts.
- Current is the flow rate of electricity measured in amperes.
- Resistance is the resistance to the flow of electricity measured in ohms.

We can state the relation of these measures as a formula:

$$P = V*I \text{ and } I = V/R$$

Where:

P = Power (W)

V = Voltage (V)

I = Current

The above equation shows that system power is a function of system voltage and current flow. The higher the voltage and/or the higher the current, the more power is delivered. Equation 2 shows that current flow is a function of system voltage and resistance. Resistance is introduced into the system based on the size of the conductor. The larger the conductor, the less resistance and the higher the current flow. Thus, the selection of system voltage is an iterative process considering the total power requirement and the conductor size.

The selection of a distribution voltage for the mini-grid project requires several considerations:

- What is the power delivery requirement for the system? Answer this question by determining the total load to be served by the mini-grid.
- What voltages are standard in the country? This question is important to allow for the possibility of future connection to the national grid. Using local standard voltages will facilitate the acquisition of system components such as transformers, pole top units such as insulators, fuses and other distribution system components.
- What is the geographic expanse of the project? Consider that higher voltages are used when power must be transmitted over long distances. One advantage to mini-grid systems is that they often serve individual small, centralised villages – thus reducing the need to transmit power over longer distances.

[1] Map of the Nigerian national transmission published by the Global Energy Network Institute and available at www.geni.org/globalenergy/library/national_energy_grid/nigeria/index.shtml

- What is the consumer density in the village? In some village cultures, living quarters are dispersed, perhaps each with a few hectares of land between neighbours, while in other village cultures homes are arranged very close together. This makes a significant difference in voltage selection – the more dispersed the load, the higher the voltage (and/or the larger the conductor) needed.
- Are there any system expansion plans? If there are unserved loads, say perhaps an adjacent village or a larger commercial establishment that may eventually be served by the mini-grid system through a system expansion, this could be a factor in voltage selection. Again, the longer the lines distance, the higher the voltage requirement.

Conductor sizing for each circuit of the distribution system is based on the following:

- *Distribution voltage selected for the project:* Our equations show that the higher the distribution voltage, the smaller the conductor requirement.
- *Conductor cost:* Incremental sizing of standard conductors gives us a significantly high cost of upgrading from one conductor size to the next.
- Length of the line segment: The longer the line segment, the greater the resistance from the conductor.
- *Voltage drop*: Voltage drop is experienced when current flows through a conductor. Since household appliances and lighting require a standard voltage of 220 to 240 volts, any voltage drop in the distribution line from the generating source to the house will degrade the voltage along the line. Voltage drop is reduced on distribution systems primarily by increasing conductor size. A typical AC distribution system should limit voltage drop to between 5% and 10%.
- *Ampacity:* Maximum electric current a conductor can safely carry without damage. The ampacity of a conductor depends on insulation temperature rating, electrical resistance of the conductor material (e.g. copper or aluminium) and conductor operating temperature. Ampacity tables are provided by all conductor manufacturers and should be consulted before cable sizes are finally selected.
- *Energy quantity to be supplied by a given line segment*: Our equations also showed that the higher the power requirement, the higher the current demand, resulting in a larger conductor requirement (lower resistance).
- *Load distribution along the line segment: Larger* conductors will often be used from the generating source to the point of load concentration and smaller conductors will be used to deliver power within the load pocket. This reduces the conductor cost and lowers voltage drop.
- *Anticipated load growth on the line segment:* It is important to size conductors to meet future growth to avoid the expense of upgrading conductors as the system load grows.

» *Conductors (cables)*

Once the load characteristics have been determined, the selection of a conductor to most effectively serve both the current consumer load and future load growth at a minimum cost can be assured by following the standard approach for proper conductor sizing. In this process, both the voltage drop at the end of the line as well as energy (kWh) losses along the line, both of which depend on conductor size, must be kept within acceptable bounds.

CONDUCTOR TYPES

For electricity distribution conductors, two materials are generally used: copper and aluminium.

Copper is available in several forms. Hard-drawn copper is used as a conductor because of its higher strength. Annealed copper is used as a ground wire and for other applications where it is necessary to bend and shape the conductor. Annealed conductors cannot be reliably soldered or welded for splicing, so splicing sleeves are used for joining conductor segments.

Aluminium is presently widely used but it only has two-thirds the conductivity of copper. Comparing two conductors with the same resistance per unit length, an aluminium conductor requires 1.6 times the area of a copper conductor to carry the same current. Aluminium is preferred over copper in many cases because its smaller weight-to-strength ratio permits longer spans and potentially fewer poles. But a pure aluminium conductor stretches easily in high winds or if objects fall on it. Therefore, to increase its strength, aluminium strands can be wrapped around a steel core, a construction referred to as an aluminium conductor steel-reinforced (ACSR) cable.

Described below are the basic conductor types for use in mini-grids as well as their key characteristics:

- Bare conductor: One of the most common conductor types used with conventional low-voltage distribution systems around the world. ACSR is most commonly used.
- Single insulated conductor: Consists of copper or aluminium over which a layer of plastic insulation is laid. The conductor may be stranded or solid, with solid conductors predominately constructed in smaller sizes and used primarily for low-voltage system applications such as residential wiring.
- Multicore and aerial bundled cable (ABC): Composed of one or more insulated stranded conductors, commonly in aluminium, wrapped around a messenger conductor. The messenger serves as both a conductor and the member supporting the entire conductor bundle weight and can be either insulated or bare. ABC is designed specifically for use with distribution lines, whereas multiplex has been specifically manufactured for use as a conductor for secondary drops. Multiplex cables with one, two or three conductors wrapped around the messenger conductor are referred to as duplex, triplex, and quadruplex cables, respectively. The messenger is commonly ACSR to provide the necessary strength.

The Nigerian Electricity Management Service Agency (NEMSA) issued strict rules governing poles for electricity distribution in Nigeria in 2016 as listed below:

1. Use of split conductors and cables resulting in sudden snapping of conductors and networks collapse posing risk to lives and property is prohibited.
2. Use of fake or non-copper (aluminium) cables for indoor wiring and installation is prohibited Use of split conductors and cables resulting in sudden snapping of conductors and networks collapse posing risk to lives and property is prohibited.
3. Use of fake or non-copper (aluminium) cables for indoor wiring and installation is prohibited.

» *Low-voltage systems*

Low-voltage systems are technically defined as those using less than 1,000 volts. However, in common practice low voltage is considered to be approximately 240 or 480 volts. Short mini-grid distribution systems are commonly equipped with a low-voltage distribution system and operate at 240 volts.

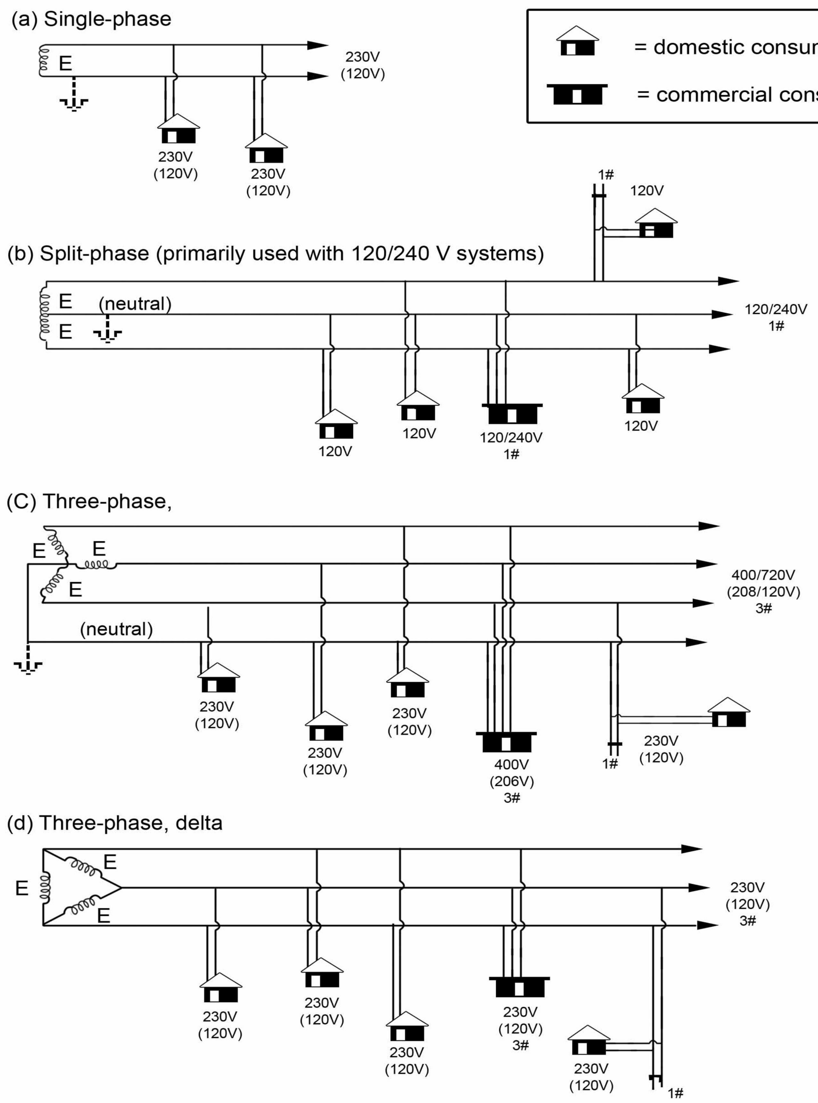


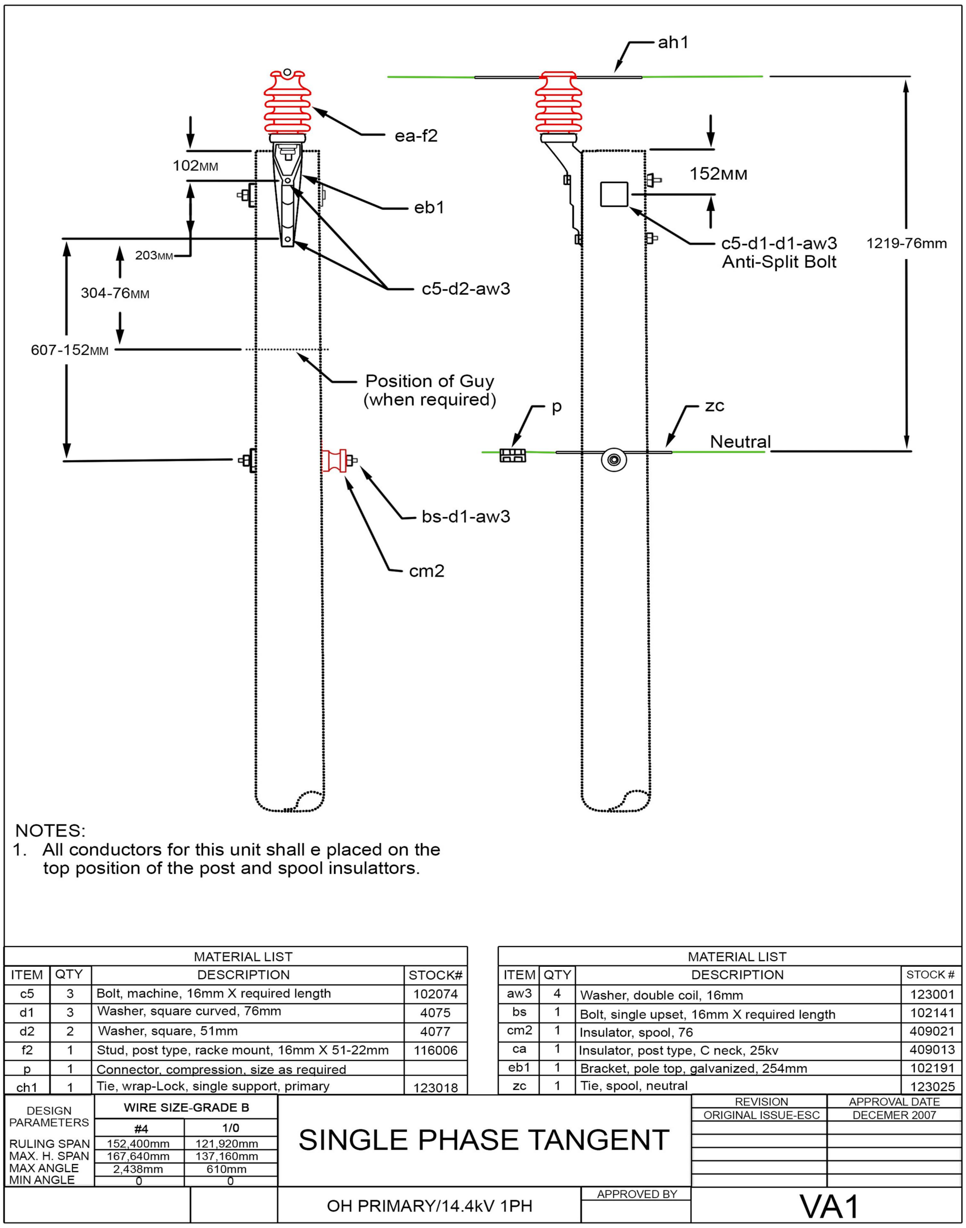
Figure 4.5. Four possible basic distribution line configurations for a rural mini-grid application. The supply (on left) can be either a generator or a transformer. E represents commonly used voltage in the country *–Source: ESMAP Technical Paper 007 Mini-Grid Design Manual 21364, The World Bank Group Energy Sector Management Programme 2000*

SINGLE-PHASE SYSTEMS

For this configuration type, two conductors from the powerhouse serve the entire community at a nominal voltage that is set between 220 V and 240 V nominal. To ensure easy system maintenance as well as local availability of construction materials and consumer appliances, the voltage should coincide with the standard in use in Nigeria.

If the powerhouse is located in the middle of the load centre, single-phase lines might take off from the powerhouse in several directions. Consumer connections to this system are straightforward: The mini-grid is comprised of a pair of conductors that pass by each consumer and the service drop simply taps both of these lines. This is the simplest option to design and is therefore the most commonly used for mini-grids. However, it is not the most efficient option.

While mini-grids frequently use this basic configuration due to its straightforward setup and operation, it is typically the most costly configuration.



MATERIAL LIST			
ITEM	QTY	DESCRIPTION	STOCK#
c5	3	Bolt, machine, 16mm X required length	102074
d1	3	Washer, square curved, 76mm	4075
d2	2	Washer, square, 51mm	4077
f2	1	Stud, post type, racke mount, 16mm X 51-22mm	116006
p	1	Connector, compression, size as required	
ch1	1	Tie, wrap-Lock, single support, primary	123018

MATERIAL LIST			
ITEM	QTY	DESCRIPTION	STOCK #
aw3	4	Washer, double coil, 16mm	123001
bs	1	Bolt, single upset, 16mm X required length	102141
cm2	1	Insulator, spool, 76	409021
ca	1	Insulator, post type, C neck, 25kv	409013
eb1	1	Bracket, pole top, galvanized, 254mm	102191
zc	1	Tie, spool, neutral	123025

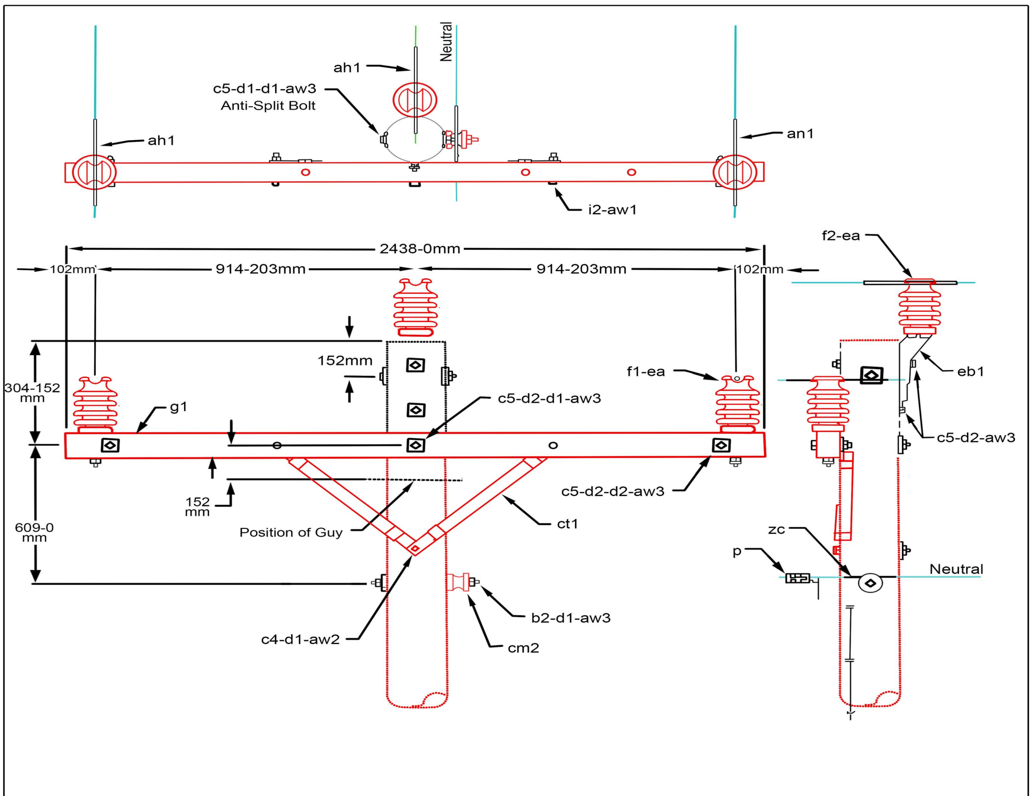
DESIGN PARAMETERS	WIRE SIZE-GRADE B	
	#4	1/0
RULING SPAN	152,400mm	121,920mm
MAX. H. SPAN	167,640mm	137,160mm
MAX ANGLE	2,438mm	610mm
MIN ANGLE	0	0

REVISION	APPROVAL DATE
ORIGINAL ISSUE-ESC	DECEMER 2007

Figure 4.6: Single-phase tangent

THREE-PHASE SYSTEMS

A common tangent structure for a three-phase, multi-grounded, four-wire distribution system is shown in *Figure 4.7*. This configuration offers a significantly higher power distribution capability by carrying three-phase conductors on a common structure. Single-phase taps can be taken off of this three-phase line to serve smaller load pockets in a radial or looped configuration.



MATERIAL LIST

ITEM	QTY	DESCRIPTION	STOCK#
c4	1	Bolt, machine, 13mm X required length	102057
c5	6	Bolt, machine, 16mm X required length	102074
d1	5	Washer, square curved, 76mm	4078
d2	7	Washer, square, 51mm	4077
f1	2	Stud, post type, crossarm mount, 16mm X 178mm	116002
f2	1	Stud, post type, crossarm mount, 16mm X 51-22mm	116006
g1	1	Crossarm, distribution, RUS ttype 76, 5,156	603281
l2	2	Bolt, carriage, 3mm X 102 - 12mm	102006
p	1	Connector, compression, size as required	
ah1	3	Tie, wrap-Lock, single support, primary	123018

MATERIAL LIST

ITEM	QTY	DESCRIPTION	STOCK#
aw1	2	Washer, double coil, 10mm	123001
aw2	1	Washer, double coil, 13mm	123001
aw3	7	Washer, double coil, 16mm	123001
bs	1	Bolt, single upset, 16mm X required length	102141
cm2	1	Insulator, spool, 76mm	409021
ct1	2	Brace, wood, crossarm, 711mm	102182
aa	3	Insulator, post type, C neck, 25kv	409013
eb1	1	Bracket, pole top, galvanized, 254mm	102191
zc	1	Tie, spool, neutral	123025

DESIGN PARAMETERS	WIRE SIZE-GRADE B			
	#4	1/0	4/0	477
RULING SPAN	121,920mm	121,920mm	-	-
MAX. H. SPAN	137,160mm	137,160mm	-	-
MAX ANGLE	24,38mm	610mm	-	-
MIN ANGLE	0	0	-	-

THREE PHASE TANGENT

REVISION | APPROVED DATE

OH PRIMARY/14.4kV 3PH

APPROVED BY

vc1

Figure 4.7: Three-phase tangent

As with the single-phase distribution system, service transformers are used to step down the voltage from the primary medium system voltage to common household voltage levels of 120 or 240 volts.

European countries, the United States, and many other areas utilise a three-wire three-phase system (*Figure 4.7*). As previously mentioned Nigeria uses 11 kV and 33 kV systems for distribution. This configuration is commonly referred to as a "Delta" system. Note there is no dedicated neutral return wire. In these cases, two-phase conductors must be extended for single-phase radial lines running off a three-phase feeder line. Both systems are arguably equally operable with preference primarily based on origin and local custom.

Figure 4.8: Europe, the United States and other areas utilise a three-wire three-phase system

» *Transformers*

Mini-grid systems utilising medium-voltage distribution systems require service transformers to "transform" the medium voltage (> 1,000 volts) to a common household current of 120 or 240 volts. A typical single-phase, two-bushing transformer is illustrated below (Figure 4.9). Figure 4.11 shows how the transformer would be connected to a single-phase distribution line to provide a two-wire, 240 V secondary service drop.

In mini-grids a single transformer can serve several homes. The size of a transformer destined to serve several homes can be calculated as a function of the average monthly energy usage of each home (kWh) and the number of homes connected to the transformer. Formulae are then applied that account for diversity in energy usage among households, i.e. not everyone runs all of their appliances at the same time. Tables are typically used to determine the transformer size for multiple homes.

The figure above shows a typical single-phase, medium-voltage grounded distribution system with a single-phase transformer and an associated low-voltage (here: 240 V) service drop to a residence.

Figure 4.9: Typical single phase transformer

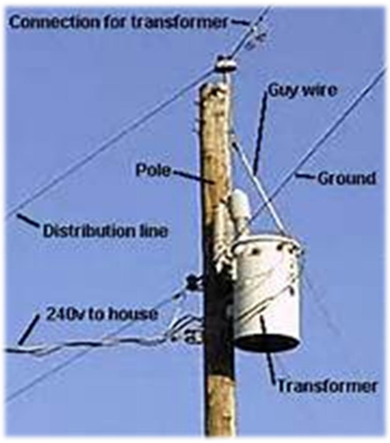


Figure 4.10: Single-phase transformer on a pole

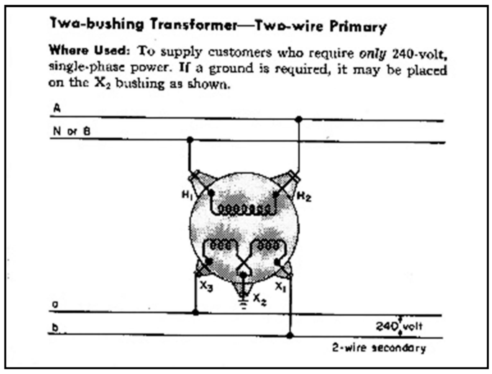


Figure 4.11: Wiring a transformer for single-phase loads

Note: Transformers can be connected in a variety of configurations in an electrical circuit dependent on the loads and final use. For example single-phase or three-phase, 3-, 4- or 5-wire connection etc. It is recommended that an electrical engineer with relevant experience and know-how on transformer selection and installation is engaged at this point in design process.

» *Poles*

Distribution line and service drops are typically placed overhead and must be supported at a sufficient height above the ground to keep them out of the way of vehicular traffic and out of reach of villagers. This is necessary to maintain the integrity of the line as well as to prevent the risk of shock to individuals who might otherwise accidentally come into contact with the conductors. These are the principal reasons for using poles and are the main factors in determining their length.

Poles must be strong enough to resist forces generated by wind or the tension in the conductor that would tend to bring them down, again affecting the integrity of the line and present-ing a safety risk to villagers. Some of these forces, such as those associated with the tension in the conductors at a bend in the line, are permanent forces and are counterbalanced through the use of guy wires.

POLE OPTIONS

Poles are made from a variety of materials, with the most frequent being wood, concrete, and steel. None of these materials has a clear advantage in all situations; rather, the selection process should include several criteria under site-specific conditions. These include availability, cost, weight and ease of handling, strength, and durability.

Before proceeding with a review of pole options, some general words of caution about poles: Because they can be the most expensive component of a distribution system, there is an incentive to minimise project costs by selecting the least expensive pole option. However, a less costly pole usually implies reduced strength and/or quality. This has several implications:

- Weaker, poorer quality poles and the conductors they support are more likely to fall under stress, resulting in a greater safety hazard to the population.
- Shorter life implies the need for an additional investment when poles will later need to be replaced. In addition to the cost of new replacement poles, the community will incur the additional cost of removing the old poles, resetting the new ones, and reconnecting the conductors, guys, etc., all of which contribute to additional costs and hassle. It is also likely that the manpower and expertise will no longer be on site when the poles need to be replaced.

Table 4.2: Characteristics of pole materials

Pole material	*Characteristics*
Wood	• Lighter than the equivalent concrete pole, most common alternative, and easier to handle in the field. • Not as susceptible to breakage during transport and handling. • Can usually be field-drilled, permitting greater flexibility in the placement of mounting bolts and facilitating later modification. • Not adversely affected by airborne salt in coastal zones that can cause corrosion of the reinforcing steel in concrete poles. • Local plantations permit self-sufficiency in the production of one of the costliest components of a rural electrification, thereby creating employment, reducing the need for foreign exchange, and lowering the cost of RE. • Larger, conventional wooden poles are easier to climb directly (with gaffs, sharp metal spurs affixed to the inside edge of a boot). • Properly managed, wood is a renewable resource, requiring much less energy in the manufacture of poles and contributing no net carbon dioxide or other greenhouse gases, unlike those associated with the production of cement or steel for poles. • Offsetting these advantages is the fact that untreated wood poles are susceptible to decay and insect damage, especially in humid climates such as the Nigerian Delta region. The inspection of fence posts or building timbers of the allegedly resistant species should be able to verify resistance to (or propensity for) decay and insect damage. • One alternative to finding resistant trees is to chemically treat wood poles. Pole treatment significantly extends pole life and should be considered with assistance from wood pole professionals.
Concrete	• Where wood poles are not an option due to issues presented above, steel-reinforced concrete is an alternative. • Permits local manufacture with relatively inexpensive, readily available materials, i.e.

Pole material	Characteristics
	cement and reinforcing steel. • Manufacture of concrete poles requires good design, quality materials, and competent execution. • A major disadvantage of concrete poles is their weight and the subsequent difficulty in handling, transport, and installation, especially in areas with no vehicular access. They are more susceptible to cracking and breaking than wood poles.
Steel	• Advantageous alternative when the grid has to be constructed in an area without vehicular access, where suitable trees cannot found and where concrete poles cannot easily be made or transported. • Construction design permits a pole to be fabricated of smaller sections that can be easily transported and assembled on-site. • Strength is predictable and steel poles can be designed and manufactured to a more precise tolerance. • Susceptible to corrosion (rusting) and appropriate precautions must be taken, including galvanising or painting. • Costs are significantly higher than wood and, in most countries, higher than concrete.

The Nigerian Electricity Management Service Agency (NEMSA) issued strict rules governing poles and lattice structures for electricity distribution in Nigeria in 2016 as listed below:

1. Use of untreated wooden poles, whose frequent failures usually result in sudden collapse of distribution network/systems, is prohibited.
2. Use of untreated wooden cross-arms, whose frequent failures usually result in sudden collapse of distribution network/systems, is prohibited.
3. Use of un-galvanized channel/angle irons whose frequent failures usually result in sudden collapse of distribution network/systems is prohibited.
4. Use of un-galvanized and proper tie straps whose frequent failures usually result in sudden collapse of distribution network/systems is prohibited.
5. Use of un-galvanized bolts and nuts whose frequent failures usually result in sudden collapse of distribution network/systems is prohibited.

» *Grid layouts*

MAPPING

Mapping activities should begin with a sketch of the community, starting with the general features found in the village and ending with the placement of specific homes, shops, schools, and other potential village loads. Initial distance estimates might be determined using simple methods such as counting paces of a known length. Global positioning system (GPS) units are becoming increasingly common and work well for basic mapping functions. Eventually, the map should be converted to a scaled map, ideally starting at a known landmark.

The principal use of this map will be to provide a base on which to lay out the distribution lines for the mini-grid in order to begin more detailed design work (sizing of the power system, conductor, and poles). This mapping should occur before or during the load assessment referenced above so that the location of abnormal loads such as commercial establishments or motors loads can be easily identified.

In addition to assessing the initial consumer load, future growth of this load must be estimated as realistically as possible. Consideration should be given to anticipated load growth from new consumers, either from new households or from existing villagers who are not yet willing to commit to connecting to the grid. And finally, some thought may already have been given in the community to the establishment of new shops and commercial loads in the near future or new institutional loads such as clinics, schools, or government offices.

Key elements to consider when mapping the grid layout are presented below.

1. Powerhouse or plant location: Several factors will affect the location of the powerhouse or plant, but choosing the location is simplified by the fact that the available options are usually very limited. Relevant factors include:
2. Voltage drop: Locating the powerhouse as close to the load centre as possible is critical in reducing distribution system costs. The further the conductor must run to serve all loads, the greater the voltage drop or the greater the cost for a larger conductor.
3. Location of the energy source to be harnessed: Ideally, the energy source is abundant near the load centre (village). Solar energy has the unique advantage over wind and hydroelectric systems in that it is adequate as long as sunlight reaches the ground. Densely forested areas may require the remote location of solar power stations or the removal of trees that cause shading.
4. Noise: If diesel gen-sets are included in the energy supply system, noise pollution can become a significant change factor in the village. The gen-set might be located at a more isolated part of the village if effective silencing of the exhaust is not possible.
5. Placing the lines: Once the powerhouse location has been chosen, the distribution line must be positioned to bring the electricity to the vicinity of the consumers. The best layout for the distribution system will be one that meets the criteria for reducing voltage drop while also minimising costs and ensuring safety and reliability. In general, the shortest line will minimise expenses, because it will reduce the cost of both the conductor and poles. Poles are often the most expensive component of a distribution system, and an important part of the design process is to be economical in their use. Factors to be considered in the layout of the distribution system include:
6. Location of roads, trails and paths: Whenever possible, lines should be placed along public rights of way. Should street lighting also be a priority, this is facilitated by locating poles along the principal arteries. Care should be taken if roads carry commercial traffic to assure sufficient clearance under the conductor for the vehicles to safely pass underneath. Road crossing should be avoided or minimised whenever possible.
7. Presence of trees: When conventional lines are built, trees are often the first casualties. The right-of-way along line is generally cleared of trees to prevent them from interfering with the operation of the line, i.e. branches from falling and breaking conductors or from electrically shorting-out the line.
8. Religious buildings/areas: Buildings or areas of religious or cultural significance must be identified and a clear understanding of what constraints these impose on line routing should be established.
9. Topography: Certain areas should be avoided if they will complicate the construction or on-going upkeep and maintenance of a line. These include steep slopes, areas susceptible to erosion, swampy areas, and areas prone to flooding.

10. Line length: Because poles and conductors are the most costly component of a mini-grid project, the alignment of the line should be selected to minimise their number and length.
11. Minimising changes in alignment: Whenever there is a bend in the line, the conductor under tension imposes a lateral force on the pole that tends to tip it. Every effort should be made to minimise deviations in alignment to reduce the complexity of line design and costs.
12. Loading: If there is significant variation in system loads, e.g. a large commercial load on the system, the mini-grid should be designed to equalise or balance the power flow through all circuits as much as possible.
13. Locating poles: Once the general layout for the distribution line has been prepared, poles must be placed along that line to support the conductors with adequate clearance. This will ensure a line that does not pose any hazard to people or vehicular traffic passing beneath it. Factors affecting pole location include, but are not limited to:
    - Bends in the line: Minimise whenever possible.
    - Location of load clusters: Locate poles as close to each service point (house) as possible, as the drop supplying the home takes off from a pole rather than from mid-span.
    - Adequate ground clearance: Span lengths should be maximised but ground clearance at mid-span must be considered.
    - Pole strength: Mechanical loading of the poles (previously discussed) limits the span length and must be considered as well.

The following two graphics show the layout of a 1.3 MW mini-grid project serving 1,500 homes in four villages in Afghanistan as designed by NRECA International, Ltd. for Winrock International and later implemented by the Government of New Zealand as a solar mini-grid.

Constructing mini-grid distribution systems for village electrification is a complex yet achievable challenge worthy of the effort. Bringing electricity to remote Nigerian villages represents a life-changing event that improves local economic productivity, quality of life, healthcare, and villager livelihoods. Through diligent planning and support from experienced distribution design engineers, virtually any technical obstacle can be overcome.

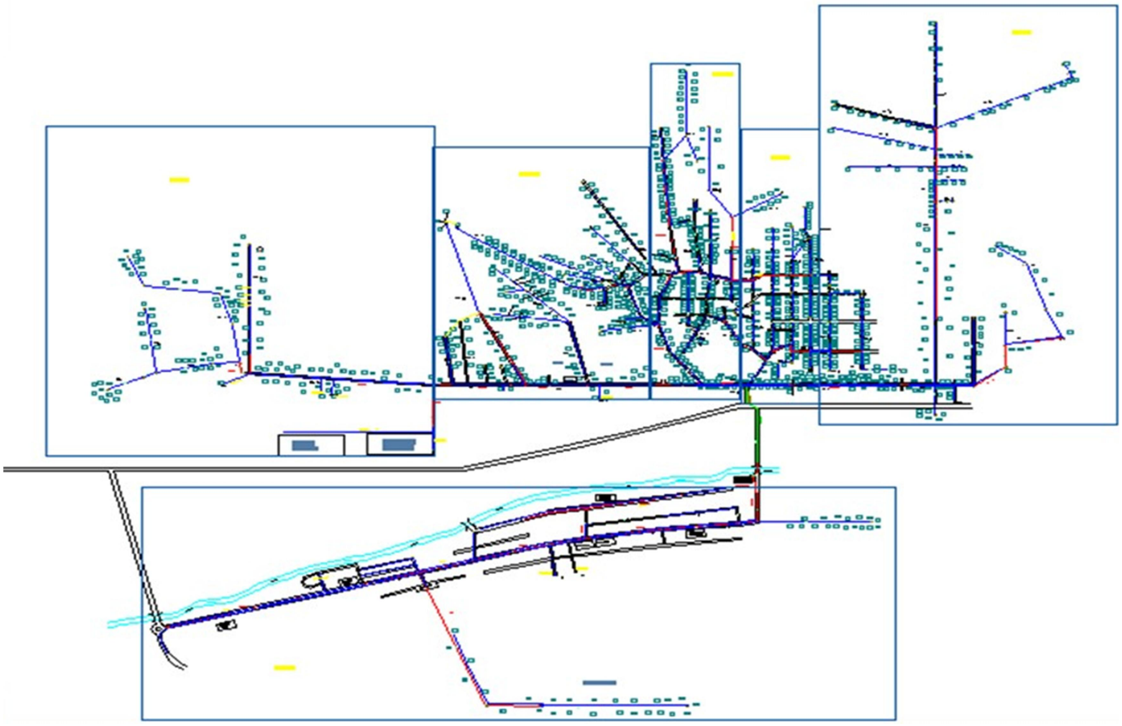


Figure 4.12: Bamyan small hydro project – *Courtesy: Distribution Design Report developed by NRECA International Ltd.*

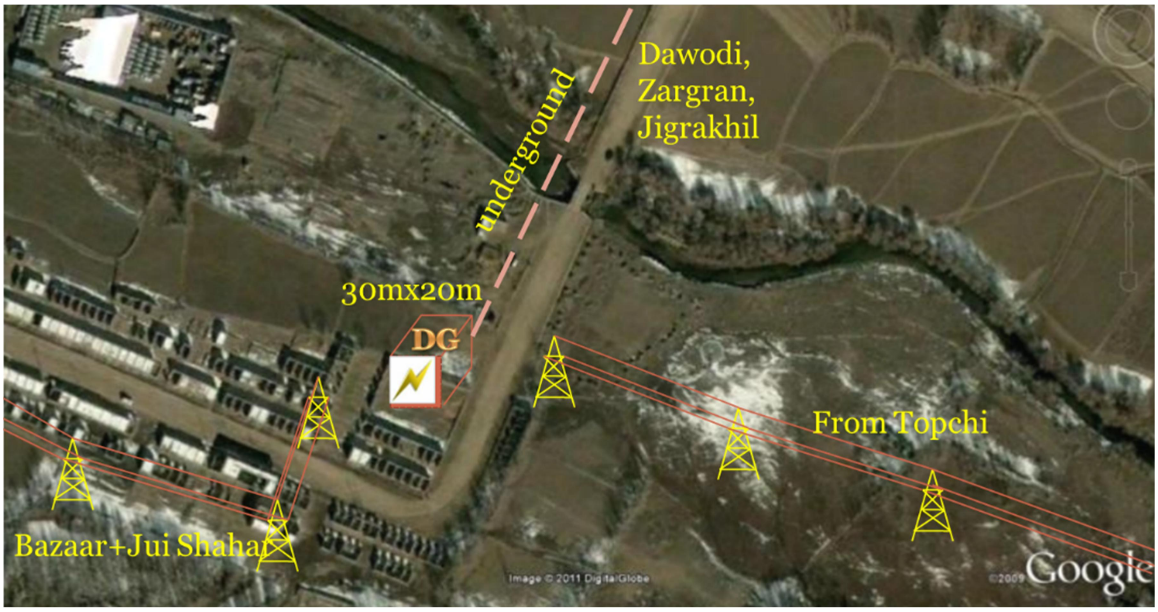


Figure 4.13: Bamyan small hydro project – *Courtesy: Distribution Design Report developed by NRECA International Ltd.*

» ***Interconnection with the main grid***

If there are plans to connect the mini-grid to a future national grid when it arrives, the mini-grid has to be designed to meet relevant national standards. Compliance with the national grid is relatively easy to accomplish and often preferable for other practical and financial reasons. Electrical contractors will already be familiar with national grid standards, for example. This will usually mean that an AC distribution grid will have to be utilised at a voltage distribution level commonly used for the national grid.

Power quality issues

- Achieving synchronisation with national grid: Matching the utility's voltage, frequency, and power quality

Institutional issues

- Compliance with national electrical standards
- Utility standard contracts
- Tariffs to expedite contracting and interconnection

Safety issues

- Compliance with national electrical codes

Stopping power supply to grid during power outages and disturbances (e.g. voltage or frequency too high or too low or phase imbalance).

PRODUCT LISTINGS

Grid-tied mini-grids should use listed equipment that is certified by a recognised organisation in accordance with designated standards (e.g. Underwriters Laboratories, American Wind Energy Association). All electrical components should comply with, or exceed, the technical specifications and be listed by a testing agency. Examples of test standards include UL, JET, and DNI; other common markings such as the European CE marking do not involve third-party testing but only show the manufacturer's declaration that a product meets the requirements of the applicable EC directives.

Common international RE electrical product test standards

- IEC 61730 Photovoltaic (PV) module safety qualification
- IEC 61215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
- IEC 61646 Thin-film terrestrial PV modules – Design qualification and type approval
- IEC 61277 Terrestrial photovoltaic (PV) power generating systems – General and guide
- IEC 61727 Photovoltaic (PV) systems – Characteristics of the utility interface
- IEC 62257 Recommendations for renewable energy and hybrid systems for rural electrification
- IEC 61400 Wind turbines
- AWEA 9.1-2009 Small Wind Turbine Performance and Safety Standard
- IEC 61741 and UL 1741 Standards for grid-tied inverters
- IEC 61730 and UL 1703 PV module safety

SYSTEM DESIGN

Key design considerations for mini-grids begin with understanding the power load and anticipated future load growth. Once loads are established, different technology options can be chosen based on available energy resources, such as the local solar or wind resource. Mini-grids present additional design and integration challenges over the conventional grid. Support of stand-alone operations requires additional hardware, notably battery banks, which can be physically quite large. Design calculations are more complex, since these systems have bidirectional power flows and multiple energy sources. This operational complexity requires extra controls and software.

When designing a renewable energy stand-alone or hybrid mini-grid, perform the following steps to assess relevant parameters:

- Assess the available RE resource (e.g. solar, wind, hydro, etc.)
- Anticipate future load growth (e.g. village growth rates)
- Conduct realistic system sizing (e.g. using HOMER software)
- Include adequate system design safety margins (e.g. IEC norms)
- Provide for a workable mini-grid power system control strategy

» ***System configurations***

Mini-grids can have three basic configurations: AC-coupled, DC-coupled, or a hybrid system with both. There are pros and cons to the different approaches and different inverter manufacturers tend to adopt one system over others. Hybrid mini-grid systems that make use of PV and wind can be added to either the DC or the AC bus.

In an AC-coupled configuration, the solar or wind system and the energy storage system each have their own inverter. These separate inverters connect to one another on the AC side of the system. The solar inverter is normally a grid-tied inverter. The separate storage (battery) inverter can be used to control battery charging and discharging. An AC-coupled configuration offers improved conversion efficiencies and equipment availability, as well as simplified system monitoring and maintenance. Conversion efficiencies are improved because the PV system connects to standard utility-interactive inverters (~95% to 98% efficiency). AC coupling does come with some drawbacks, which are related to costs, space requirements and system control. Because AC-coupled systems require two separate inverters, they are more expensive than a comparable system deployed using a single power converter.

In a DC-coupled configuration, the solar and energy storage systems share a power converter. DC-coupled systems are generally more compact with fewer pieces of equipment and controls. DC coupling can provide better system performance, since fewer power conversion steps make battery charging from a PV array more efficient. The potential drawbacks of DC coupling include limitations related to product availability and efficiencies, available converter capacity (~90% to 95%) and energy metering. The proximity of energy storage and power conversion systems relative to the RE generation source is more important in DC-coupled systems in order to reduce voltage losses and construction costs.

4.3. MINI-GRID HYBRID SYSTEMS

TOPOLOGIES

Sized and designed correctly, a mini-grid can provide the same service quality as the national grid, or sometimes even better quality in countries where power rationing and frequent blackouts are common in the national grid. Mini-grids are also scalable and can add additional generation capacity to meet growing loads.

A mix of energy sources can accommodate seasonal resource fluctuations, with solar power complementing wind generation during calm seasons with less wind, or complementing hydropower generation shortfalls during the dry season.

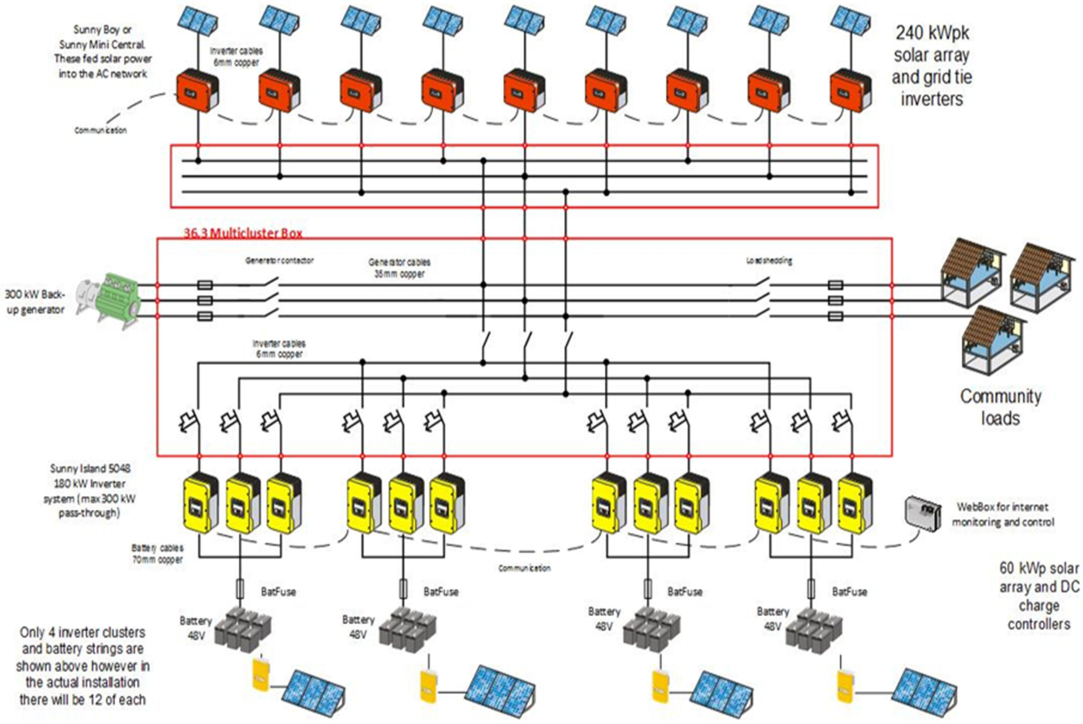


Figure 4.14: Example of solar-diesel mini-grid layout for Bamiyan, Afghanistan – *Courtesy: Robert Foster, 2015*

A long-term investment perspective for mini-grids is required for developing successful and sustainable village power and mini-grid systems.

Overall, the most important criteria for mini-grid adoption are reliability, durability and cost-effectiveness. Additional criteria may include:

- Loads: RE plants should be able to generate installed capacity to meet loads most of the time. The starting load can be small to reduce installation costs and then be scaled up as the consumption grows.
- Reduction in variable costs: Significant reduction of fossil fuel consumption
- Reduction in GHG emissions: Fulfilment of greenhouse gas obligations and/or sale of certificates
- Scalability: RE penetration rate can be scaled up as needed and systems can be scaled at all levels (DC, high voltage, etc.).
- Energy independence: RE resources are available on site and no synchronisation is required.
- Metering: Pre-paid meters and/or smart meters enable more efficient operation and easy collection.
- Planning security: Reduced fuel price volatility and delivery logistics
- Tariffs: Plant income should cover at least operation, maintenance costs and payback of loans and should generate some return on equity.
- Social aspects: Projects are socially acceptable while better for the environment.

» ***Solar mini-grids***

Mini-grids are especially well suited for integrating solar photovoltaics (PV) whether for islanded or grid-tied systems. With solar system costs dropping dramatically, mini-grids are now competitive in many on-grid and off-grid situations. Solar mini-grids typically have advanced controls capable of balancing loads and energy resources. Some hybrid systems combine PV and wind generators with batteries, inverters, and controllers, but without a fuel-based gen-set.

Solar photovoltaic (PV) systems are a cost-effective and viable solution to supply electricity to remote locations via mini-grids. PV mini-grid systems are becoming one of the most popular power systems in recent years and can be easily coupled with existing diesel grids to displace fossil fuel consumption. PV has become much more affordable since PV module prices have dropped by 80% over the past five years and are expected to drop by half again in about the next five years.

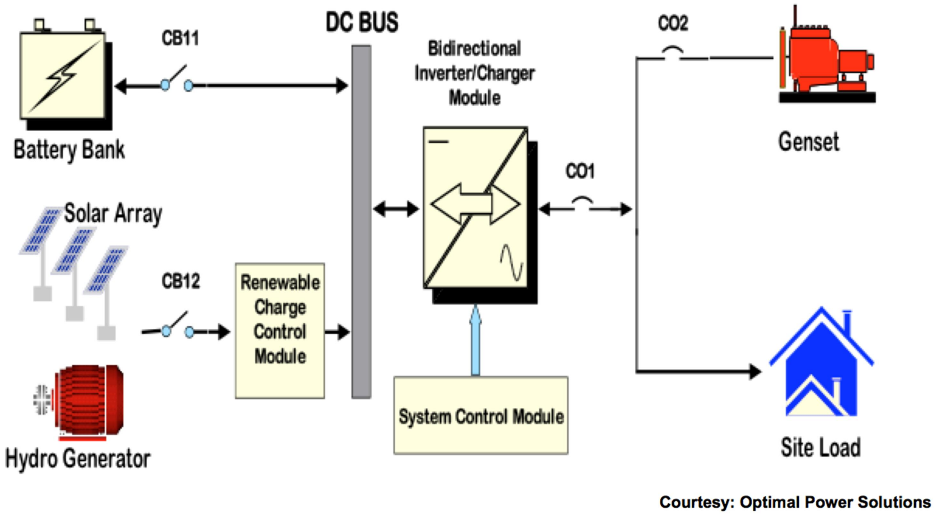


Figure 4.15: Example of a PV-diesel hybrid mini-grid – *Courtesy: Optimal Power Solutions*

General pros and cons for solar mini-grids include the following aspects:

Advantages	*Disadvantages*
• No fuel costs	• High capital costs
• Low maintenance	• Energy storage required for night-time operation
• Established supply chain	
• No GHG emissions for power generation	

» *Diesel mini-grids*

Hybrid mini-grid systems often combine fossil fuel gen-sets with one or more renewable energy electricity sources (usually solar and/or wind electric units), batteries, bi-directional inverters, and microprocessor controls. Hybrids are often competitive on a life-cycle cost of energy basis, with other options available for providing off-grid power for loads ranging from households to community services and enterprises.

Single-source diesel mini-grids have been the traditional mini-grid solution in use for decades at remote sites like islands, jungles and deserts. RE can be easily be integrated in existing diesel mini-grids and greatly reduces operational costs. Diesel gen-sets provide energy on demand, which means that they operate according to the exact needs of the user. One drawback to diesel generators is that they produce significant carbon and carcinogenic particulate emissions. They also require periodic maintenance, as well as regular cycling; but, when coupled with renewables these negative effects can be greatly reduced.

Mini-grids running completely on diesel have the advantage of being dispatchable on demand and delivering power on a schedule. However, the ability to run a diesel gen-set does not always match the availability of fuel, especially in poor rural villages with limited ability to pay. The isolated conditions of many rural areas can also make the delivery of diesel fuel an expensive challenge. In ecologically sensitive areas, the environmental impacts of potential diesel fuel spills and pollution must also be taken into account. Diesel gen-sets are noisy and polluting, and diesel fumes are known carcinogens and have direct health impacts, especially when the generators are located near residences.

There are several rationales for using hybrid (renewable/diesel) power systems in off-grid applications. These systems are integrated to optimise the overall system performance, costs, and lifetime. Where the availability of solar and energy resources is good to excellent and the delivered cost of diesel fuel is high, the combination of renewables and fossil fuels permits a significant fraction (30–80%) of the total electricity output to come from renewables without sacrificing the reliability and continuity of the electricity supply. In environmentally sensitive areas (national parks, forest reserves, ecotourism facilities, etc.), there are obvious local environmental benefits from running the diesel only a few hours each evening rather than on a continual basis.

For loads that vary significantly over 24 hours (e.g. rural communities with high evening power demands for lighting and entertainment, but lower daytime loads, often not operating air conditioners), operation in a hybrid mode permits limiting diesel run-time to a few hours at night (for powering night-time loads and charging the system batteries), rather than continuously. This limited operation time increases the chronological life of the diesel gen-set by a factor of four to ten, and increases fuel efficiency by operating the diesel gen-set at or near its rated capacity (and highest efficiency).

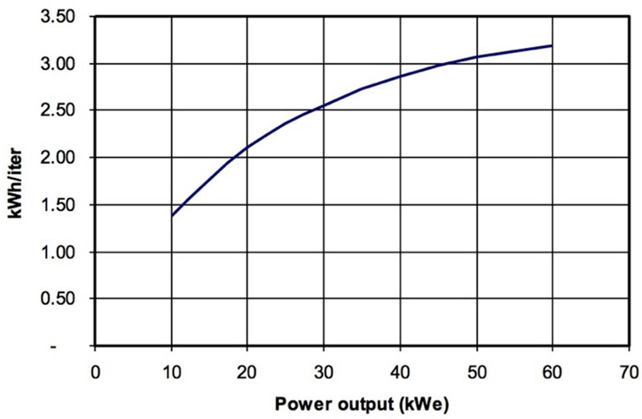


Figure 4.16: Typical efficiency curve for 60 kW diesel gen-set

As the figure below shows, the typical efficiency of a small (60 kW_e) diesel gen-set drops from roughly 3.3 kWh/litre when operated at its rated power to 1.4 kWh/litre, when operated at 10 kW_e (15% of rated power). Retrofitting an existing gen-set with the other elements of a hybrid power system can be a practical option if the gen-set is appropriately sized and in good condition or if it can be rehabilitated at an acceptable cost. Hybrids that combine PV and wind generation with batteries and inverters, but without a fossil fuel gen-set, can be practical in environments where the solar and wind resources complement each other at a reasonable level.

Advantages	***Disadvantages***
• Low capital costs • Established supply chain	• High operating fuel costs • High maintenance requirements

Advantages	*Disadvantages*
• Dispatchable power	• Complicated fuel logistics • High price volatility • High GHG and carcinogenic emissions

» *Hydro mini-grids*

Hydropower plants convert the power of flowing water into mechanical energy and when coupled to an electric generator, they can be used to produce electric power. Hydro plants were the original mini-grid and several of the earliest power plants in many countries were actually small hydro mini-grids before national grids were developed. Some have been in operation for many decades.

Small or micro hydropower is typically the most affordable RE technology for mini-grids and has been in use for over a century. It is also the most site-dependent RE technology, as the electrical power generated by a small hydropower system is directly proportional to the hydraulic head, the water flow rate, and the turbine generator efficiency. A variety of turbine types and designs have been developed to maximise overall technical and financial performance over a wide range of head and flow rate conditions. Small hydropower is a mature technology which has been installed all over the world over the past century with hundreds of thousands of systems in operation globally.

Small and micro hydropower systems can power either low- or medium-voltage mini-grids and can be used to link the power generation stations with multiple communities and load centres. If the hydro resource is adequate, this is normally the most inexpensive option for a small-scale power supply to rural communities. Micro hydropower systems are of special relevance to off-grid rural communities and enterprises. With a reliable stream or river flow, household- and village-scale hydroelectric units can provide full-time AC power, generally at costs far below those of solar, wind, or biomass power systems.

Advantages	*Disadvantages*
• Low capital costs for generation equipment • No operating fuel costs • Established supply chain in many countries • No GHG emissions for power generation	• Medium maintenance requirements • Performance dependent on seasonal water availability • Location-specific (suitable sites are limited) • Design (and possibly operation) needs to be coordinated with other water users (e.g. agriculture)

» *Wind mini-grids*

Wind-powered mini-grids have been around for over 25 years and are popular as hybrid systems coupled with other power sources like diesel or solar, though they are often used to displace diesel. Hybridisation permits extensive use of non-dispatchable renewable energy resources (sunlight, wind) within a fully dispatchable mini power plant. Depending on the wind speed in a wind/diesel hybrid unit, the contribution of wind to the output electricity can range from about 7 to 90%. On an annual basis, a hybrid plant should be designed to contribute 50 to 80% of the total energy production.

While the wind itself is free, the capture of that energy is not free and its low density means that the initial cost of wind generators is relatively high. If energy storage is needed, the initial cost can even double. Storage needs can be minimised with a wind-diesel hybrid system. Even though the wind is variable, it is statistically dependable and relatively easy to monitor.

The successful application of wind-powered mini-grids is site-specific, since wind conditions can vary dramatically from place to place. Wind resources should generally be assessed before a mini-grid system is installed. Suitable locations for wind systems are usually near mountain ranges and coastal locations with persistent trade winds.

The output of a wind generator, rotational kinetic energy, can be converted to mechanical, electrical or thermal energy. A typical wind generator used in mini-grids consists of the rotor (blades and hub), permanent magnet motors, conversion system, controls and the tower.

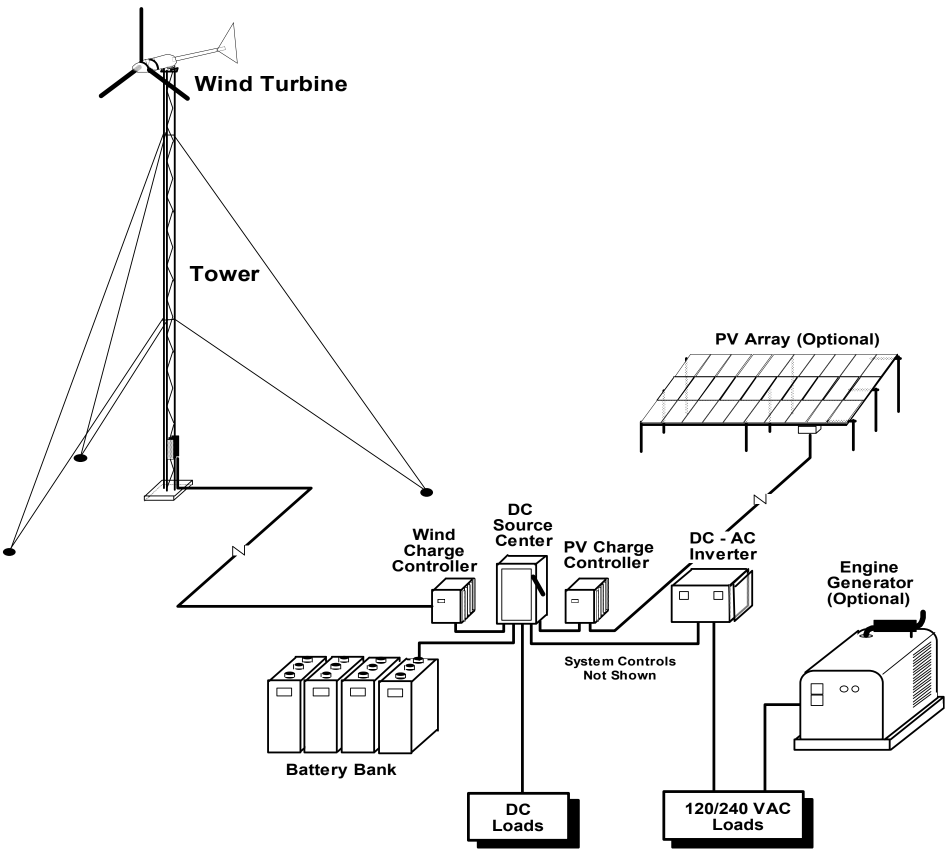


Figure 4.17: Wind-diesel hybrid system example schematic – *Courtesy: Bergey Windpower*

SMALL WIND HYBRID SYSTEMS

"Small" hybrid power systems – typically those with a daily electricity supply capacity of 50 to 500 kWh per day – generally have the "DC bus" configuration shown above. The "bus" is the electrical busbar or connection point for either DC systems (e.g. batteries, DC appliances) or AC systems (for connecting AC loads). In this illustration, the wind turbine provides power to charge a battery bank and to a bi-directional DC/AC/DC inverter to contribute to powering the load (e.g. community mini-grid). The diesel gen-set is used both to help charge the batteries and to provide AC power directly to the mini-grid.

The following figure shows the fraction of electricity provided by the wind turbine in a simulated wind-diesel hybrid plant. The mix of diesel and wind-generated electricity were calculated for a wind-diesel hybrid made up of two 7.5 kW_e Bergey Excel wind turbines, one 15 kW_e diesel gen-set, an associated battery bank, inverter and controls. As the annual average wind speed increases, the fraction of electricity provided by the wind turbines grows from roughly 5 to 90%.

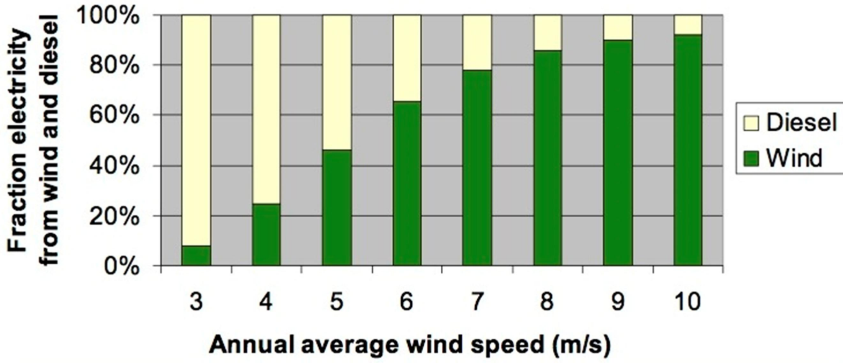


Figure 4.18: Calculated output fractions from a wind-diesel hybrid power plant

Advantages	*Disadvantages*
• No operating fuel costs • Low maintenance • No GHG emissions for power generation	• Higher maintenance requirements (rotating machinery) • Supply chain in Nigeria not established • Few qualified technicians available

» *Biomass mini-grids*

Biomass is an attractive fuel for mini-grids since it is renewable and can be locally sourced. The energy density of biomass is relatively low compared to petroleum, i.e. the yield of biomass per unit growing area of land or water is relatively small. Currently, biomass-based electricity generation is a niche market where electricity is expensive and fuel is cheap or incurs a disposal cost, e.g. waste wood, sawdust, etc. Technology options for small mini-grids using biofuel include gasifiers, digesters, and biodiesel.

Biofuels also can support local farmers and boost the local economy. Key crop considerations include water usage, fertiliser requirements and soil depletion. There are also ethical issues that come with changing land use and the use of food for fuel instead of human consumption. Intensive cultivation of biomass may place a strain on water resources, deplete soil nutrients, and disrupt land use patterns by withdrawing land from farming or natural use.

Advantages	*Disadvantages*
• Low capital costs for generation equipment • Renewable fuel supply	• Relatively high operating fuel costs • Relatively high maintenance requirements • Complicated fuel logistics if resource is not local • Poor supply chain for specialised biomass conversion equipment • High GHG emissions for power generation

» *O&M implications*

O&M requirements vary significantly for different hardware. More complicated hardware with rotating machinery requires greater maintenance than solid-state hardware like PV modules. Batteries are often the weak link and require great care in their design and operation to avoid abuse and a premature and expensive battery bank replacement. Maintenance of mini-grids is dependent on the technology employed in the system.

Table 4.3: Maintenance requirements of mini-grid system components

Component	*Maintenance requirement*
Diesel	• High maintenance • Moving machinery • Regular oil and air filter changes • Generator overhaul every ~5,000 hours for small diesel gen-sets and up to 20,000 hours for larger MW diesel units
Batteries	• Flooded lead-acid batteries require monthly fluid level checks • Sealed batteries require no regular maintenance
Inverter	• Complex power electronics can be damaged by power surges (e.g. lightning strike or system short). Proper overcurrent protection as well as system grounding and bonding are key for a long inverter life.
Solar PV	• Low O&M: Solid-state device with no moving parts
Hydropower	• Medium maintenance: Moving parts require regular lubrication
Wind	• Medium maintenance: Moving parts require regular lubrication
Biomass	• High maintenance: Cleaning and regular lubrication required

Operator training is fundamental to ensure the long-term success of the mini-grid system. Rural stakeholders do not typically have the technical know-how and experience to deal with RE technologies or power grids. They may also not be accustomed to utilising and paying for electricity. Thus, education and training are critical to the long-term sustainability of the project in the local community

HYBRID SYSTEM SIZING AND OPTIMISATION

There are a variety of techniques and software resources that can be used to size a mini-grid system. First, it is important to establish the loads that will be powered. The next step is to determine which locally available energy resources might be used to meet the load (e.g. solar, wind, hydro, and biomass). Then, based on the resource, size the appropriate power system. Common design steps for sizing a mini-grid system are as follows:

1. Establish load (kWh/day) requirements: Always try to estimate the load as precisely as possible. The penalty for over-estimation is over-investment. The penalty for under-estimation is greater fuel consumption (if there is a diesel generator).
2. Determine the monthly average renewable resource availability for the site (kWh).
3. Convert AC energy requirements to DC using balance-of-system efficiency assumptions such as:
   - Battery roundtrip net efficiency = ~60–75%
   - Inverter net efficiency = ~85%
   - Wiring net efficiency = ~97%
   - Controls/switches net efficiency = 90%
   - Generation system efficiency (technology-dependent)
   - Plant capacity factors (technology-dependent)
4. Establish site conditions and other parameters to calculate the required monthly generator performance.
5. Calculate the “load coverage (LC)” for each month.

6. Recommend an annual average LC (e.g. ~75% for hybrids with diesel back-up).
7. Iterate calculations to fit project design goals.
   - Calculate a target fraction for renewables or a minimum life-cycle cost of energy (LCoE).
8. Choose complete system architecture.
9. Size the energy storage requirements.
   - Battery-based sizing
   - Battery life is affected by depth of discharge, chemistry type
10. Weigh economic factors:
    - System design is based on a trade-off: up-front costs vs. lifetime and replacement costs
11. Consider cycle life/performance factors.
    - End-of-life considerations: Is the system recyclable? Are its components potentially hazardous to the environment?
12. Size the inverter.
13. Determine surge requirements (induction motors).
14. Size back-up generator (if needed).
    - Rule of thumb: Generator kW = 1.25 × total renewables kW
15. Complete the systems design balance.

Prepare equipment and services budget.

» *Economic factors*

A number of economic factors influence the choice to develop mini-grids in Nigeria. Mini-grids can be profitably run and can attract investments from the private sector, NGOs, commercial banks, and users themselves, and are thus less dependent than grid-based electrification on large-scale public funding for their expansion. Mini-grids can be fully subsidised, partially subsidised, or run completely for profit and return on investment (ROI). Tariff structures can likewise be subsidised or for profit.

In Nigeria, some of the key financial barriers to mini-grid financing include:

- High transaction costs
- Capital development costs
- Lack of long-term equity and financing
- Limited knowledge of and access to new technologies
- Lack of guarantees to secure investments
- Poor knowledge of the profitability of green investments
- Insufficient capacity of various stakeholders, including banks

Mini-grids require adequate structural and financing models to be successful. Hybrid RE mini-grid systems can be optimised to reduce the payback period on the investment and improve ROI.

» *System control*

A hybrid mini-grid configuration increases system complexity. Hybrid configurations integrate a variety of energy generation sources such as wind, solar, diesel, micro hydro, or biogas digesters into a DC-and/or AC-coupled grid. The various RE generators are commonly used to augment a diesel generator to reduce fuel expenditures and the diesel gen-set is often relegated to back-up use to avoid an oversized battery bank. An example mini-grid control strategy is shown in the figure below:

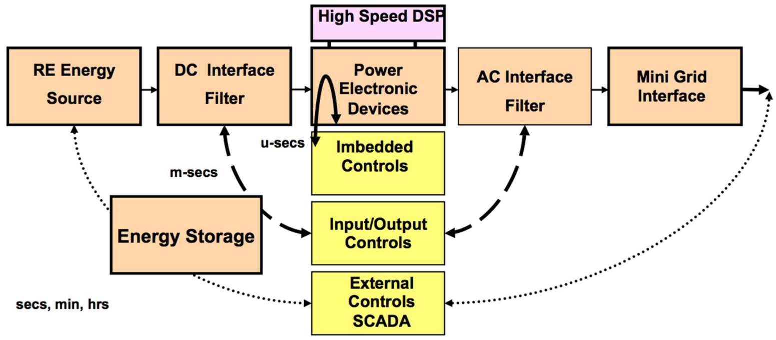


Figure 4.19: Example of a mini-grid power system control strategy

» *Software tools*

There are various software tools available to the mini-grid system designer. Each tool has its strengths and weaknesses and may be more suitable to certain systems than others. For instance, PVsyst is a tool that is mostly used by designers of grid-connected systems, but it can be used to analyse shading in an off-grid system. Another example is RETScreen, which can be used to design off-grid systems as well as to conduct the financial analysis for a proposed system. Other tools include PV*SOL, SMA Sunny Portal and HOMER. We will introduce HOMER in greater detail in the next section.

HOMER (HYBRID OPTIMISATION MODEL FOR ELECTRICAL RENEWABLES)

HOMER is a specialised software tool for micro-grid decision-making and optimisation. HOMER was originally developed by the National Renewable Energy Laboratory (NREL) 20 years ago and is now a private company. HOMER combines both engineering and economic analysis. The micro-grid optimisation software is suitable for a wide variety of systems, from small village power systems to larger island utilities, as well as both small off-grid and on-grid systems. It allows knowledgeable users to input technology choices to optimise various energy generation options based on the local energy resources (solar, wind, hydro) and configurations by modelling performance, life-cycle cost of energy, carbon emissions, etc.

HOMER simplifies the task of evaluating design options for both off-grid and grid-connected electric power systems for remote, stand-alone and distributed generation applications. HOMER's optimisation and sensitivity analysis algorithms permit the user to quickly evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. Like RETScreen, HOMER only runs on Windows-based personal computers.

HOMER provides the following:

- Simulation: The model simulates the operation of hybrid mini-grids for an entire year, with simulations lasting one minute to one hour, based on locally available renewable energy resources from the HOMER database. Users can also input their own resource data.

- Optimisation: The software examines all possible system combinations (solar, wind, diesel, hydro, gasifier, etc.) and then sorts the systems according to the optimisation of different variables.
- Sensitivity: HOMER compares thousands of possible system combinations in a single run to determine the relative importance of particular variables. It allows the user to compare a wide range of mini-grid system configurations and determine which variables and system types are of the greatest importance.

HOMER models both conventional and renewable energy technologies. The energy components modelled include the following:

- Power sources: PV, wind, micro hydro, fossil fuel generators, micro-turbines, and fuel cells
- Storage elements: Batteries and hydrogen
- Loads: Daily profiles with seasonal variation, deferrable (water pumping, refrigeration), thermal (space heating, crop drying) and efficiency measures

HOMER may be downloaded and used at no cost. Users must register with NREL to download the software. When the user installs HOMER, a free 30-day licence is automatically provided. This can be renewed at no cost an unlimited number of times. To subscribe to HOMER and receive a free 30-day trial version, as well as learn about HOMER software training dates, users can visit the HOMER website.[1]

4.4. PROTECTIVE MEASURES

FUNCTIONS OF ELECTRICAL PROTECTIVE DEVICES

» Insulation

All active bodies as conductors and connectors must be covered with an insulating material which can withstand several times the nominal operation voltage and which can only be removed by destruction. Installations with no more than 25 V_{AC} or 60 V_{DC} do not necessarily require insulation.

» Enclosures

Enclosures for components such as switches or sockets must be properly secured and removable with the use of tools. They must ensure a minimum protection class of IP2X.

» Spacing

Transmission lines must be installed so that people cannot touch them under normal operating conditions.

» RCD protection

A residual current device disconnects L from N within 0.2 seconds if there is an imbalance of more than 30 mA between L and N in a circuit. If someone touches a live conductor, for example, and current of more than 30 mA flows though his or her body, the RCD will disconnect. RCD protection always requires insulation and enclosures as parallel protective measures; it is not permitted as the sole protective measure. See explanation on residual current devices in chapter 3.2.

[1] See http://homerenergy.com

» *Automatic disconnect of power supply*

In an earthed system where the conductive housing of electrical equipment is directly connected to ground, any insulation failure that permits contact with a live housing component will result in a short circuit and the fuse or circuit breaker will interrupt the power supply. The power supply must be interrupted in under 0.4 seconds in a 240 V circuit and under 0.2 seconds in a 415 V circuit. In order to disconnect within that time period, there must be a sufficient short-circuit current flowing in the circuits. This can only be achieved if the total impedance of the circuit is low enough, which requires a low ground resistance and the correct cable cross-section with respect to the cable length. Also, the fuse or circuit breaker must have the correct rating based on the circuit impedance.

» *Double insulation*

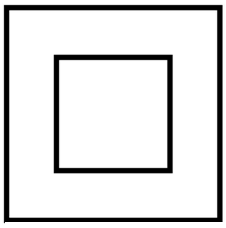


Figure 4.20: Label for double insulation

Double insulation protects from dangerous contact voltages on the equipment housing in case of faulty insulation. Double-insulated equipment requires no ground connection and receives a protection class 2 rating.

» *Protection by non-conductive spaces*

Protection by non-conductive spaces can be achieved by laying a non-conductive floor (resistance of more than 50 kΩ), which is a requirement for certain work spaces.

APPLICATION

» *Protection of conductors and electrical equipment*

Conductors get warm when electric current is flowing. Temperatures that are reached depend on:

- Current
- Cross-section
- Conductor environment (method of laying, ambient temperature)

Taking these three parameters into account, fuses or circuit breakers must be installed to protect conductors from overcurrent and overheating.

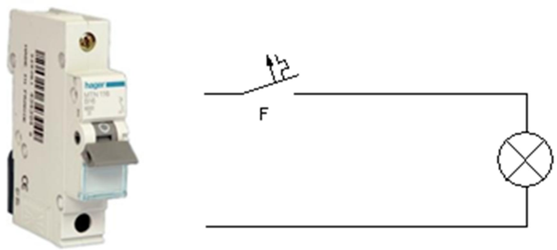


Figure 4.21: Single-pole AC circuit breaker (left), circuit drawing with breaker (right)

The relevant information for the current carrying capacity of cables can be found in the ampacity charts of the manufacturer or obtained from the regulating authorities. Below is an ampacity chart for a BS 6004 (flat grey twin + earth) cable. The fuse or circuit breaker must be rated below the current carrying capacity for the respective cable and method of laying.

Electrical consumers usually only consume excessive current when defective. Motors might increase their current consumption significantly if the motor is mechanically blocked (e.g. water pump blockage). To safeguard against dangerous overheating in defective components, many devices have an inbuilt fuse, either in the plug or inside the enclosure.

CURRENT-CARRYING CAPACITY (AMPS)						
Conductor cross sectional area	enclosed in an insulated wall		enclosed in conduit on a wall or in trunking etc.		clipped direct	
1.0mm^2	11A	10A	13A	11.5A	15A	13.5A
1.5mm^2	14A	13A	16.5A	15A	19.5A	17.5A
2.5mm^2	18.5A	17.5A	23A	20A	27A	24A
4.0mm^2	25A	23A	30A	27A	36A	32A
6.0mm^2	32A	29A	38A	34A	46A	41A
10.0mm^2	43A	39A	52A	46A	63A	57A
16.0mm^2	57A	52A	69A	62A	85A	76A

Figure 4.22: Excerpt from ampacity chart

Motor circuits should be protected with a motor circuit breaker or a thermal overload relay added at the contactor which is rated according to the nominal current of the motor. These breakers or relays protect the coils from overheating in case of problems such as overcurrent due to overload, under-voltage or the failure of a phase.

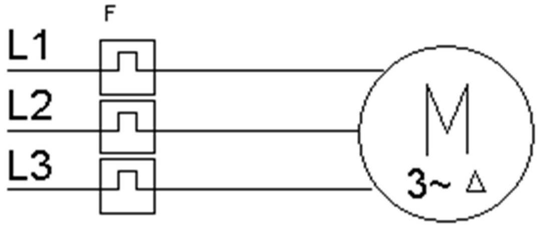


Figure 4.23: Circuit diagram showing protected 3-phase motor

» *Protection of people*

Electric current is dangerous for humans and animals for several reasons:

- All body fluids are electrolytes and conduct electric current.
- Almost all organs are controlled by electrical impulses from the brain.
- The heart works by electrical impulses which it generates independently from the brain.

The voltage impulse from the brain to control a muscle is approximately 50 mV. If an external current flows through the body, this impulse is much stronger than natural voltages generated by the brain or heart. The contracting of muscles (including the heart) also becomes much stronger, meaning that an external current takes control over both muscles and organs. This is particularly dangerous for the heart as it can start to contract according to the current frequency, which is 50 Hz for utility-grade AC. This leads to ventricular fibrillation, cardiac arrest and potentially death.

The effect of current running through the body depends on:

- Current strength
- Duration of exposure
- Pathway through the body
- Current type

Currents over 50 mA are life-threatening after 500 milliseconds if the current passes through the heart, which is often the case when the left arm is the point of contact with the dangerous voltage.

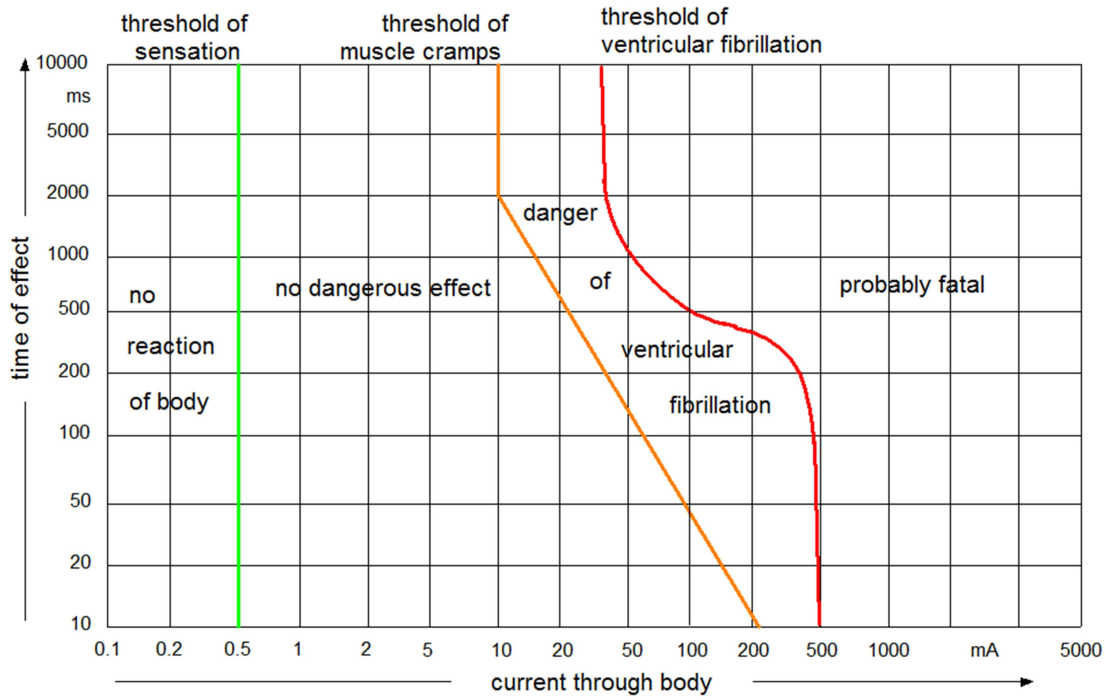


Figure 4.24: Effects of electricity on the human body as a measure of time and current

The strength of the current depends on the contact voltage and on the resistance. The resistance is the sum of all resistances the current passes through before reaching ground. This can include the resistance of the floor on which a person is standing or that of another structure he or she is touching. Different surfaces have different resistances; dry tiled flooring has a much higher resistance than wet grass, for example. The resistance of a human body can be very much influenced by the skin (dry or wet) and shoes. Safety boots with electrically resistive rubber soles have proven very effective and saved many lives in this context.

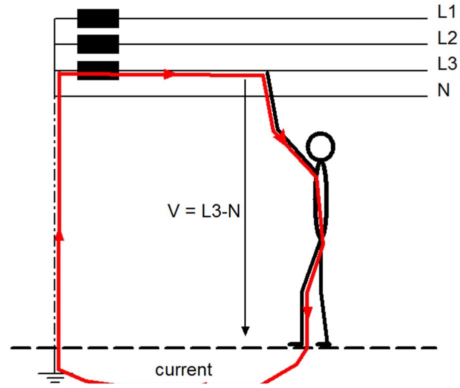


Figure 4.25: Direct contact with dangerous voltage

AC voltages of more than 50 V and DC voltages from 120 V can be life-threatening for humans; for animals just one half of these voltages can be fatal. Contact with dangerous voltages can be direct or indirect. Direct contact occurs when a person touches an electrical component or a circuit which is energised under normal operation and in proper working order (i.e. non-defective). See *Figure 4.25*.

Indirect contact occurs when a person comes into contact with dangerous voltage due an insulation failure. See *Figure 4.26*.

EARTHING

Earthing of an electrical system means connecting one of the live conductors coming from the source (transformer or generator or inverter) to earth. The term grounding is typically also used in the industry. In three-phase low-voltage systems, it is mostly the star point of the source (transformer) which is connected to earth via an earth electrode, making this conductor the neutral conductor.

One of the live conductors from a single-phase transformer is chosen, making this conductor neutral.

Connecting one of the live conductors to earth provides an additional possible pathway for the current to return to the source. This also creates the risk of electric shock.

In unearthed systems, it is possible to touch the live conductor without getting an electrical shock (see later *electrical separation*). Birds can sit on a HV line; for example, without getting harmed as current does not flow through their body (they have no path to complete the circuit).

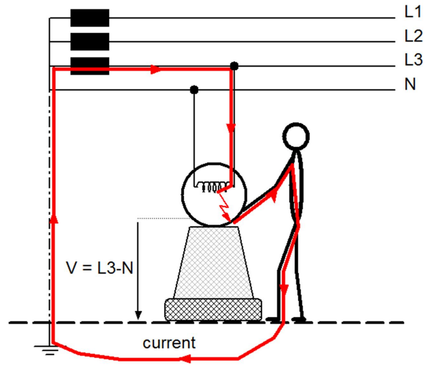


Figure 4.26: Indirect contact with dangerous voltage

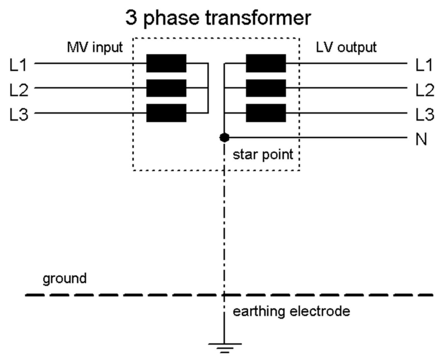


Figure 4.27: Earthing a three-phase transformer

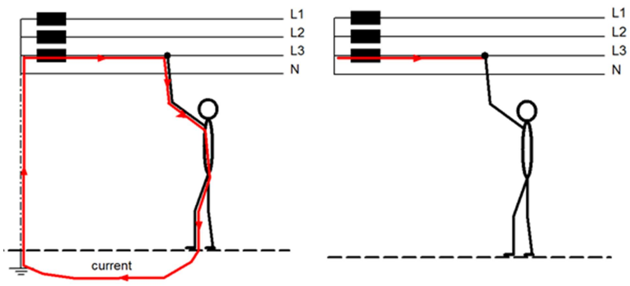


Figure 4.29: Current flow through the human body in an earthed system (left) and unearthed system (right)

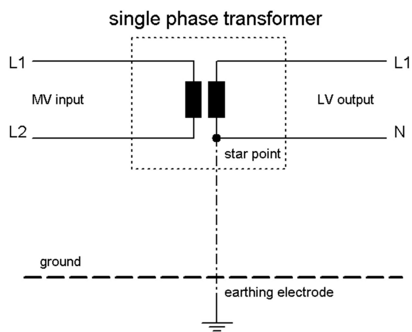


Figure 4.28: Earthing a single-phase transformer

However, earthing of an electrical system is necessary for several safety-related reasons:

- Electrostatic charging / lightning protection
- Risk of shock due to capacitive effect of unearthed lines
- Prevention of self-earthing
- Function of protective devices

Apart from the reasons above, there are also some technical reasons for earthing such as voltage stabilisation or the proper functioning of radio equipment.

ELECTROSTATIC CHARGING / LIGHTNING PROTECTION

The grid, which includes all wiring connections from the transformer coil up to the last consumer in each household, is a huge network of interconnected conductors. These conductors are subject to electrostatic charging; in large networks like those in a city, these many kilometres of conductors can accumulate an enormous electrostatic charge with a potential of several kV to earth. In an unearthed system, this charge would find its own way to earth in the form of dangerous accidental DC sparks.

When one phase from the transformer coil is connected to earth, the electrostatic charge from any of the phases can use this path to discharge into the earth. As electrostatic charge is DC, the coils of the transformer have no inductive reactance (resistance) to the direct current.

The same applies for lightning-induced overvoltage and lightning currents caused by direct lightning strikes into the line.

RISK OF SHOCK DUE TO CAPACITIVE EFFECT OF UNEARTHED LINES

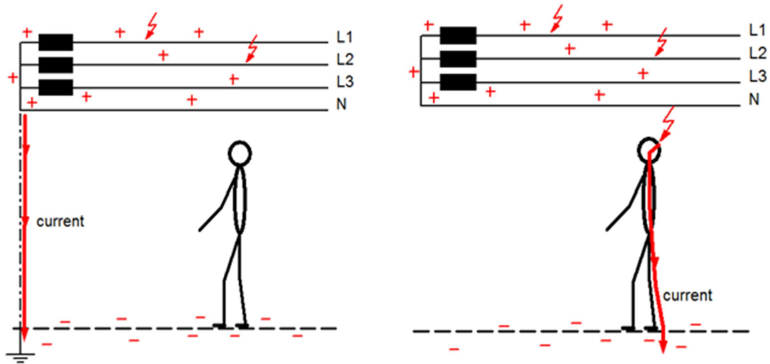


Figure 4.30: Current flow through the human body in an earthed system (left) and unearthed system (right)

In a completely unearthed system, there is theoretically no shock hazard if a person touches a live wire, as no dangerous current can flow through the body and earth and subsequently return into the coil. However, there can still be a dangerous current flow due to the capacitive effect of the lines. Each two lines of a network form a capacitor, meaning there is an electric field between them. The longer the lines, the stronger the capacitive effect. When a person touches one of the lines they create a pathway between the capacitor and earth. As the surface area of the ground can be very large, the capacitive effect to the other line(s) can be so strong that a very dangerous current will flow through the body.

SELF-EARTHING

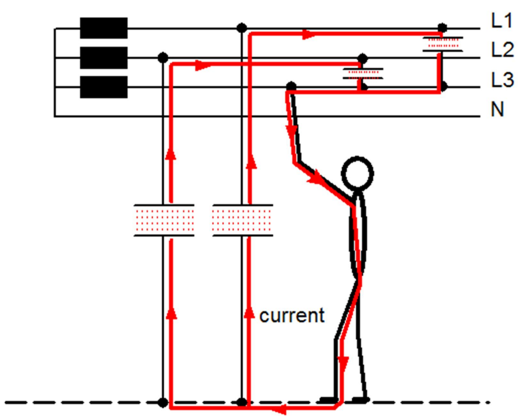


Figure 4.31: Dangerous current due to capacitive effect when touching a live line

In a large grid connecting hundreds of houses to one transformer, with each house containing several metres of wiring and many electrical devices, sooner or later accidental self-earthing will occur. This can happen because of a fault where the metal body of the device connects one phase to earth, because of a tree touching an overhead line, because of a person touching a live wire or because of many other unforeseen circumstances. This accidental earthing brings the ground to the same potential as the live wire that has been touched. No one will have noticed or gotten shocked – at least so far. There is some equipment that can detect this fault, but in a large network that connects hundreds of households with all their consumers, it will be impossible to locate. In this accidentally earthed system, if another person now touches a live wire which is not the same phase as the accidentally earthed phase, this person will get shocked.

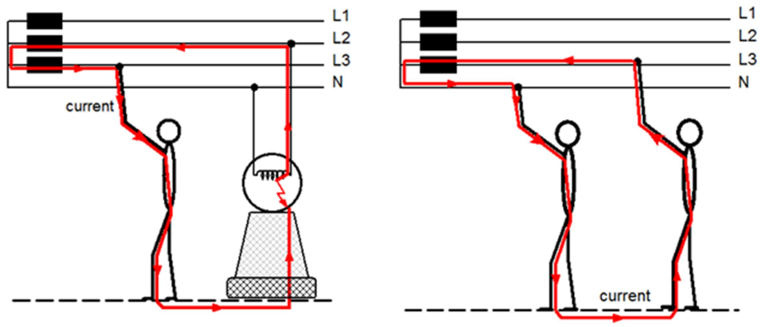


Figure 4.32: Accidental earthing by defective device (left), second person (right)

In an earthed system any insulation failure in equipment with an earthed metal body will lead to a short circuit and automatic disconnect by a fuse or circuit breaker. When the metal body of the equipment is connected to earth, the voltage when touching the equipment will always be zero. Earthing can be done via a separate earthing conductor (as in most sockets) which connects the metal body of the device direct to the next earthing electrode and to star point of the transformer.

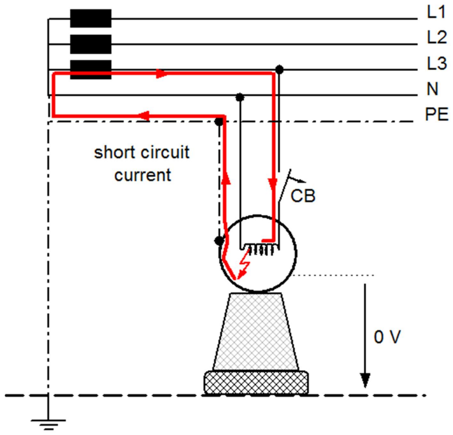


Figure 4.33: Potential across earthed equipment is always 0 volts.

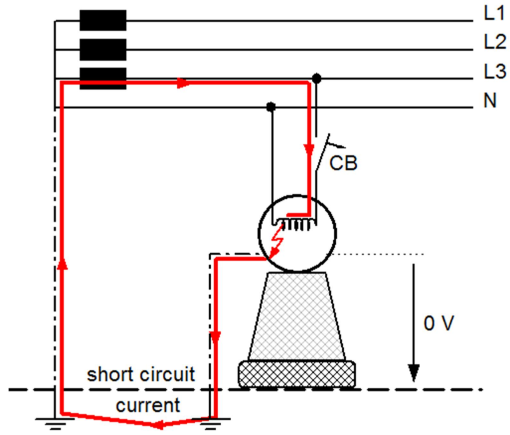


Figure 4.34: Direct earthing of equipment

Earthing can be also achieved when the equipment has its own direct connection to an earthing electrode.

Protective measures against electric shock		
• Protection against direct and indirect contact	• Protection against direct contact	• Protection against indirect contact
• xtra-low voltage (ELV) installation	• Insulation	• Automatic disconnect of power supply
	• Enclosures	• Equipotential bonding
	• Spacing	• Protective insulation
		• Non-conductive spaces
	• Added option: RCD protection	• Non-grounded local equipotential bonding

Note: Protective measures against direct contact must be applied at AC voltages above 25 V or DC voltages above 60 V.

ELECTRICAL SEPARATION

Electrical separation can be achieved by connecting equipment to the grid via an isolation transformer. In case of faulty insulation and contact with a live part in the equipment housing, there will no dangerous voltage to ground as the two-wire supply from the insulation transformer is not grounded.

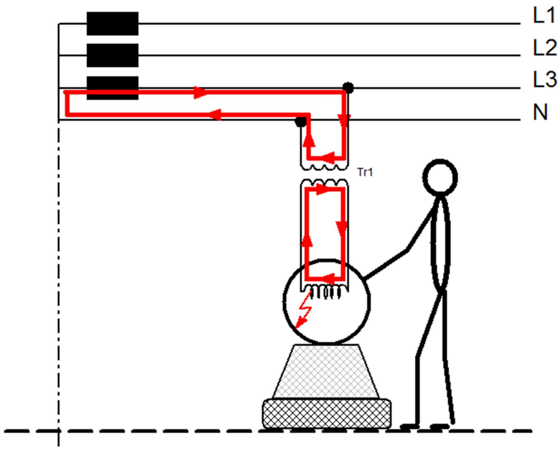


Figure 4.35: Electrical separation with isolating transformer

EQUIPOTENTIAL BONDING

All conductive housings of electrical equipment and all metallic structures of the building (e.g. water pipes) are directly connected to ground. This configuration also makes them interconnected. The potential between the housing and ground will always be zero and the risk of dangerous voltage due to contact with the housing is therefore eliminated.

NON-GROUNDED LOCAL EQUIPOTENTIAL BONDING

If more than one piece of equipment is connected to an isolation transformer, their housings must be connected to each other in order to avoid dangerous voltages in the event of an insulation failure in two or more pieces of equipment.

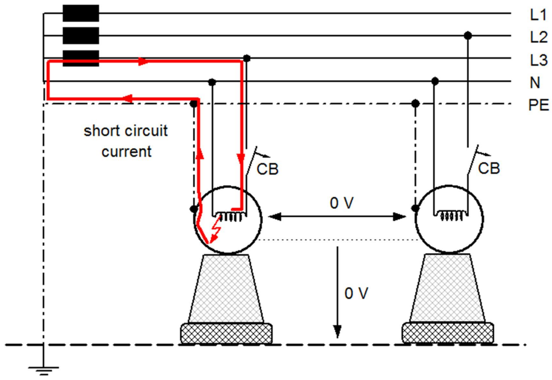


Figure 4.36: Faulty insulation in grounded equipment automatically trips circuit breaker. Potential to ground and between equipment is 0 V

4.5. METERING

Metering of energy usage for mini-grid systems has essentially leapfrogged conventional electromechanical metering technologies to take advantage of newer electronic metering equipment and solid state controls, which allow features such as pay-as-you-go (PAYG) and pre-paid meter offerings. These technologies are presented in more detail below.

When speaking about electrical energy, there are two related, yet different, measurement parameters that need to be understood: consumption and demand. Consumption is a more familiar concept for most people. Simply put, it is the total amount of energy used. Demand, on the other hand, is the immediate rate of that consumption.

Mathematically, energy consumed is represented by *kilowatt hours* (kWh). These are what the electric meter records as the dials turn. The rate of consumption (power) would be kilowatt hours per hour or just *kilowatts* (kW). Typically, electric demand is not measured for residential customers. Commercial customers, in turn, are charged for both the energy they use and the rate at which they use it. The faster the collective customer base uses energy, the more the utility must be able to supply.

The amount of energy that the system must be able to generate to meet the instantaneous load (even if only for a short duration) is called its *capacity*. This concept is also used when designing a system or building to ensure electrical distribution equipment is properly sized.

The capacity of a utility must be able to meet the demand so no customers are deprived of their electricity.

We all probably know someone who cannot turn on their toaster and microwave at the same time without blowing a fuse. This example demonstrates a circuit without the capacity to meet a specific demand. However, if these devices are operated one after the other, the required energy would be available.

» *Types of meters*

ELECTROMECHANICAL METERS

Utilities have used electromechanical meters to measure energy usage for over 100 years. Improvements in electromechanical meters over the past century have been primarily in the area of accuracy, now at 98% to 99%, and reliability, currently at 25 years or more of useful life. The electromechanical meter operates by counting the revolutions of a disc which rotates at a speed proportional to the power consumed. The number of revolutions is therefore proportional to the energy usage.

SMART METERS

Electronic meters are replacing traditional electromechanical meters in many residential, commercial and industrial applications because of the versatility, improved accuracy, and low cost afforded by electronic meter technology. This trend is also observed in Nigeria. Many circuits are now electronic with LED indicators or an LCD display. These meters are microprocessor based and have non-volatile memory to record and store energy usage data. Many electronic meters can accept several add-on modules such as a real-time clock, LCD display, communication ports/modules, etc.

» *Smart metering techniques*

Using this electronic meter platform, a number of "smart" features can be added as described below:

1. Demand metering: Demand recording, in kW or kVA, is a very low-cost upgrade available in most electronic meters.
2. Two-way and net metering: Two-way metering of energy is typically used when a distributed generation source, such as grid-connected solar system, is installed in a residence or commercial facility. The two-way meter is capable of measuring energy flowing into the facility from the grid, as well as the energy generated by the solar installation that flows out of the facility and into the utility distribution grid. The meter can also display the net energy, which is the amount of energy that flows into the facility through the meter minus the amount of energy that flowed out of the facility. Net metering is a very common feature in many rooftop solar systems now operating in Europe and America. Currently many tariffs allow for "net-zero" solar generation, which means you can produce as much energy (during the daylight hours, of course) as you draw from the utility during all other times – thus you can actually have a net meter reading of zero kWh at the end of a billing cycle. Of course there are usually service availability charges imposed by the utility so you still have to pay for the privilege of being connected to the grid.
3. Automated meter reading: Electronic smart meters are available that can transmit energy usage information back to a utility central receiving point using a low-frequency

signal injected directly into the distribution power line. This power line carrier technology can send meter readings on request, or on a periodic basis for billing purposes. Other automated meter reading technologies communicate with the smart meter and transmit energy usage information via cell phone or other communications technologies.

4. Outage management: With two-way communication to the meter, the utility can "ping" or communicate with the meter remotely and determine if there is power at the meter. Utilising outage management software that is linked via the two-way communication path, the location of meters without electricity can easily and quickly be determined in case of a power outage on the distribution system.
5. Time-of-use (TOU): Power generation and transmission costs are very dynamic and can vary significantly even over a 15-minute interval. Factors influencing the fluctuating cost of power include: cost and availability of the fuel source, cost and availability of transmission access, and constraints on the distribution system. In several countries (not currently including Nigeria), utilities are offering time-of-use (TOU) rates that reflect the varying cost of these time-dependent variables.
6. Variable rate: Advanced metering technology can be applied to a mini-grid system for innovative tariff design. For RE-based mini-grid systems, which often include a diesel gen-set, the cost of generation can vary significantly from day to day. The cost of energy generated by the solar component during a sunny day can be significantly less than the cost of operating a diesel gen-set at night; however, cloudy periods with reduced solar generation can also affect power generation costs. A variable rate tariff and corresponding metering technology could send signals to consumers to reduce energy usage during higher-cost periods, regardless of the time of day they occur.

Figure 4.37: In-home energy dashboard used by Escom, South Africa – *Courtesy: Eskom Holdings SOC Ltd, www.eskom.co.za*

To make a variable tariffs work, consumers must be notified of the dynamic rate changes. This is typically accomplished using a "dashboard" installed in the home that receives a signal from the smart meter or other communication channel indicating the change in rate. A red flashing light may indicate a high-cost energy period while a green light encourages energy usage at a lower rate. The smart meter receives the same signal and determines and reports energy usage during the variable rate periods. The simplest form of time-of-use metering is a two-tier peak/off-peak rate. For example, a utility serving primarily residential load will typically have a diurnal peak in the late afternoon when residents return home from work. This load is typically comprised of heating or cooling loads, lighting, entertainment, and cooking. The utility must invest in generation and transmission facilities to serve this peak load – even if it only lasts for a few hours of the day. Lowering this peak demand can yield significant generation and transmission cost savings to the utility. Consequently, utilities offer a time-of-use (TOU) incentive for consumers to use energy during the non-peak times and charge them more for energy used during the peak load period. Often, the peak time is static and defined as, say, 4.00 pm to 10.00 pm daily.

- Remote connect/disconnect: Smart metering technology can provide a tool to manage one of the most difficult issues related to mini-grid or conventional utility operations – that of disconnecting customers who are in default and re-connecting them once their bill has been paid. In the past, this was accomplished by sending an employee of the utility to the residence and physically removing or replacing the meter. Smart meter technologies can eliminate this labour expense.
- Pre-paid smart meters: Using the demand control feature mentioned above and a smart meter with software to alert customers when a pre-established amount of energy has been consumed, a simple pre-paid tariff can be established using smart meter technology. Various communication technologies can link pre-paid smart cards or vouchers to a reader that then accesses and controls the disconnect device. This option, which is widely used in Nigeria, is discussed in more detail below.
- Pay-as-you-go systems (PAYG): Many recent mini-grid systems are not using conventional electromechanical meters or even the previously discussed electronic smart meters but rather modern solid state electronics and communication channels to provide energy services using a system that is very similar to that of pre-paid cellular phones.

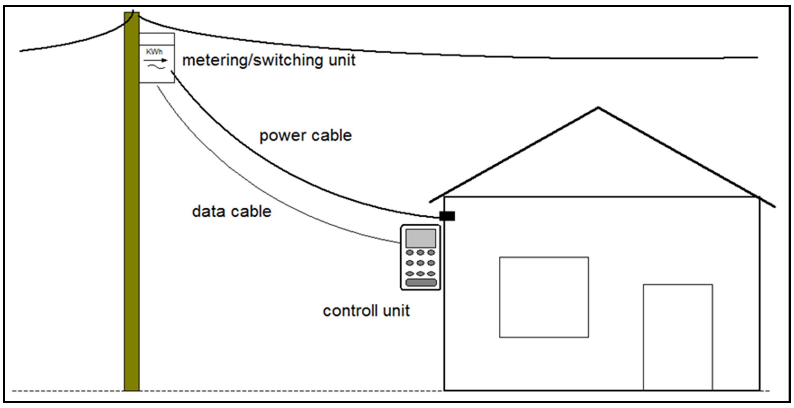


Figure 4.38: Pay-as-you-go system with major components

In a typical pay-as-you-go (PAYG) meter installed on a mini-grid distribution system, consumers purchase electricity through a smart card or a voucher using a pre-assigned pre-pay code. The amount paid, together with other information is encoded in the smart card or on the code. In order to transfer the credit, the consumer inserts the card in the PAYG meter or types the code into a small keyboard on the control unit at the home. The meter reads the data and begins recording energy usage up to the purchased limit. When the pre-purchased limit is reached, the consumer proceeds to one of perhaps several conveniently located dispensaries in the village and purchases additional energy units by reprogramming the card or purchasing a new voucher. These PAYG systems have most, if not all, of the features of previously discussed smart meters including:

- Automated energy use reporting
- Outage management
- Time-of-use rate accommodation
- Remote connect/disconnect

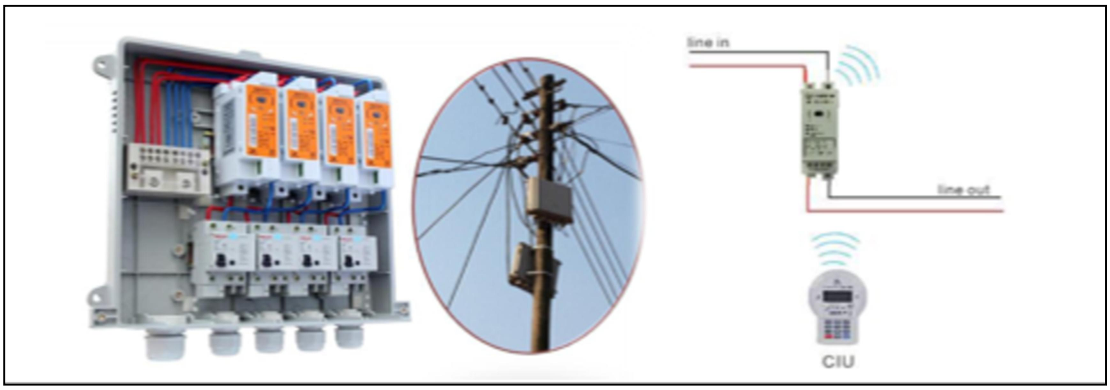


Figure 4.39: PAYG hardware mounted in a weatherproof cabinet (left) and mounted on a pole (centre) to avoid tampering. Programmable logic controller (PLC) with line in/line out (upper right) and remote programming unit (lower right)

» *Load limiters*

Load limiters are very useful devices in mini-grid systems used in rural electrification applications when local power and energy availability is limited. Load limiters can replace meters when electric energy is sold in a "flat rate" plan with a power consumption limit, for example 100 W per connection.

A load limiter is a simple electronic device using a positive temperature coefficient (PTC) thermistor to cut-out when the load exceeds a specified wattage. When the current flow through the PTC is too high, the temperature rises and, above a certain threshold, the resistance suddenly increases to values of 100 kΩ and more which, in turn, restricts the power flow – thus limiting the load. When the load is reduced, the element cools and the normal resistance is restored. If the excess load is not disconnected, the process repeats, which results in a constant on/off operation (e.g. blinking of the light bulb) until the excess load is disconnected. Load limiters are cheaper than meters and are particularly advantageous when a constant but limited power supply is available as for example from a small hydropower scheme.

Figure 4.40: 100 W load limiter with heat sink

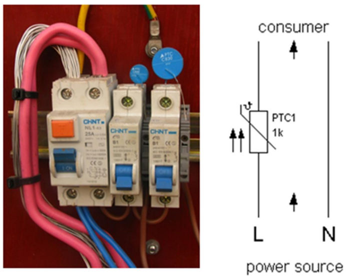


Figure 4.41: PTC thermistors in distributor boards (left), PTC in load circuit (right)

***Example:* Mini-grid with load limiters in Nepal**

In Nepal, load limiters have been used in rural electrification projects since the 1980s. They were first used in stand-alone micro hydropower projects. Load limiters are particularly appropriate for these projects because marginal operating costs are minimal; the cost of operating the plant is largely independent of how much of its capacity is used. PTC thermistors and thermal micro circuit breakers are used as load limiters and have generally been found to be reliable. Most connections are of 100 W (0.5 A) or less.

In 1989, load limiters were installed at the Andhi Khola electrification project, a 5 MW scheme that supplies electricity to the local area and sells excess power back to the grid. Rural and semi-urban consumers are supplied and more than 95% of households have a connection. Initially, there were three load limiter options: 25 W, 50 W and 250 W, with the 250 W option designed to enable consumers to use a low wattage cooker that was promoted by the project. A 100 W option has been recently introduced. Before the 100 W option was available, rural consumers generally subscribed to the 50 W load-limited supply, whereas the semi-urban consumers tended to have a 250 W load limiter or meter. The monthly costs for the load-limited supplies are USD 0.34 for 25 W, USD 0.70 for 50 W, and USD 1.90 for 250 W. The average monthly consumption of the metered consumers is 87 kWh at a cost of USD 3.70 (1994).

Each rural community served by a load-limited supply is organised in a users' group, and one member from each group is employed as a service person to collect the tariff and carry out basic repair and maintenance work. Because every household has a load limiter rather than a meter, the monthly fees are fixed. This is advantageous for the electricity company and the service person, since both know the amounts of money due from each consumer. The service person is then responsible for collecting monthly fees and for periodically depositing a predetermined sum into the local bank account of the electric utility.

Source: Case example of mini-grid project in Nepal using load limiters. The World Bank Group Energy Sector Management Programme (ESMAP) Technical Paper 007 Mini-grid Design Manual

4.6. COMMISSIONING

A mini-grid commissioning plan should be developed long before installing a system in order to ensure proper system installation and performance in line with standards. A commissioning plan can be used to verify the compliance of the as-built system with the original design. The commissioning plan is not intended to serve as a "design review" of the installed system. Commissioning is done to ensure that the system has been appropriately installed as per the original system design and drawing, and that all key components and the overall system are functioning properly. Commissioning usually involves a variety of checks and tests such as:

- Visual walk-through
- On-site safety inspection
- Generation system voltage test
- Generation system current-voltage power rating
- Battery test
- Inverter test
- Engine generator output test
- Power processing functional tests

The test results are normally written into a "commissioning results report." No testing should be performed that might alter equipment warranties. Since inverters are normally equipped with data acquisition systems, it is recommended that certain validations be confirmed by data analysis. Performing the tests in this way will enable a complete evaluation of system performance in all modes with minimal incursion into the system control structures.

» *Checklist for commissioning*

Since there are a variety of power generation technologies (e.g. solar, wind, hydro, biomass, diesel) for a mini-grid system, along with multiple variations of inverters, turbines and other component types, a "one size fits all" commissioning checklist does not exist. System commissioning needs to be done using a customised approach taking into account the specific equipment and the manufacturer's commissioning recommendations. While official commissioning formats are not specified by any national or international standards, there are general recommendations on evaluation points for mini-grid system commissioning. In any commissioning plan, it is important to pay attention to the recommended commissioning procedures for manufacturer equipment, as these vary considerably depending on the hardware used. Applicable standards require the installer to develop a customised commissioning plan appropriate to the particular system and hardware.

» *PV array commissioning and testing*

System performance is based upon how well the PV arrays supply power to the mini-grid and charge the battery banks. The tests are designed to evaluate the overall system performance.

OPEN-CIRCUIT VOLTAGE TEST (ON-SITE TEST)

An open-circuit voltage measurement of each string of the sub-array shall be obtained under clear-sky conditions with an irradiance of over 500 W/m^2. Testing will identify correct array wiring, module polarity, and open-source circuits. For any string, an open-circuit voltage deviating more than 10% from the norm will be investigated for possible cause.

PV ARRAY FIELD TESTING

In this series of tests, each of the string modules is checked for open-circuit voltage. These field tests will help indicate if one of the bypass diodes in a single module has failed in a shorted mode. Shading tests will be conducted on any under-performing strings to find the exact module and failed diode.

As you measure the string currents, also make sure to record the inverter AC power. The measurements listed below should be taken twice in order to measure the DC/AC conversion efficiency of the inverter.

- Photovoltaic temperature (°C)
- Photovoltaic array DC voltage
- Photovoltaic array DC current
- Power being delivered by PV (kW)
- Energy delivered by PV (kWh)

PV ARRAY CURRENT-VOLTAGE I-V CURVE TEST (ON-SITE TEST): ONLY POSSIBLE WITH AN APPROPRIATE I-V CURVE TRACER

I-V curves are used for two purposes: first, they show the maximum power point that each circuit can produce under the test conditions. Second, the shape of an I-V curve is useful when diagnosing problems within the circuit. The presence of weak and failed modules in the circuit results in "sags" along the curve. The I-V curve charts all possible voltage and current values, including I_{SC}, V_{OC}, I_{MPP}, and V_{MPP}, as well as calculating P_{MPP}.

A few randomly selected PV modules should be tested to verify manufacturer power claims and then normalised to standard test conditions (STC). This will help verify the module tolerance specified on the manufacturer nameplate for subsequent system testing for the manufacturer for system testing.

The I-V curves for sub-array segments will be obtained under an irradiance of at least 800 W/m^2, weather permitting. Strings with abnormal I-V curves will need to be investigated. Summation of the I-V curves for individual strings will be used to determine a full array rating. These array segment curves will be combined and normalised to give a single array rating at 1000 W/m^2 with a module temperature of 25°C.

» *Battery testing*

Best results for battery system testing are obtained if the battery bank is near full charge. The battery bank should be previously connected and equalised.

SPECIFIC GRAVITY (ON-SITE TEST)

The test team will measure and record the electrolyte temperature and specific gravity of at least 10% of the cells in the battery bank after the batteries have been at rest for at least two hours. The readings will be recorded and any variation greater than 15% highlighted.

BATTERY VOLTAGE AT REST (ON-SITE TEST)

The battery voltage of each battery bank cell is measured and recorded after the batteries have been at rest for at least two hours to reduce any surface charge. The readings will be recorded and any cell voltage variation greater than 15% highlighted.

BATTERY VOLTAGE UNDER DISCHARGE (ON-SITE TEST)

The voltage of each battery bank cell will be measured and recorded under discharge. The PV array and the generator will be disabled during this time. The maximum available site load, not to exceed 80% of nameplate rating, will be applied to the system. The readings will be recorded and any variation greater than 15% highlighted.

The following values and set points for will be obtained and evaluated each battery bank:

- Battery status indicator
- Battery temperature (°C)
- Battery DC voltage
- Battery DC current
- Power delivered by the batteries (kW)
- Voltage setting for equalise cycle
- Length of time for equalise cycle
- Voltage setting indicating fully charged battery (HVD)
- Voltage setting indicating maximum battery depth of discharge (LVD)

» *Power conditioning unit functional tests*

All power conditioning units (PCU) will be measured to determine their proper function in all modes. This includes both the sub-array string inverters and the battery inverters. Inverter DC-to-AC efficiencies, display accuracies and additional harmonic distortion tests will be conducted as permits. Determine the conversion efficiency of the string inverter under clear sky conditions (irradiance greater than 1,000 W/m^2).

There are several factors that influence the inverter's performance in converting DC power available from the array to grid-compatible AC power: conversion efficiency, MPPT capability, operating temperature, input voltage level, and power-limiting features. Simultaneous consideration of these factors, along with the electrical characteristics of the array, the available solar resource, and relevant weather data is required to verify compatibility of system components and to optimise system performance.

PCU OUTPUT (ON-SITE TEST)

The PCU output will be tested under typical maximum load conditions. The output voltage and frequency will be monitored. The readings will be recorded and any deviation from the vendor/manufacturer specifications of 15% or more will be highlighted.

The following programmable values and set points will be evaluated for each PCU:

- Inverter temperature (°C)
- Inverter phase A RMS voltage
- Inverter phase B RMS voltage
- Inverter phase C RMS voltage
- Inverter phase A RMS current
- Inverter phase B RMS current
- Inverter phase C RMS current
- Inverter real power (kW)
- Inverter reactive power (kVAR)
- Inverter energy delivered (kWh)
- Inverter frequency (Hz)

BALANCE-OF-SYSTEM (BOS) TESTING: SWITCHGEARS/WIRES (ON-SITE TEST)

All switches and disconnects will be inspected for the proper labelling of load break or non-load break components. All wiring will be inspected for correct labelling and tight connections. During the documentation review and field tests, all switchgears will be checked to ensure proper ratings. During the field test, a check will be performed to ensure that proper markings have been placed on all non-load break switches and disconnects. Proper wiring and electrical measurements for the multi-cluster box for voltages must be verified for the following:

- Phase 1 to neutral
- Phase 2 to neutral
- Phase 3 to neutral
- Phase 1 to phase 2
- Phase 2 to phase 3
- Phase 3 to phase 1

ENGINE-GENERATOR PERFORMANCE TESTING (ON-SITE TEST)

The normal output of the engine generator will be determined in the actual system configuration. The generator is typically used to power the loads, charge batteries, and provide backup power. The output of the engine generator under each mode of operation will be determined. The voltage, frequency, and harmonic distortion will be measured with the generator loaded using the available site loads, not to exceed 80% of the inverter rating.

The engine-generator PCU interface will be tested and an engine-generator start initiated. The electrical transient on the AC grid must be within a range of no more than ±10% absolute deviation from the voltage sine wave. Use the manufacturer's commissioning sheet for the generator.

The following programmable values will be evaluated for each generator:

- Generator control indicators
- Generator phase A RMS voltage
- Generator phase B RMS voltage
- Generator phase C RMS voltage
- Generator phase A RMS current
- Generator phase B RMS current
- Generator phase C RMS current
- Generator power (kW)
- Generator energy (kWh)
- Generator reactive power (kVAR)
- Generator frequency (Hz)

4.7. OPERATION AND MAINTENANCE

Good practice guidelines suggest that sustainable projects revolve around the proper operation and maintenance of a facility as indicated in Figure 4.42. Unfortunately, most projects both in Nigeria and abroad are prone to fail for lack of proper consideration of operations, maintenance and management. Project developers and stakeholders need to design and adhere to an O&M plan upon commissioning. Questions to consider within the plan include ownership of the completed project facility, for example: Will the facility be commercially operated? Will it be owned by the government, community, investors or a combination of these stakeholders? Will these factors change or remain the same in the future (i.e. in the next 10 or more years)?

STEPS, PROCEDURES AND CONSIDERATION

Routine maintenance of a facility should include monitoring, diagnosis and control to identify, rectify and minimise potential problems that may cause operational downtime. Maintenance activities are usually technical and involve fieldwork. More recently, the option of using remote data acquisition systems to gather monitoring information on a pre-emptive basis has been gaining ground – as opposed to relying on reactive maintenance once faults are present. Remote systems are geographically neutral, equipped with fault detection, GPS mapping and troubleshooting functions. However, remote monitoring systems depend on reliable Internet connectivity. Facilities in rural locations may have poor connectivity and thus problems with logging the required data for proper remote monitoring.

Operational facilities are considered assets and as such, asset management activities, mainly financial, commercial and administrative/office-based are required to ensure that energy production translates into the appropriate revenue stream.

Different technologies have different requirements for operations and maintenance (O&M). Project developers are required to customise O&M schedules to suit specific needs of the facility and technology in use. Documentation of O&M plans is advisable.

Training and skills transfer for local personnel responsible for O&M should be included in contracts with technology partners or suppliers. Personnel should be trained correctly from the outset of the project in order to perform all relevant routines and reduce the need and cost of bringing in foreign experts whenever possible. At the village level, detailed technical training for end users must cover both the applications and limits of electricity use. Health and safety measures are also important when carrying out facility maintenance activities. Industry requirements and national regulatory guidelines in Nigeria such as the Grid Code, Health and Safety Code as well as the Nigerian Electricity Health and Safety Standards Manual along with other applicable guidelines[1] should be consulted.

» *Mini-grid sustenance*

Many mini-grid systems that operate reliably feature advanced engineering for high-value applications, such as an uninterruptible power supply for remote microwave repeater stations. For less reliable or failed systems, common problems include component failure, poor or virtually non-existent maintenance, inadequate support by the supplier, and a rapid increase in electricity demand that drives the systems into a virtually pure diesel gen-set mode. In one case the latter problem was observed when poor villagers who supposedly could not pay for electricity purchased refrigerators, freezers, and colour TV sets once full-time AC power was available to them.

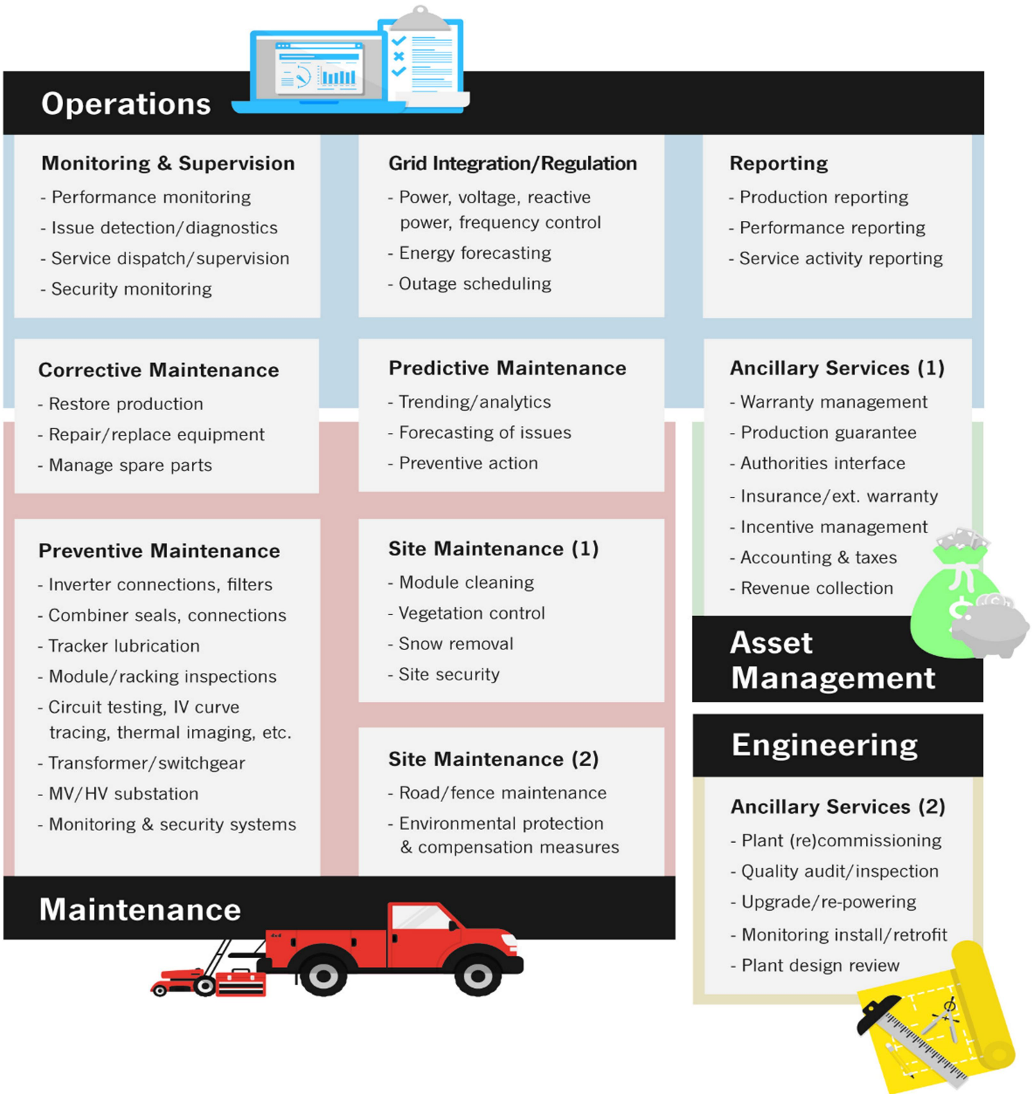


Figure 4.42: Example of O&M action point of a solar PV power plant
– *Courtesy: SoliChamba Consulting and GTM Research, "Megawatt-Scale PV Plant O&M"*

Once commissioned, hydropower and solar PV plants usually have low operation costs and require little maintenance. Costs may differ according to location, scale and technology type.

[1] Refer to NERC codes and manuals, www.nercng.org/index.php/document-library/Codes-Standards-and-Manuals/

Studies[1] have shown that small-scale hydropower operations and maintenance costs represent between 2 to 4% of total capital costs. One rule of thumb for gauging operations and maintenance costs for a power delivery system is that they should run between 1/30th and 1/8th of the total capital costs on an annual basis[2].

Example: An off-grid 4 kW$_P$ solar PV system was installed in the Genesis Academy in Kuje, Abuja, by Creeds Energy in 2013. The system for powering classrooms has a quarterly maintenance schedule:

⇒ *PV array: Verify that all panels are attached properly to mounting brackets and the roof structure or ground mount. Visually inspect the array for obvious abnormalities. Perform short-circuit current tests using a digital multimeter or volt-ohm meter to ensure that the PV array output falls within an acceptable range. Clean the photovoltaic array with a damp cloth to remove dust on a regular basis.*

⇒ *Inverter: Confirm that the inverter is producing the expected power output on the supplied meter.*

⇒ *Battery bank: Confirm that batteries are in good working condition by testing them with the multimeter. Check that the battery bank is connected in series or parallel according to the installation plan. Check that batteries are placed in a secure, dry and well-ventilated location. The first battery bank has a lifespan of two years (i.e. first replacement due in 2015).*

⇒ *Cabling: Ensure correct wire size as well as appropriate attachment and grounding.*

⇒ *Handover: Provide proper explanations and guidance on first-level troubleshooting to the facility manager who is in charge of the system on site*

Figure 4.43: PV array and battery checks

FURTHER READING

1. *"Large DC Bus Hybrid Systems for Village Power & Cell Sites", 10th Annual Small Wind Conference, Stevens Point, Wisconsin* • M. Bergey, Bergey Windpower, June 18 (2014)

2. *"Microgrids & the Ten Island Challenge", Micro-Grid Deployment Workshop, HOMER, Cancun, Quintana Roo, Mexico* • P. Boyd, Carbon War Room, November 8, 2013

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[1] See the IRENA (2014): "Operations and maintenance costs for small hydro in developing countries", IRENA Working Paper: Renewable Energy Technologies Cost Analysis Series, Volume 1, Issue 3/5 Hydropower, June 2012. www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf

[2] See USAID, Alliance for Rural Electrification (2014): "Hybrid mini-grids for rural electrification: Lessons Learned". http://ruralelec.org/sites/default/files/hybrid_mini-grids_for_rural_electrification_2014.pdf

3. *"Photovoltaics for Rural Development in Latin America: A Quarter Century of Lessons Learned"* • A. Cota and R. Foster; In Ochieng, R. M. (ed.): Solar Collectors and Panels, Theory and Applications. Rijeka: Sciyo Publishing. ISBN: 978-953-307-142-8 (2010)

4. *"Micro-Grid Transaction Acceleration,"* • M. Crowdis, Cohnreznick; Micro-Grid Deployment Workshop, HOMER, Cancun, Quintana Roo, Mexico, November 8, 2013

5. *"Bamiyan 1 MW_p Solar Mini-Grid (Afghanistan)"* • R. Foster, T. Woods and I. Hoffbeck; Solar World Congress, International Solar Energy Society (ISES), Daegu, Korea, November 9, 2015

6. *"Geothermal Energy for Village Scale,"* • R. Foster; Village Power Revisited, American Wind Energy Association, Washington D.C., December 12, 2012

7. *"Afghanistan Photovoltaic Power Applications for Rural Development,"* • R.E. Foster and A. D. Cota; Area 9.5 Modules and Systems: Off-Grid Systems, 38th IEEE Photovoltaic Specialists Conference, Austin, Texas, June 8, 2012

8. *Solar Energy, Renewable Energy and the Environment* • R. Foster, M. Ghassemi and A. Cota; In Ghassemi, A. (ed.): Energy and the Environment Series, Volume 2. Boca Raton, Florida: Taylor and Francis Publishing, CRC Press. ISBN: 13:9781420075663 (2009)

9. *"Lessons Learned from the Xcalak Village Hybrid System"* • R. E. Foster, R. C. Orozco and A. Romero; A Seven Year Retrospective", ISES Solar World Conference Proceedings, Volume I, International Solar Energy Society, Israel Ministry of Science, Jerusalem, Israel, July 7, 1999

10. *"Hybrid Energy Solutions"* • Kreagar, T., SMA America; Micro-Grid Deployment Workshop, HOMER, Cancun, Quintana Roo, Mexico, November 8, 2013

11. *"Nicaraguan Renewable Energy for Rural Zones Program Initiative"* • D. Ley, H. Martinez, E. Lara, R. Foster, and L. Estrada; Paper A185, Solar 2006, American Solar Energy Society, Denver, Colorado, July 13, 2006

12. National Electrical Code 2014, National Fire Protection Association, Quincy, Massachusetts.

13. *"Mini Grids: System Design and Energy Storage"* • S. Philips, Optimal Power Solutions; Micro-Grid Deployment Workshop, HOMER, Cancun, Quintana Roo, Mexico, November 8, 2013

14. *"The Renewable Energy Micro Grid at Punta Allen, Quintana Roo"* • A. Romero, C.V. Ecoturismo y Nuevas Tecnologías; Micro-Grid Deployment Workshop, HOMER, Cancun, Quintana Roo, Mexico, November 8, 2013

15. *"Bamiyan Small Hydro Project: Distribution System Assessment"* • O. Salinas; NRECA, Winrock International, USAID Afghanistan Clean Energy Program, Kabul, Afghanistan,May,2010

5. SOCIAL, ECONOMIC AND LEGAL FRAMEWORK

About this module

This module aims to present an overview of project planning, outline the stages of project planning, and highlight challenges likely to be faced by project planners, as well as introduce various factors that aid in successful project outcomes.

Learning outcomes

At the end of this module, the participant is able to

- Outline the procedures involved in planning RE systems
- Carry out a basic financial analysis of RE projects

5.1. POLICIES, PERMITS AND KEY INSTITUTIONS

KEY INSTITUTIONS

Various institutions are tasked with governing the activities of renewable energy and rural electrification sectors in Nigeria. The key public and private institutions that project developers liaise with during the course of planning and implementing their projects include the following:

» ***Public sector institutions***

FEDERAL MINISTRY OF POWER, WORKS AND HOUSING (FMPWH) – POWER

The FMPWH (Power) has the overall responsibility of formulating electric power policy. Its mission is to provide Nigeria with an adequate and reliable power supply by implementing power generation, transmission and distribution projects in the sector and facilitating the emergence of a private sector-led, competitive and efficient electric power industry.

The relevant departments and agencies within and under the supervision of the FMPWH (Power) include the Rural Electrification Agency (REA), National Power Training Institute of Nigeria (NAPTIN), the largely independent Nigerian Electricity Regulatory Commission (NERC), Nigerian Electricity Management Services Agency (NEMSA), and the Department for Renewable and Rural Power Access. The Ministry of Power also coordinates the Inter-Ministerial Committee on Renewable Energy and Energy Efficiency (ICREEE).

Selected mandates include:

- Conducting statutory tests and certification of electric poles (concrete, wooden, steel) and other major electrical components before they are used on the grid and networks in Nigeria
- Implementing renewable energy programmes/initiatives (solar, wind, biomass, small hydro)

RURAL ELECTRIFICATION AGENCY (REA)

The REA was first inaugurated in 2006 to rapidly expand rural and peri-urban electricity access throughout Nigeria in a cost-effective manner, employing both on-grid and off-grid options. The broad vision behind the establishment of the REA was to mobilise capital for sustained private sector-driven investment in rural electricity development in Nigeria to improve living conditions in rural areas through the enhancement of agriculture, commercial, industrial and domestic activities. The core function of the REA is to promote and support rural electrification projects of up to 1 MW capacity. It is also responsible for the Rural Electrification Policy 2009[1] and for administering the rural electrification fund (REF).

Selected mandates include:

- Providing access to reliable and affordable electricity for rural dwellers for a reasonable return on investment through an economically responsive tariff structure
- Maximising the economic, social and environmental benefits of rural electrification subsidies

To be approached for:

- Contributions to renewable energy fund by licence holders at rates to be determined by NERC

NIGERIAN ELECTRICITY REGULATORY COMMISSION (NERC)

NERC is an independent regulatory agency inaugurated in 2005 to promote and ensure an efficient market structure to meet the needs of Nigeria for safe, adequate, reliable and affordable electricity. The Renewable Energy Research and Development Division of NERC focuses on rural electrification, energy studies and various projects.

Selected mandates include:

- Setting and regulating tariffs, market rules and operating guidelines
- Issuing of licences to market participants
- Monitoring compliance

To be approached for:

- Licensing above 1 MW
- Electricity tariffs
- Renewable energy feed-in tariff
- Codes and standards
- Market rules and regulations
- Consumer protection
- Dispute resolution

FEDERAL MINISTRY OF ENVIRONMENT (FMENV)

The Federal Ministry of Environment was established in 1999 and charged with protecting the natural environment against pollution and degradation, conserving natural resources, and instituting procedures for the environmental impact assessment of all development projects. FMENV houses the Renewable Energy Programme (REP), the National Environmental Standards Regulatory and Enforcement Agency (NESREA) and the Climate Change Department.

Selected mandates include:

- Protection of the environment and natural resources in general
- Environmental stewardship, resource conservation and climate change
- Cooperation with relevant government ministries, departments and agencies, the private sector, NGOs, and international organisations on environmental matters

[1] See the section on policies and plans below for further details on the Rural Electrification Policy2009

To be approached for:

- Environmental impact assessment approval and certification
- Application for concessions (tax holiday, customs exemptions, land procurement assistance) in conjunction with the Nigerian Investment Promotion Commission

TRANSMISSION COMPANY OF NIGERIA (TCN)

The TCN provides the grid network through which power is transmitted from the electricity generation companies (GENCOs) to the electricity distribution companies (DISCOs), as well as to eligible customers and for export. Project developers need the support of the TCN for system planning and the coordination of regional interconnectors. To be approached for:

- Power evacuation studies (load flow, stability and short-circuit studies) for grid-connected power generating plants. These are a stipulated NERC licencing requirement for both renewable and non-renewable plants.
- Establishing common point of connection to grid
- Approval confirming that a proposed connection point has the capacity to handle a load which will be fed to it from a generation plant

NATIONAL BULK ELECTRICITY TRADING PLC (NBET)

NBET is the central market off-taker (or purchaser) that aims to be an effective and efficient catalyst for private sector investments in the Nigerian electricity industry. It is essentially responsible for purchasing electricity from GENCOs with long-term power purchase agreements (PPAs). As a government-owned public liability company, its PPAs with independent power producers (IPPs) are backed by credit enhancement instruments offered by the federal government.

Selected mandates include:

- Purchase and resale of electrical power and ancillary services from IPPs and from the successor generation companies

To be approached for:

- PPA negotiations for independent power production greater than 1 MW
- Submission of funding commitment
- Letter of intent issuance for PPA to be submitted to NERC

» *Private sector institutions*

ELECTRICITY DISTRIBUTION COMPANIES (DISCOS)

DISCOs are private entities that distribute and sell electricity received from the transmission grid or from an embedded generation scheme to end users. Currently, there are eleven existing DISCOs in Nigeria. Project developers may have to communicate with DISCOs depending on the structure of their power distribution plans.

To be approached for:

- Distribution negotiations
- PPA letter of intent for embedded generation

Table 5.1: Key institutions which project developers may need to approach for permits and documentation

Institution	*Description*	*Partner for*
Nigerian Electricity Management Services Agency – www.nemsa.com.ng		
Federal parastatal	• Established in 2015 for the enforcement of technical standards, technical inspections, testing and certification of electrical installations, electricity meters, instruments and commercial services in key areas of the Nigerian electricity supply industry	• Electrical Inspectorate Services for inspection, testing and certification of IPP and on-going and completed rural electrification projects
Federal Ministry of Environment – www.environment.gov.ng		
Federal ministry	• Established in 1999 • Regulator for environmental and social impact assessments (ESIAs), which are mandatory under Nigeria's EIA Act No. 86 of 1992 • Special unit for coordinating climate change matters • Special unit for renewable energy and energy efficiency; focusing on biomass use reduction and displacement	• ESIA approval and certification • Application for concessions (tax holiday, customs exemptions, land procurement assistance) in conjunction with Nigerian Investment Promotion Commission
Nigerian Electricity Regulatory Commission (NERC) – www.nercng.org		
Federal regulator	• Established in October 2005 as part of the Electric Power Sector Reform Act 2005.	• Licencing above 1 MW • DISCO tariff charges • Codes and standards • Market rules and regulations • Consumer protection • Dispute resolution
Transmission Company of Nigeria		
State entity, currently with outsourced management		• Power evacuation studies and establishing common point of connection to grid
Electricity distribution companies (DISCOs)		
Privatised companies, mostly with state shares	• See section 4.1 on the national grid	• Distribution negotiations • PPA letter of intent for embedded generation
National Bulk Electricity Trading Plc – www.nbet.com.ng		
Federal public liability company	• Incorporated in 2010 in line with the Roadmap for Power Sector Reform and the EPSR Act of 2005	• Power purchase agreement (PPA) negotiations for independent power plants greater than 1 MW • Submission of funding commitment • Letter of intent (LOI) issuance for PPA to be submitted to NERC
Rural Electrification Agency		
Federal parastatal agency under FMPWH	• Established in 2006, under Section 88 (1) of the EPSR Act	• Contribution to REF as licence holders at rates to be determined by

Institution	Description	Partner for
	of 2005 to promote rural electrification in Nigeria: • By setting up and managing the Rural Electrification Fund, • By coordinating rural electrification in the country	NERC

REGULATORY GUIDELINES FOR LICENCES

NERC is primarily in charge of licencing for generation, distribution, transmission and system operation. Below are sets of guidelines for project developers:

Generation: A generation licence authorises the licensee to construct, own, operate and maintain a generation station for the purposes of generating and supplying electricity in accordance with the Electric Power Sector Reform Act, 2005. Subject to this Act, the holder of a generation licence may sell power or ancillary services to any of the classes of persons specified in the licence. An electricity generation licence is needed for any power generation activity beyond 1 MW. A distribution licence authorises the licensee to construct, operate and maintain distribution systems and facilities.

Distribution: A distribution licensee may also have the obligation to provide electricity to its distribution customers, pursuant to the terms of a trading licence issued by NERC to the distribution licensee.

Transmission: A transmission licence authorises the licensee to carry on grid construction, operation, and maintenance of a transmission system within Nigeria, or one that connects Nigeria with a neighbouring jurisdiction subject to limitations as may be specified in the licence.

System operation: A system operation licence authorises the licensee to carry on system operation. A trading license authorises the licensee to engage in the purchasing, selling, and trading of electricity. NERC determines the terms and conditions of trading licences as may be appropriate under specific circumstances.

Prior to submitting an application to NERC, prospective license applicants should be familiar with:

- NERC Regulation for mini-grids 2016 (Draft)
- NERC Regulation on Application for Licences (generation, transmission, system operations, distribution & trading) 2010, Regulation No: NERC-R-0110A
- NERC Regulation on Licence and Operating Fees, 2006, Regulation No: NERC-R-0206
- Technology-Specific Sections of the Electric Power Sector Reform Act (EPSRA), 2005
- Section 65 (1) of the EPSRA, 2005
- Section 66 (1) of the EPSRA, 2005
- Section 67 (1) of the EPSRA, 2005
- Section 68 (1) of the EPSRA, 2005
- Section 96 (1) & (2) (c) & (d) of the EPSRA 2005

» ***NERC licensing requirements***

MINI-GRIDS BELOW 1 MW

According to NERC's draft regulation on mini-grids (2016), a *voluntary* permit is required for isolated mini-grids below 100 kW to benefit from the protection mechanisms in the regulation. On the other hand, isolated mini-grids above 100 kW must obtain an obligatory permit. To get this permit, the developer of the mini-grid shall;

- Submit an application for the intended location
- Confirm that the mini-grid shall not interfere with the expansion plans
- Ensure that the intended geographic location is an area where there is no connection to the electrical grid (unserved) and has not been assigned to another mini-grid developer
- Submit an executed agreement with the project host community to the commission for approval
- Ensure that the host community is in agreement with the installation of the mini-grid
- Ensure that all necessary land of construction and installation have been acquired
- The proposed tariff structure is based on MYTO methodology and approved by NERC
- Execute health and safety requirements as stipulated in the regulation

MINI-GRIDS ABOVE 1 MW

For grid-connected and off-grid operations above 1 megawatt (MW), there are twelve mandatory submissions common across all generation sources that need to be filed to allow for a complete licence application. These are:

- Completed application form. The form is attached as Schedule 2 of the NERC Regulation No: NERC-R-0110A document.
- Certificate of incorporation and memorandum and articles of association, or deed of partnership, or deed of trust
- Registered title deed to site, or sale agreement, or deed of assignment/gift, or evidence of submission of a titled deed to a relevant land-processing agency (as applicable)
- Tax clearance certificate for the immediately preceding three years
- Ten-year business plan
- Off-take agreement or arrangement
- Environmental impact assessment (EIA) approval certificate, or proof of submission and acceptance for processing of the EIA report to the Ministry of Environment, or details on how effluents and discharges will be managed (if proposed capacity is less than 10 MW)
- Fuel supply agreement or a letter from a fuel supplier and transporter indicating the inclusion of the fuel needs of the applicant in the supply plans of the fuel supplier and transporter
- Memorandum of understanding with or letter of intent from engineering procurement contract (EPC) contractor (if applicable)
- Memorandum of understanding with or letter of intent from the technical partner (if applicable)

- Financing agreements or letter to fund the project from financial institution(s)
- Timelines for commissioning the power plant and planned dates for commencing operations of different plant capacities

For each generation resource, specific required elements are listed within Schedule 1B of the NERC-R-0110A Regulation.

» *Licencing requirements for embedded generation*

Embedded generation is defined in NERC's regulations as "the generation of electricity that is directly connected to and evacuated through a distribution system which is connected to a transmission network operated by a System Operations Licensee", meaning the grid. Provision is also made for independent electricity distributions networks (IEDNs) that are off-grid to embed capacities above 5 MW.

The EPSR Act 2005 exempts project developers of off-grid generation systems from the need to obtain a licence. The exemptions apply to developers that:

- Construct, own or operate an undertaking for generating electricity not exceeding 1 megawatt (MW) in aggregate at a site;
- Construct, own or operate an undertaking for electricity distribution with a capacity not exceeding 100 kilowatts (KW) in aggregate at a site; or
- Such other capacity as NERC may determine from time to time.

For embedded generation/off-grid generation, NERC requires the following information:

- Total capacity per site
- Number of generating units per site
- Fuel type
- Size of generating units (MW and MVA)
- Terminal voltage
- Rated power factor
- Reactive power capacity (if any)
- Noise level
- System protection
- Waste management plan or environmental impact assessment (if required)
- Agreement or arrangement with DISCO for network use
- Manufacturer's name, year of manufacture, warranty

» *NERC licencing process*

The flowchart below provides an overview of NERC's licencing process for mini-grids above 1 MW.

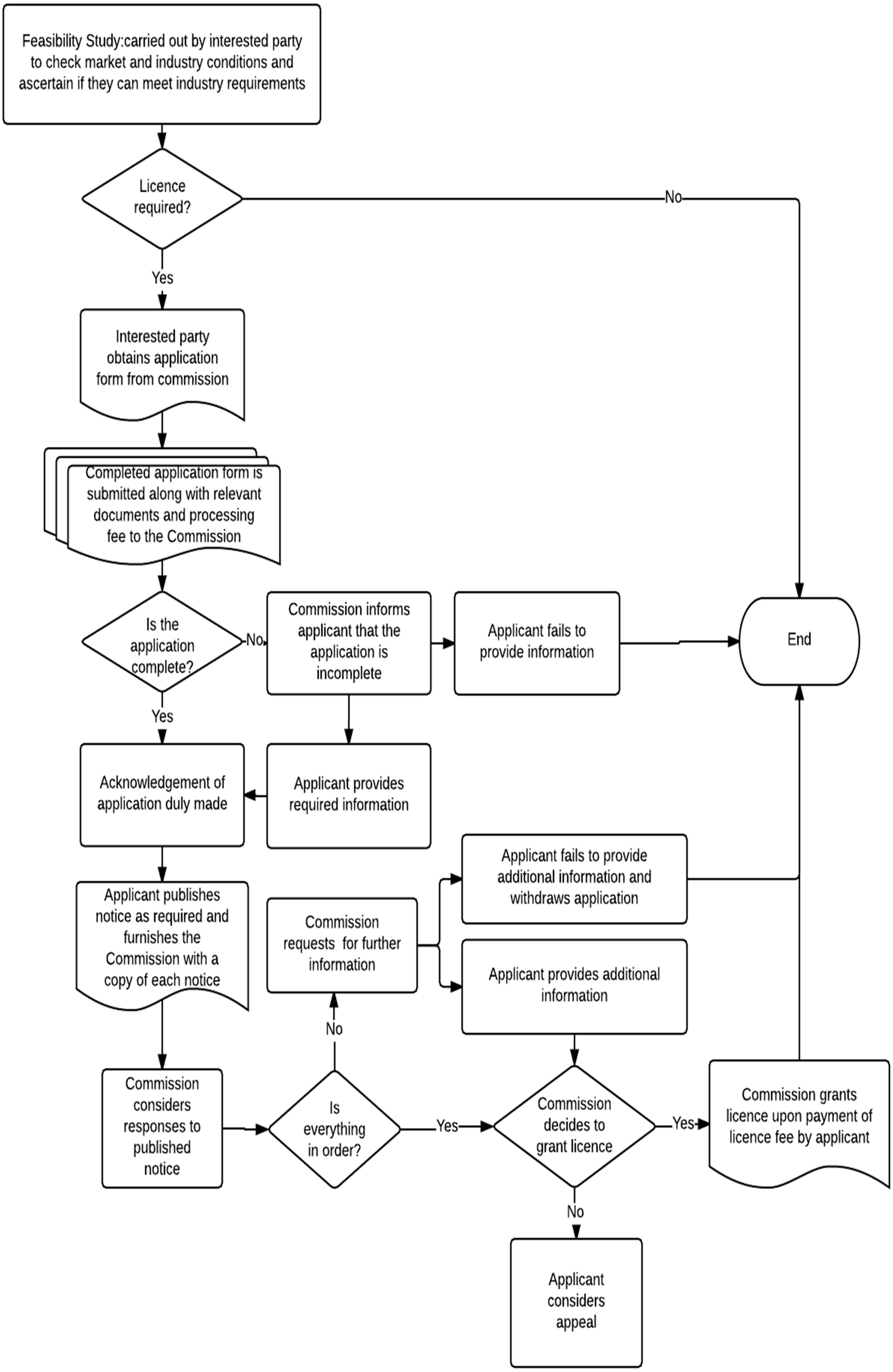

Figure 5.1: Licencing process – *Source: Handbook on Application for Licences, NERC*

Table 5.2: Timelines and cost scale for grid-connected projects

NERC requirement	Estimated time	Estimated costs	Notes
Completed application form	1 week	Low	An example of the application form can be found in Schedule 2 of NERC-R-0110A. It is important to note that this application form is crucial as a first step and must be properly completed by the applicant. Failure to complete this form correctly or completely can lead to delays in the processing and due-diligence section of the NERC audit of your application.
Certificate of incorporation and memorandum and articles of association, or deed of partnership, or deed of trust	4 to 6 weeks	Low	It is important that the directors of the company are clearly defined at this time. NERC's legal due diligence team will conduct a CAC review and any difference found in the CAC document will delay this process. It is advised that a law firm handle all documents and sections related to this section. This can increase the overall costs but will save time and money towards the end of the NERC process.
Registered title deed to site, or sale agreement, or deed of assignment/gift, or evidence of submission of a title deed to a relevant land processing agency (as applicable)	Up to 24 months	High to very high	It is strongly advised that a law firm conduct and handle this section of the application. It is strongly advised that land issues be resolved prior to the submission of the license application based on the level of due diligence conducted by NERC and their legal team.
Tax clearance certificate for the immediately preceding three (3) years	Up to 36 months	Low to high	As stated above, it is advised that auditors and tax professionals assist in this section. It may be possible to waive this section for a new entity. However, direct consultation with NERC is needed.
Ten-year business plan	3 to 6 weeks	Low	A complete business plan is required, not only by NERC but also by other agencies that are involved with the project and the project licencing process. It is highly advised that developers spend significant time on this section to ensure all aspects are properly covered to minimise any delays within this process. Schedule 1F of the NERC regulation R-0110A outlines the mandatory content required within a business plan.
Off-take agreement or arrangement	Up to 24 months	High to very high	This requirement relates to the connection type and off-taker. For grid-connected projects, this is NBET or the local distribution company. This item is often one of the very last to be submitted by the applicant.
Environmental impact	Up to 36	High to	This section should be initiated with dispatch,

NERC requirement	***Estimated time***	***Estimated costs***	***Notes***
assessment (EIA) approval certificate, or proof of submission and acceptance for processing of the report on EIA to the Federal Ministry of Environment, or details on how effluents and discharges will be managed (if proposed capacity is less than 10 MW)	months	very high	as it can encounter significant delays in dealing with various government departments, and involves significant associated costs. It is not uncommon for developers to abandon an endeavour due to this section. If not managed properly, the EIA process can be very expensive and can result in major delays. It is strongly advised that any developer at this stage properly consult with NERC and the federal ministry of environment on the exact scope of the EIA that needs to be performed. It is also critical that developers and funding institutions understand the scope of the work to be done. Developers should note that any EIA seeking foreign direct investment needs to be carried out under the system prescribed by the lender or foreign direct investment institution, such as the World Bank or the African Development Bank. The methodology differs from that incorporated in the Nigerian system. It is highly advised that an accredited firm carry out this section of the application to ensure that all policies and procedures are duly followed and that the report remains independent at all times.
Fuel supply agreement, or a letter from a fuel supplier and transporter indicating the inclusion of the fuel needs of the applicant in the supply plans of the fuel supplier and transporter	Up to 24 months	High – depending on technology type	It is important to speak with NERC on their requirements for technologies such as solar and wind. NERC may request fuel source studies, such as yield reports and/or wind maps to pass this requirement. If yield reports are not required in this section by NERC, lenders may require them for their financing agreements with the developer.
MoU with or letter of intent from engineering procurement contract (EPC) contractor (if applicable)	Up to 6 months	Medium	EPC and technical partners can be the same entity. It is important to note that NERC may request additional details of any partner presented in this section. It is advised that developers focus on securing strong partners, as they will need to be available to travel into Nigeria for various meetings throughout the development of the project.
MoU with or letter of intent from the technical partner (if applicable)	Up to 6 months	Medium	
Financing agreements or letter to fund the project from financial institution(s)	Up to 24 months after grant of license	Medium	This section can be linked to other sections within the application and can cause significant delays, especially if the funding source is not properly disclosed during the scoping meetings with NERC. All details on funding institutions need to be disclosed to NERC, which will conduct due diligence on the funding sources to verify and confirm. It is critical that the developer present a com-

NERC requirement	Estimated time	Estimated costs	Notes
			plete picture of their funding situation to allow for a smooth approval process. This section is a difficult requirement to pass and has been, in the past, a major impediment to projects seeking regulatory approval.
Timelines for commissioning the power plant and planned dates for commencing operations of different plant capacities	6 months	Medium	Linked to the MoU and LoI with technical partners and suppliers of the project. Significant delays can be encountered in this requirement if the MoU and LoI are taking considerable time to conclude.

ACTS AND POLICIES

The Nigerian renewable energy policy landscape is composed of numerous policy documents, guidelines and action plans. In 2013, the Nigerian Energy Support Programme (NESP) conducted a policy mapping study, which reviewed about 30 documents and agencies concerned with renewable energy in Nigeria. As the study notes "barriers leading to gaps and overlaps in the energy sector in Nigeria are not rooted in the limits or efficiencies of clean energy technologies, but are caused by inconsistencies in the policy, regulatory and institutional system in Nigeria". Key policies in this framework are outlined below.

» Approved documents

NATIONAL ENERGY POLICY 2003

The National Energy Policy hinges on a private sector-driven approach to promote the optimal utilisation of the nation's viable energy resources for sustainable development. The Federal Executive Council approved this policy document. Although not limited to renewable energy sources, the document sets out a range of energy sources such as hydropower, fuelwood, solar, biomass, wind and hydrogen.

Some of the policy's objectives include the achievement of national energy security with a diversified energy resource mix, in an environmentally friendly manner, and with indigenous participation as well as substantial private sector participation. In addition, the policy also states among its objectives the promotion of international cooperation in energy trade and project development in both the African region and the world at large.

The policy targets the rapid expansion of overall electricity access and rural electrification with diversified power generation sources to achieve an access rate of 75% by 2020. The Energy Commission of Nigeria (ECN), FMPWH and FMENV are the implementing bodies for the policy.

RENEWABLE ENERGY MASTER PLAN (REMP) 2005

Nigeria's Renewable Energy Master Plan identifies considerable potential for generating solar, small and large hydro, biomass, biogas, and wind energy throughout the country. REMP is solely devoted to renewable energy sources. It highlights the gradual movement from a fossil-fuel economy to one driven by an increasing share of renewable energy, as well as the need for active private sector participation. REMP 2005 is an approved document that sets out short-, medium- and long-term targets for renewable energy sources within the national energy supply mix. There is also a REMP 2012 (not approved), which is a follow-up on the recommendation of the National Energy Policy 2003.

Objectives include expanding access to energy, especially in the rural areas, increasing the scope and quality of rural services (for schools, health centres, water supply, information, entertainment) and improving learning, capacity-building, research and development related to various renewable energy technologies in the country. The ECN is the implementing agency for REMP.

RURAL ELECTRIFICATION POLICY 2009

The policy seeks to express the intention of federal government to enable greater access to electricity and to meet its 2020 rural electrification target in Nigeria. One of its key objectives is to promote more environmentally friendly alternatives to the prevalent kerosene, candle and vegetable oil lamps and fossil fuel-powered generating sets.

Like the National Energy Policy, the targets of the Rural Electrification Policy include making reliable electricity available to 75% of the population by the year 2020. In addition, it aims to utilise renewable energy resources for at least ten per cent of all new connections by 2025. The implementing bodies for this policy include the FMPWH, NERC and REA.

RURAL ELECTRIFICATION STRATEGY AND PLAN (RESP) 2015

RESP sets out how the federal government intends to accomplish the goals of the former policy and EPSR Act 2005. RESP primarily seeks to expand affordable access to energy in rural grid and off-grid locations.

Like the Rural Electrification Policy, a key objective of RESP is the promotion of cleaner power and lighting alternatives through the use of more convenient and more environmentally friendly alternatives to the prevalent kerosene, candle and vegetable oil lamps and fossil fuel-powered generating sets. The main target of RESP is to make reliable electricity available to 75% of the population (rural or urban) by 2020.

RESP was prepared for the Bureau for Public Enterprise (BPE) by the Nigeria power sector reform team. Other coordinating agencies include FMPWH, REA and NERC.

NATIONAL RENEWABLE ENERGY AND ENERGY EFFICIENCY POLICY (NREEEP) 2015

As a steering framework to boost access to and the sustainable growth of clean energy within Nigeria's energy mix, the NREEEP highlights the need for a "coordinated and comprehensive renewable energy policy linked to an equally comprehensive energy efficiency policy". It is aligned with the regional ECOWAS Renewable Energy Policy and the ECOWAS Energy Efficiency Policy, mandating the development and implementation of a National Renewable Energy Action Plan as well as a National Energy Efficiency Action Plan, both of which were drafted, approved and published as of December 2016.

Some of the objectives of the NREEEP include increasing the proportion of Nigeria's electricity generated from renewable energy sources to a level that meets or exceeds the Nigerian government's national target for renewable electricity generation for 2020 and beyond. In addition, it seeks to transform provisions for renewable electricity and energy efficiency generation activities into policy statements and district plans of states. The proposed implementing ministry for NREEEP is the FMPWH.

REGULATION ON FEED-IN TARIFF FOR RENEWABLE ENERGY SOURCED ELECTRICITY (REFIT)

Approved in December 2015 and to be enforced by NERC, the REFiT defines special tariffs for renewable energy power generation assets dependent on technology and size. These special tariffs shall be reviewed every three years, with the outcomes affecting only power generation assets that come on-stream aftterwards. By design, the REFiT targets the inclusion of up to 2 GW (10% of Nigeria's target power generation by 2020) of power generation capacity by 2020 to the national grid. The REFiT also defines the obligations of the various stakeholders as well as penalties for non-compliance.

Table 5.3: Benchmark capacities for technologies to qualify for REFiT

Technology	*Minimum capacity (MW)*	*Maximum capacity (MW)*
Solar Photovoltaic	1	5
Small hydropower	1	30
Biomass (including municipal solid waste)	1	10
Wind	1	10

The REFiT also considers hybrid renewable energy generation assets that fall within the scope for application of the special tariffs.

» *Draft documents*

REGULATION FOR MINI-GRIDS 2017

The regulation for mini-grid intended to accelerate electrification in areas without an existing distribution grid i.e. "unserved areas" and also areas with existing non-functional distribution grid i.e. "underserved areas". However, the regulation shall encourage the involvement of all stakeholders such as communities, non-governmental organisations, private sectors, etc. in achieving nationwide electrification. In addition, certain risks like sudden tariff changes, stranded mini-grid operator investment, etc.

In this regulation, mini-grids are classified into two categories based on interconnection, namely: Isolated mini-grids which are not connected to the distribution network (DISCO) and interconnected mini-grids which are connected to the distribution network.

The regulation explains the process of obtaining the necessary permits for the different classes of mini-grids based on the power generation capacity as listed below:

- Isolated mini-grids with generation capacity above 100 kW but less than 1 MW
- Isolated mini-grids of up to 100 kW distributed power
- Interconnected mini-grids

RENEWABLE ELECTRICITY ACTION PROGRAMME (REAP) 2006

REAP highlights the significance of renewable energy in adding value to the national electricity mix and the opportunity to scale up electricity access for semi-urban and rural dwellers as indicated in the National Economic Empowerment and Development Strategy (NEEDS) and targets of the former Millennium Development Goals (MDGs). REAP is a 10-year programme designed to provide a framework for the Federal Government of Nigeria to implement the renewable energy policy regulatory guidelines. The final version of the document was completed in December 2006 but is yet to be approved.

The objectives of REAP include setting achievable targets for renewable electricity and strategies for reaching those targets, establishing a funding and programme management framework, and providing a mechanism for programme monitoring and evaluation. The proposed implementing bodies for the REAP are FMPWH, Energy Commission of Nigeria (ECN), NERC and REA.

Under REAP, a series of 10-year targets for the contribution of renewable electricity to the economy (2007–2016) was defined as follows:

- 5% contribution to total electricity generating capacity, excluding large hydropower
- 735 MW cumulative renewable electricity generating capacity
- 5 TWh (terawatt-hours) of energy
- 2 million new connections
- 1 million solar home systems
- 2,000 rural solar school electrification systems
- 2,000 rural solar clinics electrification systems
- 10,000 solar street lights
- 500,000 jobs
- 100 billion Naira renewable electricity industry
- MT CO_2 emission reduction

ENVIRONMENTAL IMPACT ASSESSMENT ACT 1992

The EIA Act stipulates that any person or authority that seeks to undertake or authorise activities that may significantly affect the environment has to give due prior consideration to the environmental effects as well as the appropriate mitigation procedures.

The Department of Environmental Assessment under the Federal Ministry of Environment is responsible for enforcing laws guiding EIA projects. General principle 4 under the EIA Act states that an environmental impact assessment shall include at least the following:

- Description of the proposed activities
- Description of the potentially affected environment including specific information necessary to identify and assess the environmental effects of the proposed activities
- Description of the practical activities as appropriate
- Assessment of the likely or potential environmental impacts of the proposed activity and the alternatives, including the direct or indirect cumulative, short-term and long-term effects
- Identification and description of measures available to mitigate adverse environmental impacts of the proposed activity and assessment of those measures
- Indication of gaps in knowledge and uncertainties which may be encountered in computing the required information
- Indication of whether the environment of any other state, local government area or areas outside Nigeria is likely to be affected by the proposed activity or its alternatives
- Brief and non-technical summary of the above points

Note that the EIA Act of 1992 was amended in 2014 to incorporate strategic environmental assessment: "In line with current international best practices, the committee introduced a section of strategic environmental assessment to cover areas such as policies, plans and programmes which have long-term effects on the environment".

» *Global and regional policies*

Apart from the national policies, plans and guidelines, Nigeria has also made commitments to uphold various international policies, conventions and agreements such as the United Nations Sustainable Energy for All (SE4All) initiative which is outlined in section 1. Another such policy is the ECOWAS Renewable Energy Policy (EREP) 2012, whose vision is "to secure an increasing and comprehensive share of the Member States' energy supplies and services from timely, reliable, sufficient, cost-effective uses of renewable energy sources enabling universal access to electricity by 2030[1]".

5.2. NON-FINANCIAL APPRAISAL

ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Environmental impact assessments (EIA) are used to comprehensively measure the potential environmental consequences of a proposed project prior to the decision to implement. Environmental ethics suggest that developers take balanced decisions to promote sustainable development through the identification of appropriate enhancement and mitigation measures for the benefit of humans, existing ecosystems and future generations.

» *Technology-specific environmental impacts*

The type and intensity of environmental impacts can vary greatly depending on the specific technology used, the geographic location, and a number of other factors. By understanding the current (baseline) and potential environmental issues or changes that may occur as a result of a proposed renewable energy source, developers can take steps to effectively avoid or minimise these impacts. Some of the impacts associated with producing power from renewable wind, solar, geothermal, biomass, and hydropower can be significant and may warrant the conduct of an EIA.

Solar power: The Sun provides a tremendous resource for generating clean and sustainable electricity. The environmental impacts associated with solar power can include loss of land use, water use and habitat, as well as risks associated with hazardous materials used in manufacturing. Nevertheless, the types of impacts vary greatly depending on the scale of the system and the technology used, whether photovoltaic (PV) solar cells or concentrated solar thermal plants (CSP). One major concern is usually the disposal and recycling of storage batteries at the end of their useful life.

Hydropower: Hydropower includes both massive hydroelectric dams and small run-of-the-river plants. One environmental impact associated with hydropower dams is flooding, which destroys forest, wildlife habitat, agricultural and scenic lands. Flooding is said to cause the vegetation and soil in the area to decompose and release both carbon dioxide and methane. Furthermore, if too much water is stored behind the reservoir, the downstream river segment can dry out. Reservoir water tends to have lower oxygen and temperature levels compared to normal river water. All these factors can have adverse effects on downstream animal and plant life. Like any infrastructure project, hydropower dams are a source of greenhouse gases produced during the installation and dismantling of the plant. Global warming emissions released over the lifetime of hydroelectric plants are said to be much higher for plants built in tropical areas.

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[1] Source:www.ecreee.org/page/ecowas-renewable-energy-policy-erep

Wind power: Harnessing power from the wind is one of the cleanest and most sustainable ways to generate electricity as it produces no toxic pollution or global warming emissions. Wind is also abundant and inexhaustible, which makes it a viable and large-scale alternative to fossil fuels. Despite its vast potentials, there are a variety of environmental impacts associated with wind power generation that should be recognised and mitigated. The most widely documented impacts are birds and bats colliding with the turbines as a consequence of habitat disruption and changes in air pressure around the spinning turbines. For humans, acoustic and visual impacts have been associated with health and community concerns regarding wind farms.

Biomass for electricity: Biomass power plants share some similarities with fossil fuel power plants: Both involve the combustion of a feedstock to generate electricity. Thus, biomass plants raise similar, but not identical, concerns about air emissions and water use as fossil fuel plants. The major difference is that the feedstock of biomass plants can be sustainably produced, while fossil fuels are non-renewable. Potential biomass sources for electricity production are diverse and include energy crops (like switchgrass), agricultural waste, manure, forest products and waste, and urban waste. Both the type of feedstock and the manner in which it is developed and harvested significantly affect land use and the life-cycle greenhouse gas emissions of power produced from biomass.

» *Nigerian EIA procedure*

Nigeria's EIA Act of 1992 makes EIAs a mandatory and an integral part of the statutory approval procedure for any project that is likely to have significant effects on the environment. Power generation, transmission, mini-hydropower development and renewable energy development all fall under categories 1 and 2 as outlined in the table below.

Table 5.4: Projects where EIA is mandatory in Nigeria – *Source: FMENV, 1995*[1]

Project category	*Project type*	*Other considerations*
1	Agriculture/agro-allied, industry/manufacturing, food, beverage, tobacco processing, infrastructure: ports, housing, airport, drainage and irrigation, railway transportation, resort and recreational development, power generation, petroleum, mining, quarries, waste treatment and disposal, water supply, land reclamation and brewery	
2	Agriculture/rural development, reforestation/afforestation, small-scale irrigation, small-scale aquaculture, saw milling, logging, rubber processing, fish processing, industry/infrastructure, mini-hydropower development, any small-scale industry development (e.g. textiles), chemical industry, power transmission, renewable energy development, telecommunication facility, rural water supply, public hospitals, road rehabilitation, any form of quarry or mining	If the project is located in an environmental sensitive area such as coral reefs, mangrove swamps, small island, tropical rainforest, areas prone to erosion, mountain slope areas prone to desertification, natural conservation areas, areas with protected or endangered species, areas of scientific interest, it moves to category 1.

[1] As cited in Nwoko, Chris O. (2013): Evaluation of Environmental Impact Assessment System in Nigeria. Greener Journal of Environmental Management and Public Safety 2(1). 22–31. www.gjournals.org/GJEMPS/GJEMPS%20PDF/2013/January/Nwoko.pdf

Before the certification decision and subsequent monitoring, the Nigerian EIA procedure follows the general procedural steps of opening the proceedings, screening and/or scoping, conducting an environmental impact study and report, and preparing environmental impact statements.

The project proponent, irrespective of whether from the private or public sector, initiates the EIA process. The project proponent prepares a project description with a summary of the technical, economic and environmental features essential to the project, as well as the identification of the proposed location. The project proponent in consultation with the Federal Ministry of Environment (FMENV) selects the most suitable category for the project. Based on the category, the project either goes directly to the scoping stage (if category 1) or goes through the screening stage (if category 2).

Screening is a preliminary analysis of environmental impacts to determine whether a full-scale assessment is necessary. Scoping is carried out to determine the range of the issues to be addressed and to identify the significant issues related to the proposed action.

There is a need for public consultation at various stages of the EIA procedure. Public consultations call for the participation of affected or interested parties with regard to the proceedings and outcomes of the EIA. Interested parties include the general public, pressure groups, environmental associations, independent experts or institutions, and other local or federal authorities. There are several advantages to requesting and strengthening public participation: If the public is involved from the early stages of an EIA, additional information might be made available to the decision makers, potential environmental concerns can be voiced by affected persons, and public attitudes will become clear with regard to support for the proposed activity or resistance to it and can be dealt with accordingly. Generally, involving the public in the EIA will increase the credibility of government decision-making and help to achieve subsequent public support or acceptance of the final decision concerning the proposed activity.

Next, the FMENV decides whether an EIA is needed or not; if an EIA is required, the proponent proceeds to carry out a scoping assessment and a second round of public consultation. A draft report is then submitted to the FMENV and reviewed for adequacy. If found adequate, a third round of public consultation is carried out before the decision to approve and certify or to reject the proposal.

After certification, the project may proceed to implementation. It will still be necessary to monitor the actual developments during the preparation, implementation and operation stages of the project. By monitoring the actual impacts and results of the project and comparing them to the predictions and standards made by the EIA, it is possible to detect undesirable developments and take measures to correct, reduce and, if possible, eliminate the harmful impacts. Monitoring can be used both as a tool for post-project auditing and as a method of evaluating the quality of the EIA. Possible deficiencies of the EIA can then be recognised and avoided in the next EIA with a similar scope, thereby continuously improving the EIA procedure.

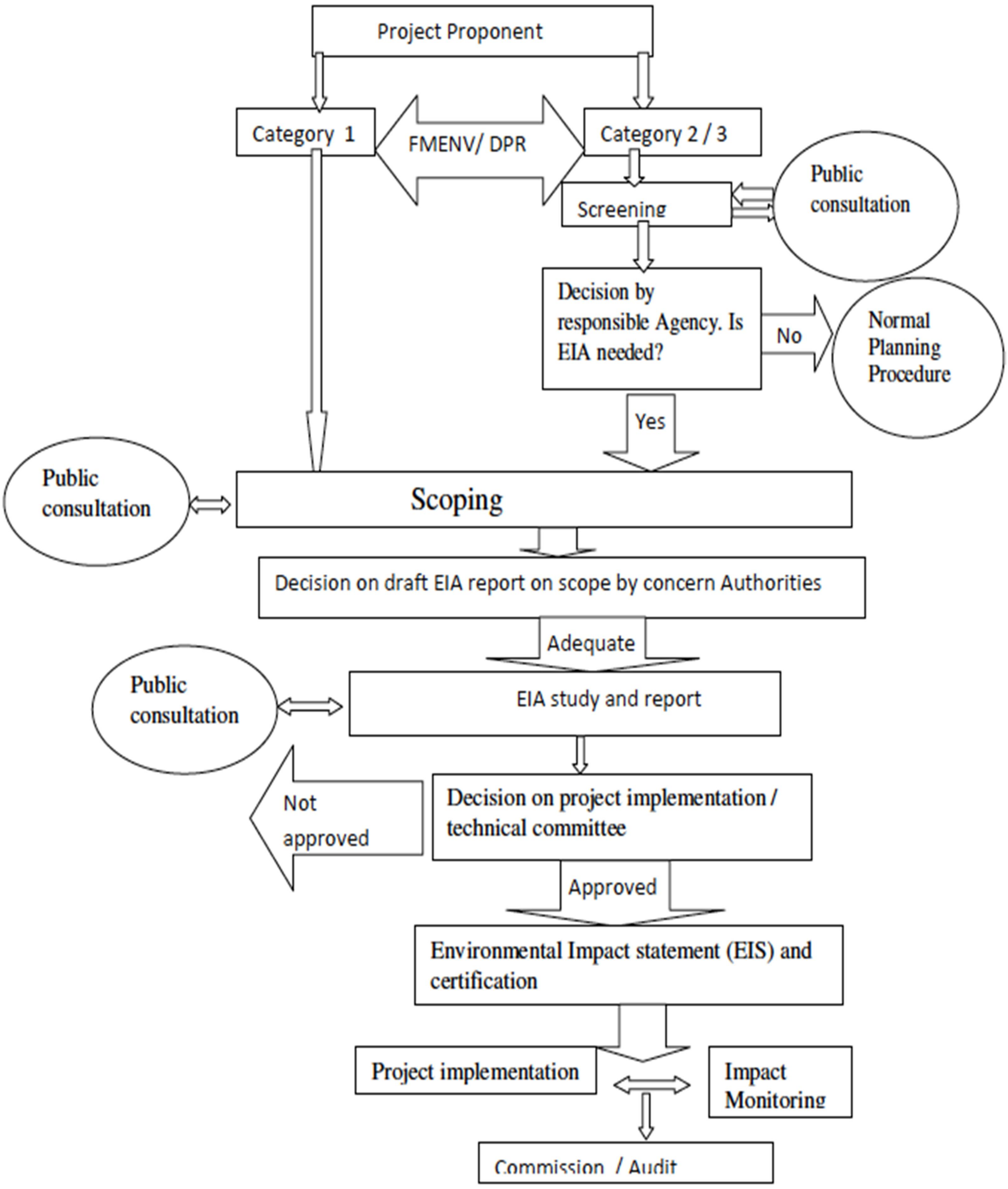

Figure 5.2: EIA procedure in Nigeria – *Source: Chris O. Nwoko*[1]

» *Best practices in EIA*

Key principles for effective EIA:

- Focus on the main issues: Stick with the most likely and serious potential impacts. Mitigation measures should focus only on workable, acceptable solutions. Conclusions of the EIA should be communicated in a concise form, including a summary relevant to the needs of decision makers.
- Involve all appropriate stakeholders: This includes those appointed to manage and undertake the EIA, those who can contribute with facts, ideas or concerns about the project (e.g. scientists, engineers, developers, policy makers, groups affected by or interested in the project), as well as those who have authority to permit, control or alter the development.

[1] Nwoko, Chris O. (2013): Evaluation of Environmental Impact Assessment System in Nigeria. Greener Journal of Environmental Management and Public Safety 2(1). 22–31. www.gjournals.org/GJEMPS/GJEMPS%20PDF/2013/January/Nwoko.pdf

- Involve stakeholders at an appropriate stage: Integrate stakeholders where they can contribute to the design and mitigation measures as they are developed. If approached too late, the developer may have to bear a costly project redesign and conflicts are likely to arise.
- Link information gained to decision-making stages: It is important that the EIA process be designed to have multiple or on-going inputs into the development of the project.
- Present clear options for managing impacts (mitigation measures): A key issue is commitments to mitigation. Are mitigation measures really going to be implemented? Will they help? Are they realistic (for example has a cost-benefit analysis been conducted)?
- Institute an environmental management plan for internal monitoring: This step is recommended for the project developer despite monitoring by the authorities.
- Provide information in a simple and useful form to decision makers and managers:

Briefly present hard facts and predictions of impacts, comment on reliability of information and summarise consequences of alternatives.

Use simple terminology and vocabulary that decision makers and those likely to be affected can understand.

Present essential findings in a brief format and support with additional materials where necessary.

Make the documentation easy to use and present information visually wherever possible.

SOCIAL IMPACT ASSESSMENT

Socio-economic impacts affect quality of life and livelihoods. Social impact assessments seek to understand those affected and their likely responses, compare identified effects with experiences in similar cases and use an appropriate expertise and knowledge base to determine mitigation measures. Best practice for social impact assessment (SIA) involves:

- Predicting adverse impacts
- Specifying impacts for individual groups
- Explaining reasons for differences between groups
- Highlighting impacts on vulnerable groups
- Guarding against representational bias – has your analysis included all groups equally?
- Forecasting likely demographic changes arising from project requirements
- There is no separate information/guideline on national requirements for project SIAs; in many instances, are a part of the EIA and are only required separately for larger international projects such as those funded the World Bank or the African Development Bank.

» Social norms

The dynamics of local cultural norms and resulting definitions of social acceptability can heavily determine whether a project succeeds or fails. Appreciating how these definitions and norms operate in different cultures, religions and ethical systems and making informed decisions from the onset is critical.

According to P.R. Shukla, "the social engineering perspective considers alternative development paths which best suit the transitional needs of a developing country while keeping in view the specificities of prevailing socio-economic dynamics"[1]. Going above and beyond a market-based "technology fix" perspective, the social engineering approach also considers socio-economic dynamics, equity and sustainability. The founder of the Colombian eco-village Gaviotas, Paolo Lugari, once said, "There is no such thing as sustainable technology or economic development without sustainable human development to match"[2].

Social engineering in project development should therefore react to human variability, which is mostly unpredictable. It is the approach one takes to deter opposition and allay concerns – either factual, emotional, or both.

A simple approach considers:

- Communication and willingness to communicate by all stakeholders involved
- Participation and suitable forms of involvement for the situation and stakeholders (passive, keeping informed, consultation, functional, informal/formal interaction)
- Expectations, both financial and non-financial, as well as gender-based expectations
- Feedback and suggestions, which should be solicited from different groups – from the elders to the laymen. Useful information is everywhere!
- Multi-dimensional thinking to prevent preconceptions or an arrogant or "know-it-all" attitude. No two communities or projects are ever the same!

» *Economic impacts*

Economic impacts are often centred on employment and the relative immigration of workers versus local employment. During project implementation, it is likely that the local population will increase and cause greater stress on local services (such as health care) and infrastructure (for example roads and sewerage). Employment opportunities will also be created. These include:

- Construction employment related to the implementation phase of the project, e.g. site clearing, EIA experts, civil works engineers
- Direct employment at the project, e.g. project manager, systems engineers, installers
- Increase in employment, if any, brought about by linkages between the proposed development and local firms, e.g. local energy service companies managing fee collections and maintenance, security companies for the site
- Possible increases in service sector employment, e.g. transportation of materials and people, hospitality and catering

The magnitude and extent of economic impacts depend on the following main factors:

- Duration of construction: Length of construction activities in terms of days, months, etc.
- Operational periods: Lifespan of facility and personnel required for operations, maintenance and management

[1] Shukla, P. R. (ed.) (1997): Energy Strategies and Greenhouse Gas Mitigation. New Delhi: Allied Publishers.

[2] Weisman, Alan (1999): Gaviotas: A Village to Reinvent the World. White River Junction, VT: Chelsea Green Publishing Company.

- Temporary workforce requirements: Skills required and number of people to be employed during each project phase
- Earnings expected: Depending on local rates, project budgets, characteristics of the local economy
- Raw materials and other inputs available for purchase locally
- Capital investments dedicated to the project development activities

5.3. COMMUNITY MOBILISATION

Community mobilisation is a core component in the successful implementation of rural electrification projects, especially where facilities are to be situated within communities. The mobilisation process can also be used as a gateway to engendering development in a range of other spheres such as women's empowerment, savings groups, water and sanitation improvements, natural resource management, improved cooking stoves and the use of biogas.

Experience shows that most communities tend to be welcoming on first approach. Central gathering points like town halls are always good locations to begin interacting with communities. Introduce yourself and engage in informal dialogue to obtain basic information.

Try to ascertain the power dynamics within the community and identify the key person(s) or groups that need to be approached formally. You may ask if it is okay to be escorted around the community to establish its suitability for a potential project, for example, as well as to gauge the social dynamics and relative security of the location. Be open with information, but do not raise expectations too much or too early. Get contact details from a point person you intend to communicate with later on. It is worth having a local person guide you through communities if you do not share a common language or traditions with the people in the community.

Mobilise community members and arrange for a more formal meeting to introduce your proposed project and your community engagement strategy. You may be able to form functional groups at this point or organise for a later meeting. Keep in mind that equitable representation is something to strive for throughout the project. The proactivity of a project developer can instil a sense of responsibility for renewable energy systems within the community.

Keep community groups involved at various stages of the project leading up to implementation. Project developers should strive to make their projects as beneficial to the local community as possible. Seeking the permission of the locals to showcase their experiences and tell their story about the project can help gain trust and support. Spreading information about their achievements as a community can also give local communities a sense of pride and strengthen their sense of responsibility for the upkeep of the project.

In Nepal, for instance, community mobilisation conducted as part of the UNDP's Rural Energy Development Programme served as an innovative and essential vehicle for self-governance to ensure active participation of local people at all levels of managing and operating rural systems, primarily micro hydropower and other community development initiatives. The programme was designed to place local communities at the centre of the process by implementing a community mobilisation process based on the four pillars of participation, transparency, consensus decision-making and inclusion. The case of scaling up decentralised energy services in Nepal certainly illustrates how support for local governance became a key enabler in the scaling up of decentralised energy services to rural areas. REDP ensured the participation of both male and female beneficiaries, transparency and consensus based on inclusive decision-making processes. Experience to date indicates that this approach was highly effective in strengthening ownership at the local level and ensuring the sustainability and cost-effectiveness of the programme's interventions and activities.[1]

In Rije, an off-grid community in Kuje, Nigeria, for example, community youth from the Osalase Youth Association were mobilised and involved in conducting energy audits for the community. Another notable example is the Roguwa community project by the UNDP in Nasarawa state, where young people were trained as installers during project implementation. This innovative approach warrants a brief case study, which is presented below.

CASE STUDY: Sustainable energy for the Roguwa community

Despite its proximity to the Federal Capital Territory, the community of Roguwa in Nasarawa state is among the many communities that do not have access to grid electricity. Travelling from Abuja to the Roguwa community only takes about one hour. The community is located in the Karu Local Government Area of Nasarawa state. Roguwa is not connected to the electricity grid, a circumstance which had forced villagers to rely heavily on local kerosene lamps and petrol generators (popularly called "I better pass my neighbour").

Figure 5.3: Roguwa community members

The inhabitants of Roguwa community are predominantly farmers. Their main source of drinking water is a commercial borehole located in a central place in the community. Many of the community members also fetch water from an open well adjacent to the Emir's palace. At the time of our visit in August 2013, the open well was drying up. In line with the UN Sustainable Energy for All (SE4ALL) initiative, the GEF-supported Nigeria Energy Efficiency Programme implemented by the UNDP and the Energy Commission of Nigeria selected the Roguwa community as a pilot site.

» *Project objectives*

The project aimed to increase access to sustainable electricity in the community in order to boost economic activities, to reduce CO_2 emissions and associated respiratory ailments among community members, to increase access to clean and potable water, to build the capacity of youths to install and maintain solar off-grid systems and to create awareness of the potential of sustainable energy in meeting national development and environmental sustainability goals.

» *Baseline economic analysis of Roguwa community*

Households and businesses in Roguwa community relied on kerosene lamps, gasoline generators and dry-cell batteries for lighting, phone charging and powering of home appliances. Individual households spend on average NGN 10,800 annually on kerosene fuel and phone

[1] UNDP (2011): "Poverty reduction – Scaling up local innovations for transformational change". New York: UNDP. www.undp.org/content/dam/undp/library/Poverty%20Reduction/Participatory%20Local%20Development/Nepal_REDP_web.pdf

charging while shops spend over NGN 100,000 per annum. In addition, the community spends NGN 750 per day (NGN 273,750 per year) on fossil fuel to run the generator which serves the water borehole. The generator will work for about six hours in a day to fill the overhead tanks with a storage capacity of 13,000 litres. The average household spends approximately NGN 10 to buy 50 litres of water. The total revenue from the sales of water in a day is NGN 2,600, with a gross profit of NGN 1,850. This equals NGN 275,250 annually.

PROJECT ACTIVITY 1: TRAINING OF COMMUNITY YOUTH

As part of the sustainability plan, a sensitisation and training workshop was organised in 2014. The workshop served as a platform to empower community stakeholders by teaching them the basic skills to install and maintain PV systems. The workshop was attended by over 180 participants. Very few women were present. Workshop attendees included the community head and religious leaders, among others. In addition to the workshop, four technicians from the community received practical training to install and maintain PV systems; they were selected by community elders to assist the Local Energy Regulatory Committee (LERC) with project management on behalf of the community.

Figure 5.4: Sensitisation and training workshop in Roguwa community

PROJECT ACTIVITY 2: PHOTOVOLTAIC INSTALLATIONS

A 4 kWP solar micro off-grid power station was installed which generates a minimum of 14 kWh daily. The plant proved sufficient to power the pump of the 13,000-litre water tank. 63 beneficiaries including households, businesses and health centres were connected and each household and shop was provided with two LED lamps for lighting and a wall socket for phone charging and low-power home appliances. Electricity is supplied to the community from dusk to dawn and water is pumped into the overhead tank for four to five hours daily. The plant requires very little maintenance, has no recurring costs and it is capable of generating a total savings of over NGN 1.6 million annually with a zero carbon footprint.

Table 5.5: Summary of beneficiaries

S/no.	Descriptions	Quantity
1	Households	50
2	Health centre	1
3	Drugstores (medicine shop)	2
4	Businesses (5 shops, 1 barber, 1 game centre, 1 discotheque)	8
5	Eatery	1
6	Shoe mender shop	1
	Total	**63**

The solar power plant is made up of 20 units of 200 W_P solar PV panels arranged in five arrays with 4 panels per array. All solar arrays were ground-mounted and tilted at angle of 15° due south of the Equator. Current limiters were installed at different points along the mini-grid. These components prevent the beneficiaries from drawing more current than the individual allocations for each household.

Figure 5.5: Solar array in Roguwa community

PROJECT ACTIVITY 3: LOCAL ENERGY REGULATORY COMMITTEE

A four-member committee called the Local Energy Regulatory Committee (LERC) was formed, with the members being nominated by community leaders and gender balance as an additional consideration. Supported by the technical team, the committee is responsible for day-to-day management of the facility. LERC collects an agreed monthly energy fee from beneficiaries, 50% of which goes to facility maintenance and up-scaling, while the other 30% is set aside as a token for the LERC members, who work on part-time basis. The cost of water shall remain unchanged and 20% of the total revenue collected shall be placed in a revolving fund.

The community was recently divided into two groups for load shedding after the community had decided to connect seven additional households. Load shedding was implemented to prolong the system battery life and to prevent over-discharge. Routine maintenance is carried out by the committee, which ensures that the following activities are performed on the system:

- Cleaning of PV modules to remove dust and bird droppings
- Cleaning the system to remove dust, insects and spider webs
- Good housekeeping of and around the system
- Assisting the project/technical officer in checking distribution lines for any fault or illegal connections of houses or appliances
- Cleaning of battery terminals

5.4. OWNERSHIP MODELS AND FUNDING

OWNERSHIP AND OPERATING MODELS

» *Private company ownership*

This model is often preferred by for-profit developers or private companies due to their financial (or near financial) viability status. They operate in a purely commercial nature as their aim is to fully cover costs and to benefit from returns made on a non-subsidised portion of capital cost. Private companies also operate as joint ventures or collaborate under a public-private partnership with the government. This model is usually adopted by large-scale, grid-connected project developers in Nigeria.

» *Community ownership*

Community-based organisations (CBOs), associations, cooperatives and micro-enterprises can be self-operated and/or self-owned. This model tends to thrive in rural communities because the community has close ties to its own members and is able to collect on due payments to keep the system running. The operating structure for community ownership/operation can be in the form of a commercial or non-commercial entity.

There are a number of different examples of the community ownership model. One is Pokhari Chauri, a rural settlement of 239 households in Kavre district, Nepal, where the community formed a cooperative – the Chauri Khola Micro-Hydro Cooperative Ltd. – to manage the system and income generated[1]. In contrast, Tungu-Kabiri community in Kenya established a commercial enterprise that owns, operates and maintains a micro hydropower plant. This complete community ownership model has been central to the project's success. A 10-member community committee manages the day-to-day operations of the plant and conducts consultations with the wider community about how the power generated should be used[2]. In Ndelle, Senegal, an off-grid village system supplying 1,200 inhabitants is also owned by the community through a village energy committee, with local technicians providing operational support.

» *Government ownership*

Governments can also take ownership and manage operations of renewable energy and rural electrification projects. Many examples exist, many of which provide electricity as a social service at no fee. One recent example is Nigeria's "Light-Up Rural Nigeria"[3] project. Global experience, however, indicates that projects owned solely by government tend to suffer from a lack of continuity and often end up poorly maintained, chiefly arising from the lack of revenue collection.

» *Mixed ownership*

This variant relies on a combination of two or more of the above-mentioned models for the ownership and management of renewable energy projects. Mixed structures tend to perform better and remain sustainable in the long term. Governments, non-governmental organisations (NGOs) and international development organisations oftentimes fund and manage projects, as was the case for Jigawa state's project where the Japanese government and United States Agency for International Development (USAID) sponsored a USD 450,000 rural electrification project. The project was implemented and maintained by the Solar Electric Light Fund (SELF), an NGO based in the USA[4].

» *Types of funding*

While a wide variety of instruments can be used to finance renewable energy projects, three categories characterise the major types: equity, debt and grant funding.

[1] See Yadoo, A. (2012): Delivery models for decentralised rural electrification. London: International Institute for Environment and Development (IIED). http://pubs.iied.org/pdfs/16032IIED.pdf (accessed Aug. 30, 2016)

[2] See Klunne, Wim J. (2007): "Small hydropower development in Africa". ESI Africa. July 31, www.esi-africa.com/small-hydropower-development-in-africa-8038/ (accessed Aug. 30, 2016)

[3] See also Premium Times (2014): "Jonathan inaugurates "Light-Up Rural Nigeria" project in Abuja", January 14. www.premiumtimesng.com/news/153317-jonathan-inaugurates-light-rural-nigeria-project-abuja.html

[4] See Omisore, Bolanle (2011): "Nigeria's solar projects yield both failure and success", National Geographic, November 3. http://news.nationalgeographic.com/news/energy/2011/11/111102-solar-power-in-nigeria/

Table 5.6: Types of funding

Type	*Risk scale*	*Level of control*
• Equity funding: An equity investment can be made in support of a specific project. Equity funds can be provided to the company carrying out the project.	• Highest risk with higher expected returns	• Equity investors maintain the right to get involved in the decision-making processes of a project or company in order to protect their investment.
• Debt funding: Lenders who provide debt financing to a project do not own shares in the project. They provide capital for the purpose of earning interest.	• Medium risk with modest expected returns	• Because lenders must be repaid before distributions can be made to shareholders, lenders bear less risk than equity holders. For this reason, the potential return to lenders is limited to risk-adjusted market interest rates.
• Grant funding: Governmental and international organisations offer grants (donations) to promote environmental and developmental policies.	• No expected returns	• Minimal or no control wielded by granting body. However, project reporting including use of funds may be required.

Renewable energy entrepreneurs, project developers and rural communities are likely to require a mixture of substantial grant (subsidies) and equity or debt financing if they are to invest in large-scale electrification infrastructure. Yet, it can be difficult to gain access to commercial financing because of the degree of risk in the early stages of project development as shown below.

At the early stages of a project, as shown in *Figure 5.6* developers rely on their own money and contributions in kind, typically labour ("sweat equity"), loans from friends and family and sometimes high net worth people ("angel investors") who believe in the potential of a project.

The intermediate stages (development and technical feasibility) require impact funding from donors, grants, subsidies, philanthropic institutions and development financiers. Both early-stage and mid-stage funding are usually sunk costs that may not be recovered before projects prove commercially viable.

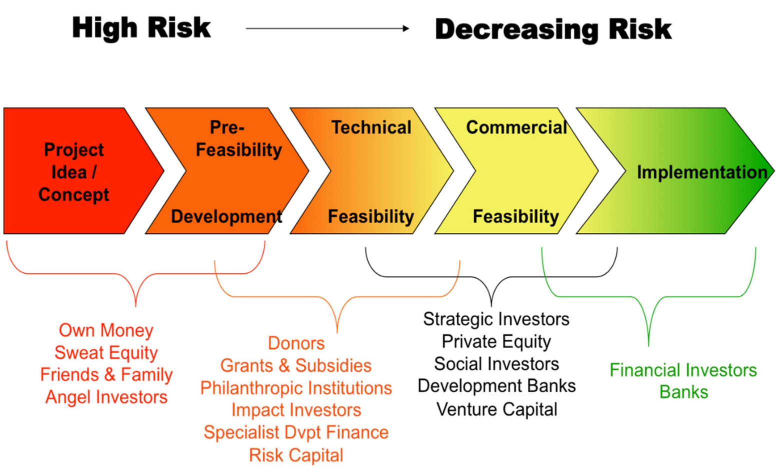

Figure 5.6: Project financing stages and sources

The commercial stage requires seed funding, equity from strategic investors, private equity, social investors, low-interest loans from development banks and venture capitalists for a return on investment.

Once the project becomes commercially viable and moves on to implementation, debt financing from financial investors and banks can be accessed.

Finding the right structure for renewable projects is about finding the right balance of risks and returns, and spreading these across the project participants.

» ***Access to project funding***

Availability of financing creates an enabling environment for renewable energy projects to develop. Potential sources of project financing include:

- International donor assistance: On medium- to large-scale projects, international entities work to improve the lending terms offered by national financial institutions. Through partial risk guarantees, grants and technical support, they assist financial lending institutions (commercial banks) in developing innovative loan products and identifying high-quality products and trustworthy developers with sound business models in whom to invest. Examples include Winrock International, Africa Development Bank and USAID.
- Micro-finance institutions: When structured to suit local situations, microfinance lending can support small-scale renewable project developers.
- Social investors: Socially motivated financing organisations improve access to funding, either through the direct provision of loans or equity financing or through technical and business support for rural energy businesses and aspiring entrepreneurs. Yet, the investment process can be slow and arduous, particularly as due diligence cannot rely on standard assessment procedures in the absence of credit histories. A successful case has been the Grameen Bank in Bangladesh which has focused on building relationships and offering collateral-free group loans, as well as aligning its overall strategy, culture and structure to fit the local situation.
- Carbon emissions financing: This form of environmental financing supports projects that reduce greenhouse gas emissions. Through joint implementation and a clean development mechanism (CDM) process, project developers can generate emissions credits for renewable energy projects that reduce emissions. Experiences have shown, however, that it is extremely difficult to make carbon financing economically viable for rural electrification projects because most of these projects remain economically unviable due to high project transaction costs (e.g. writing the project design document and conducting annual monitoring).
- Government funds and grants: The Central Bank of Nigeria MSME Fund offers funding for renewable energy and energy-efficient products and technologies. The fund combines a mixture of commercial, developmental and grant-based funding. Loans are to be managed and administered by microfinance institutions (MFIs), non-governmental organisations (NGO), financial cooperatives, deposit money banks (DMBs) and development finance institutions (DFIs). Other programmes include the Bank of Industry (BOI) Access to Renewable Energy competition.
- Crowd funding: This new public investment model has been gaining ground in the USA and elsewhere. It has been successfully applied to financing utility/commercial-scale solar projects by Mosaic, a California-based start-up company. Crowd funding is a rewards-based funding model where small amounts of equity are sold to many investors through social media with a reasonable expectation of return on investment.

5.5. PRODUCTIVE END USES

Productive end use is energy consumed for the production of goods or provision of services, with resultant income plus welfare benefits. Identifying the main productive activities at a project site is important in designing appropriate and sustainable projects. Productive uses differ widely from location to location. For instance in Nigeria, while energy and electricity may be required to support farming in the North, in the South it may be used more prevalently for fishing and aquaculture. Agro-processing is dominant in the West, markets in the East and so on. Projects designed around the needs of business tend to add significant value because they facilitate specific activities that contribute to economic and hence social advancement. Productive end uses also help generate income from the sale of electricity, thus providing a sustainable foundation for RE projects and eventually benefiting all consumers. Project developers are well advised to design their projects with productive end uses in mind for greater project sustainability on the whole.

The following points can help identify such opportunities:

- *Surveying local energy resources:* What resources are currently being used to supply energy/electricity? Why that choice? Are there waste streams that could be reused to generate energy/electricity without taking away from current use? For example, rice husks may be a good by-product for bioenergy but they are also used as animal feed.
- *Identifying existing productive activities in a project location:* Taking time to understand the local energy supply and consumption patterns as well as the peak usage periods will make it easier to design appropriate technologies.
- *Quantifying the added value gains from enhancing energy inputs for selected productive uses:* For example, if there is a market day where women sell their farm produce, what extra value will be gained by providing lighting for the market stalls to operate after dark?
- *Identifying potential socio-economic issues and/or benefits:* For example, will the standard of living improve by providing refrigeration to vendors selling fish? What spin-off effect(s) will this have on enabling new enterprises to emerge?
- *Gauging willingness to pay:* Will the user earn enough marginal income to cover operations and maintenance costs? How willing is the user to do so?
- *Identifying community champions:* Are there youths, associations and leaders within the community willing to participate as local support groups for the project? Can they be trained in first-level maintenance and security?
- Productive uses will not necessarily develop organically unless active promotion by way of awareness-raising, training, seed capital and tariff discounts is offered. Some productive uses linked to energy needs in rural communities are presented in Table 5.7

Table 5.7: Examples of productive end uses

Agriculture	*Rural businesses*	*Household*	*Community*
• Land preparation/tillage • Weeding • Harvesting • Drip-feed/sprinkler irrigation • Grain milling	• Oven cooking (bakeries) • Cooking and water heating (food kiosks, small restaurants) • Beer brewing	• Cooking • Lighting • Charging cell • phones • TV & radio	• Refrigeration of medicines and vaccines • Use of medical equipment • Lighting (medical

Agriculture	*Rural businesses*	*Household*	*Community*
• Oil pressing • Drying (fruits, vegetables, • coffee, tea, meat, fish, spices) • Smoking (fish, meat, cheese) • Food and drink cooling (e.g. milk chilling and pasteurisation) • Ice-making (fish storage) • Water heating (e.g. textile • dying, separating nut kernels) • Sawmilling • Electric fencing • Improved warehousing • Fish hatcheries and fish • Farms (water circulation and purification) • Lighting (e.g. to increase night growth in nurseries)	• Grinding • Compressors, welding (vehicle repair) • Drilling & cutting, welding, use of lathes and mills (metal workshops) • Refrigeration, freezing, lighting (shops) • Colour TV, lighting (bars) • Use of electrical cosmetic • appliances (barbers) • Charging batteries/cell phones • Cutting and filing (carpentry, crafts) • Use of sewing machines (clothing outlets) and possibly power looms • Use of computers/printers (internet cafés)	• Use of sewing • machines • Fans • Refrigeration	clinics, especially for night births, religious buildings) • Street lighting • Computing • (education) • Drinking water • pumps • Sewage pumps

REVIEW QUESTIONS

i. Consider the policies above. Can they be improved? If so, how?

ii. What other business and community engagement models do you think could be used in your locality?

iii. What impacts, negative and positive, could be prevalent in your locality? Discuss.

FURTHER READING

1. *"Small hydropower development in Africa"* • W.J. Klunne; ESI Africa. July 31, 2007. www.esi-africa.com/small-hydropower-development-in-africa-8038/
2. *Evaluation of Environmental Impact Assessment System in* Nigeria • C.O. Nwoko; Greener Journal of Environmental Management and Public Safety 2(1), 22–31; (2013). www.gjournals.org/GJEMPS/GJEMPS%20PDF/2013/January/Nwoko.pdf.
3. *"Jonathan inaugurates Light-Up Rural Nigeria project in Abuja" • Premium Times January 14, 2014. www.premiumtimesng.com/news/153317-jonathan-inaugurates-light-rural-nigeria-project-abuja.html*
4. *Energy Strategies and Greenhouse Gas Mitigation* • P. R. Shukla (ed.) New Delhi: Allied Publishers (1997)
5. *Poverty reduction – Scaling up local innovations for transformational* change • UNDP, NewYork: (2011). www.undp.org/content/dam/undp/library/Poverty%20Reduction/Participatory%20Local%20Development/Nepal_REDP_web.pdf
6. *Delivery models for decentralised rural electrification* • Y. Annabel; London: International Institute for Environment and Development (IIED) (2012)

6. PROJECT DEVELOPMENT

About this module

This module aims to present an overview of project planning, outline the stages of project planning, and highlight challenges likely to be faced by project planners as well as present factors that aid successful project outcomes.

Learning outcomes

At the end of this module, the participant is able to

- Outline the procedures involved in planning RE systems
- Carry out basic a financial analysis of RE projects
- Appreciate the role of the local community in RE projects

6.1. PROJECT PLANNING AND MANAGEMENT

INTRODUCTION

Renewable energy projects are generally undertaken to address a particular need. As is mostly the case in Nigeria, the need for reliable electricity in rural areas is immense. Proper project planning seeks to ensure that appropriate technologies and available resources (such as solar and hydro) are utilised in a cost-effective manner that benefits project sponsors, end users and the environment.

Developing renewable energy projects primarily involves undertaking a set of activities subject to significant risks and unknowns. Projects require inputs such as on-going investments of time, financial, and even political resources toward achieving a successful output (the completed project) and outcomes (objectives and associated benefits).

There are various approaches to project development. From experience within and outside of Nigeria, renewable energy and rural electrification projects tend to consist of some or all of the phases outlined in the diagram below.

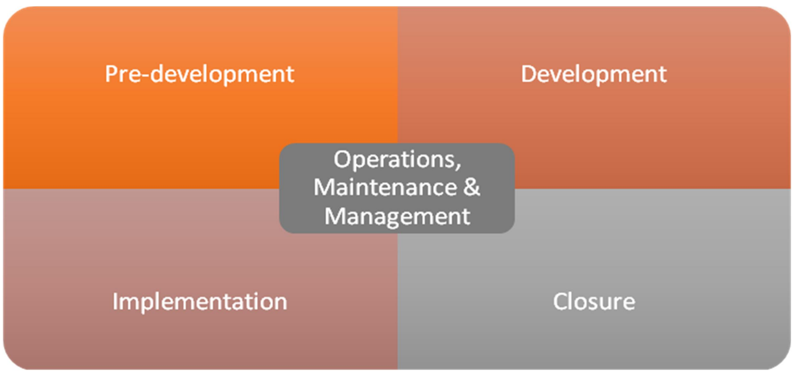

Figure 6.1: Project planning stages

» *Phase I: Pre-development*

At this stage, a project developer defines the proposed project. One way of doing this is by describing the motivation behind it. A motivated project is one that defines a clear pathway to success and enough potential that it simply cannot be ignored. Establishing the project motivation is essential to attract the resources and expertise necessary to execute the project during the pre-development stage. To establish the project motivation, project developers can use the BEPTC[1] assessment tool – baseline, economics, policy, technology, consensus – in relation to their project. The elements of this tool are outlined below.

Baseline: A statement of purpose that identifies a simple, clear and strong purpose or need for the project to exist. For example, "without access to decentralised electricity generated at the source, the majority of Nigeria's underserved rural and semi-urban communities will remain in darkness. Millions of households will continue to live in energy poverty, exposed to harmful fumes from the use of finite resources such as kerosene, petrol, diesel and firewood." Along with the statement of purpose it is also useful to include the objectives (i.e. specific, measurable, agreed and realistic goals with a set time frame) as well as the scope and desired outcomes of the project.

Economics: A reasonable and objective analysis of fundamental energy economics to establish the "bankability" of providing energy in the location, both in terms of the total costs of acquiring energy from existing sources (self-generated or utility-based) and from the proposed sources as a point of comparison. Factors such as the prevailing utility rates, spending on independent generation schemes and incentives for proposed sources need to be considered. Financial analysis tools can be used to measure or score project motivation in financial terms.

Policy: Examine the existing federal, state, local and regulatory policy environments for barriers and form strategies to mitigate or deal with them prior to expending significant resources on a project. Remember to consider both internal and external policies. Reference relevant policies in the proposal, for example, "this project supports the government's drive to improve access to electricity using renewable energy resources to make reliable energy available in rural areas as expounded in the National Renewable Energy and Energy Efficiency Policy (NREEP) approved in 2015."

Technology: Resource assessments characterise the renewable resources that are available at a specific site. Maps of renewable energy resources might be available from a simple desktop study. Assessing commercial technologies, reliability, and bankability may require more, but still relatively minimal, effort. Project developers may wish to invest in an upfront pre-feasibility study to screen areas of opportunity and establish whether the project merits a more serious investment of time and resources.

Consensus: Project developers need to generate buy-in for their project. Communication and consensus-building among stakeholders involves a creating a common understanding of the project fundamentals, and a unification of purpose. This will involve many parties' input, investment, and possibly compromise. If the project motivation is acceptable to project decision makers, they may proceed to project development activities by investing further resources.

» *Phase II: Project development*

At this stage, the project developer proposes a specific project delivery plan. Activities here involve feasibility assessments (e.g. site, resource, financial, non-financial, risks) and project design (objectives, technology design, project plan, operating models and ownership structures, project management processes).

[1] BEPTC™ is a trademark of the Alliance for Sustainable Energy, LLC, the operator of the National Renewable Energy Laboratory (NREL), a US government-owned, contractor-operated laboratory for renewable energy and energy efficiency research and development. See www.nrel.gov

THE FEASIBILITY STUDY

The first step in every project development is the feasibility study/assessment. The feasibility study consists of the following:

Situation analysis - every feasibility study is based on a comprehensive situation analysis. This analysis forms a substantial part of different planning methods. In our context, the situation analysis is focused on problems (such as the lack of energy/electricity in a given village, rural area, etc.), stakeholders and their social environment.

The issues to be tackled, as well as the scope and the depth of analysis depend on the situation to be analysed. It is not the instruments which determine the analysis, but the guiding interests which determine the choice of tools.

As problems are always connected to unfulfilled objectives, a situation analysis comprises an objectives analysis as well as a problems analysis. Moreover, since it is always people's problems and objectives which make up a situation, the analysis includes a stakeholder analysis.

A good feasibility study provides a detailed analysis of the project using the following assessments:

Site-specific assessments - identifies siting options, physical issues, space availability and other factors that may affect project execution at the considered site. The detail level of these assessments depends on the project scale as well as national legislation and technology-specific requirements. Outcomes from this assessment would be a selected site and list of required permits.

Problems analysis - identifies deficiencies and their causes by precisely describing deficiencies as the difference between a desired end and an existing/actual situation so that the symptoms become clear. In other words, this analysis answers the question: Why is an electrification project required?

Constraints and potentials analysis - constraints result from (and respective potentials refer to) resources that are available for carrying out activities (in our case electrification projects) such as know-how, capital and means of production.

Renewable energy resource and technology feasibility - an analysis is performed to establish and support resource availability, quality, and characteristics within a tight range of certainty for a specific site. This requires on-site data collected over a period of time, complemented with computer modelling. Outcomes from this assessment would be a preferred technology recommendation, i.e. an evidence-based suggestion to install a PV system instead of a wind energy system due to the better availability of sun over wind.

Commercial feasibility - this includes using financial forecasting and planning tools to help decision makers and investors determine whether the project is worth undertaking. Outcomes of this analysis would include figures detailing the system yield, capital expenditures, operation and maintenance costs, revenue and savings over time, as well as other financial indicators such as rates of return, payback, etc.

Non-financial analysis - this type of analysis includes environmental, social and economic impact assessments (see module 5.2.) for the proposed project. Outcomes of this assessment would be a survey outlining any socio-economic and environmental impacts and associated mitigation measures. Possible negative results would have to be taken into consideration for further planning.

Stakeholder or participant analysis **-** the stakeholder or participant analysis is an analysis of the problems, fears, interests, expectations, restrictions and potentials of all important groups, organisations and institutions, implementing agencies, other projects and individuals who may have an influence on a situation or (intended) project or are themselves affected by it.

The stakeholder analysis identifies individuals or groups who have problems to be addressed, agencies which implement measures, individuals or groups who supervise the project and carry overall responsibilities, as well as any other strategic groups.

It is necessary to communicate with all stakeholders, taking time to analyse relevant project participants as part of project planning.

The following points are to be considered in a stakeholder analysis:

- Social structure and hierarchy of power and the most important actors of a given situation or project, their interests and their objectives, as well as their relations amongst each other.
- Important actors or stakeholders are those both positively and negatively affected by the project.
- Women's interests: planners should put an effort into including women and fostering their participation.

Table 6.1: Extract from a stakeholder register

Stakeholder register					
Stakeholder	***Role/Interest***	***Expectation, influence, other***	***Attitude towards project***	***Strategy for management***	***Contact frequency***
• Rural Electrification Agency of Nigeria (REA)	• Funding rural electrification projects throughout Nigeria	• Potential source of funding for mini-grid project	• Unknown as of January 1	• Get them fully on board and supporting the project	• Bi-weekly updates followed by offer to meet one-on-one
• Local NGO	• Representing the interests of the local population	• Support for project implementation by communicating with local beneficiaries	• Has expressed interest for 2 years now, interested in permanent cooperation	• Analyse interest and discuss their view of the project and suggestions	• Continuous updates; monthly contact during the planning phase
• Ministry of Environment	• Permission for installing RE systems	• Avoid possible infringements with environmental legislation	• Open, principally in favour of RE projects	• Involve at a very early stage of planning	• Continuous updates during planning; bi-weekly
• Product and service suppliers	• Selling their products, provide cost estimates	• Essential stakeholder for calculating project costs	• Principally in favour	• Involve at a very early stage of planning	• Regular contact during early planning phase

Others:

- Planners, engineers, procurement specialists, accountants, regulatory agencies with jurisdiction over the project, etc.
- Other groups or departments that will participate in the project, e.g. development and training organisations at the village level.
- Other organisations concerned with the project, e.g. national and local governmental groups

Project design - a good project design consists of the following:

Technology design - following from the pre-development stage, a more detailed outline of the feasible technology is carried out with engineering design, equipment selection, and procurement activities planned for. Common stages of engineering design include conceptual design development and construction documents with full specifications, which may be used for bid and contract procurement. Note that all of these design processes require varying degrees of financial investment depending on project scale and scope.

Project plan - the main purpose is to plan time, cost and resources adequately to estimate the work needed and to effectively manage risk during project execution. Project plans help to organize and interpret information, inform decisions, and monitor project progress, in a regular, repeatable, disciplined manner. Some of the components of project plans include:

- Task schedules which are essentially work packages that break down the project scope into achievable, ordered activities and tasks. This will inform on the appropriate team structure for the project with key roles and responsibilities.
- Key milestones are intermediate targets at various sub-levels. They define targets to be reached by each task or subtask. With the successful completion of significant work segments (mostly in consecutive order), "milestone" is said to be achieved. They signal project progress and often trigger the next sequence of activities, leading to the completion of a project.
- Resource schedule identifies available inputs and dependencies such as people working on the project, budget, space, materials and equipment required. Resources are assigned to appropriate tasks.
- All projects have a finite duration. A project planner allocates time to each task based on the amount of effort it takes e.g. hours it takes to complete a task or calendar span e.g. days or weeks. An estimated time of completion for work packages and the entire project is arrived at in this way. There is always a degree of uncertainty in time estimation. Sometimes project planners factor in additional time to cover for unexpected events or delays.
- Risk analysis and assessment help to frame uncertainties and issues that are likely to adversely affect the project. As such, it is contingent on the project developer to identify potential risks (internal and external), the likelihood of the risks occurring, the impact of each risk on the project and the prescribed mitigation measure for each risk. Common risks involved in renewable energy and rural electrification projects include political risks, construction and development risk, operational risk, political risk, financial risk, regulatory risk, environmental risk and force majeure.

Table 6.2: Risk register showing a single risk entry

Risk register						
Risk ID#	***Description***	***Likelihood H/M/L***	***Impact H/M/L***	***Mitigation plan***	***Responsible Agent***	***Update***
001	• Project funding is unexpectedly cancelled	• Low	• High	• Formulate letter of interest beforehand and sign binding contracts.	• Project manager	• Agency's budget is stated for the project, discussed and signed.

» *Phase III: Project implementation*

Here a project developer delivers the project according to plan or with minimal changes to the original plan. Implementation activities include managing all the resources allocated for the project to successfully construct the proposed facility. At the end of construction, testing is usually carried out to ensure that the facility is functional before full operations commence.

» *Phase IV: Project commencement*

At this stage, all project development activities across all of the processes are finalized and formally closed. The facility is formally commissioned, handed over to the relevant managers for full operation. A post implementation review is vital at this stage for the project team and other stakeholders to learn from experiences and apply to future projects. Normally this takes the form of a "lessons learned" presentation that shows the things that went well and those that went badly on the project, any change that modifies the tangible portions of the finished work and how these variables were managed by the project team.

Every facility has an end of life where it may need to be retired or renovated. If the choice is to retire or decommission, project developers have to think of site clean-up, disposing of components in a manner that is non-polluting and not injurious to human health and the environment. Should the choice be to renovate, issues such as permit revision, new financing arrangements, negotiating new lease agreement, power purchase agreement (PPA) need to be considered.

» *Challenges*

No project is without constraints. The primary challenge of project management is to achieve all of the project goals and objectives while honouring the preconceived constraints. The primary constraints are scope, time, quality and budget. The secondary — and more ambitious — challenge is to optimize the allocation of necessary inputs and integrate them to meet pre-defined objectives. Projects are also impacted by external constraints such as policy, social issues etc. In dealing with constraints, trade-offs need to be made as to which is acceptable, which can be enhanced and which has to be managed. Barriers that developers may encounter include:

i. Development barriers: Most projects do not eventually progress along the phases from pre-development to closure. For instance, although 277 potential sites for small hydro in Nigeria have been identified, most remain undeveloped[1]

[1] Renewable Energy Master Plan 2012, ECN and UNDP

ii. Financial barriers: *H*igh investment costs, feasibility study costs, other fees and charges such as custom duties and levies form barriers to project development. Without adequate funding, projects risk not taking off or collapsing along the way.

iii. Technology barriers: When selecting the appropriate technology to use, project developers need to answer pertinent questions like is there enough resource and skillset to manage the proposed technology?

iv. Maintenance barriers: Most projects fail for lack of maintenance plans. Project developers should consider what arrangements to make for replacements and repairs. Who manages maintenance? Who pays for maintenance?

v. Business model barriers: The business model helps identify who the customer is, how to reach them and how profits be made from payments? Without a clear business model suited to the local context, projects may suffer.

vi. Policy and regulations barriers: Lack of strong policy frameworks, incentive schemes, standards and enforcement of laws can adversely affect project development by hindering investments. The level of government commitment to both policy formulation and implementation can make or mar an enabling environment for project development.

vii. Market barriers: Without a proper understanding of the existing market, alternatives available, what costs make sense to the end-users, project developers may face resistance and lack of adoption of new technology.

viii. Skills barriers: Lack of skilled local experts to operate and manage proposed technology can lead to prolonged downtime,

ix. Social vices: Theft and vandalism are some of the social vices peculiar to infrastructure developments within the country where community involvement in projects is weak. Project developers need to think through how these can be avoided and managed.

x. Stakeholder buy-in: Stakeholders can become adversaries to a project before it even begins. Without consensus and communication efforts on the developer's part, precious resources may not be made available for projects.

» ***Success factors***

Most projects are deemed to be successful when they are completed within the scheduled time, budget and quality specifications. Below are some of the less pronounced aspects that lead to successful projects beyond completion:

i. Keep it simple: It is very important that developers keep processes and plans as simple as possible.

ii. Proper understanding of costs: It is critical to understand that development and project costs are never static. Development costs include feasibility study costs, impact assessment costs, site preparation, permit and license costs amongst others. Project costs include equipment costs, financing costs, total installed cost, fixed and variable costs, operating and maintenance costs (O&M), fuel costs. Factoring in cost buffers to cover for the unexpected and having the ability to make adjustments can ensure that projects go smoothly.

iii. Social acceptance: No matter how brilliant a project, its success heavily relies on being accepted within the community where it is situated. It also follows that involving the local community happens to be the best way to prevent theft and vandalism. A project planner needs to gain the support and buy-in of community stakeholders by carrying them along from initiation to closure. Bringing all the stakeholders together is fundamental to any sustainable, successful and secure project especially in remote locations.

iv. Manage expectations: Stakeholders need to have a clear understanding of the project in terms of benefits, choices, challenges and changes. Ambiguities and concerns need to be addressed early to avoid future disputes.

v. Flexibility: In reality, projects rarely go according to plan. Project plans are therefore documents written before the start of a project. Almost everything is based on estimates that eventually need adjustments during project implementation.

vi. Clearly defined roles and responsibilities: Responsibilities within a project are assigned according to roles and skills needed to fulfil the project objectives. Management and project team members need to have delineated roles and responsibilities in order for the project to function well.

vii. Team involvement: It is important for the project team and management to cooperate and have a good working relationship for projects to achieve success.

viii. Progress tracking: Monitoring project progress and reviewing periodically is necessary to keeping projects on track. Without progress tracking, controls and adjustments cannot be made on time to avoid overruns, delays and failure.

ix. Training: It is important to incorporate skills transfer and training for local personnel on the project, who should be able to fully operate the plant, perform routine checks and maintenance. This removes the need to maintain O&M contracts with foreign entities that can drive up the overall costs of O&M.

x. Sustainability Plan: A sustainability plan provides a continuity strategy for the project beyond its completion and commissioning. Very often this is overlooked and great projects end up failing.

It is worth learning from best practices from successful projects worldwide. The table below provides some insights:

Table 6.3: Adapted from Micro-grids for rural electrification: A critical review of best practices based taking place seven case studies – *United Nations Foundation, 2014*

Parameter	***Example 1***	***Example 2***
Project	• Chhattisgarh Renewable Energy Development Agency (CREDA), India • The state's designated government agency for the development of renewable energy solutions	• Partners of Community Organization (PACOS), Malaysia
Brief	• Significant forest cover and a low rate of electrification in the Indian state of Chhattisgarh necessitated the development of off-grid electrification solutions in the form of both solar PV micro-grids and solar home lighting systems.	• Micro-hydro facility, NGO-community partnership. Together, the NGOs and PACOS use the micro-hydro projects as an entry point into a village to advocate for other issues related to the community.

Parameter	***Example 1***	***Example 2***
Successes	• Scalability and wide reach • Public-private partnership • Effective monitoring and verification • Equity and coverage	• Community building/ownership • Conservation • Community maintenance efforts
Challenges	• Limited electricity service levels • Poor payment collection • Central grid extension • Personnel security issues	• Major repairs • Community adaptation to seasonal variability • Demand-side management • Inefficiencies due to shared management responsibilities
Lessons learned	• Strong state backing is required for long-term sustainability and equity • Increase in energy needs by consumers for residential and commercial activities • Effective monitoring and verification key for quality operation	• Invest in community training • Community commitment is the key to long-term success. • Incentivize labour continuity to ensure consistent maintenance and operations • Devise thoughtful rules and enforcement mechanisms pertaining to customer usage • Cooperate with other NGOs • Communities have solutions • Government recognition necessary for protection and channels for recourse

6.2. FINANCIAL ANALYSIS

Renewable energy and rural electrification projects often require high capital expenditures. As is the case with all projects and investments, there are also associated risks and potential rewards to consider. Financial risks and returns are co-dependent categories; if returns are increased for any given level of risk, or if the perceived levels of risk are reduced for any given level of risk, renewable energy investments are more likely to occur more frequently.

Since project sponsors, lenders and investors want to achieve a return proportional to the level of risk they undertake, it is incumbent upon a project developer to understand the risk/return balance and be able to present convincing financial projections to justify investments or secure funding.

FINANCIAL FORECASTING TOOLS

Financial forecasting tools support decision-making and provide the project developer with vital information for planning. It is common to conduct a multi-criteria analysis by including two or more of the following financial analysis tools in project financial plans.

» Net present value (NPV)

NPV is defined as the sum of the present values of incoming and outgoing cash flows over a period of time. NPV is an indicator of how much value an investment or project adds to a developer or company. NPV is used to analyse the profitability of a project. The more positive the NPV, the better the returns.

If...	***It means...***	***Then...***
NPV > 0	The investment would add value.	The project may be accepted.

If...	*It means...*	*Then...*
NPV < 0	The investment would subtract value.	The project should be rejected.
NPV = 0	The investment would neither gain nor lose value.	Acceptance or rejection is not a clear-cut matter. This project would break even, i.e. it would add no monetary value. Decision should be based on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

Formula:

NPV = Sum of present value of future cash flow – initial cost of investment

$$NPV = \sum_{t=0}^{n} \frac{C_n}{1 + r^n} - C_0$$

Where

C_n = Future cash flow from time/period 1 to *n*
n = Time span
r = Discount factor or interest rate
C_0 = Initial cost of investment at time zero

» *Internal rate of return (IRR)*

IRR is used to measure and compare the profitability of investments. IRR can be defined as the discount rate at which the present value of all future cash flow is equal to the initial investment or, in other words, the rate at which NPV equals zero. That is, the cumulative NPV of all project costs would be exactly equal to the cumulative NPV of all project benefits or cash flow if both were discounted at the internal rate of return. Solving for IRR is an iterative process where different rates are tried until arriving at the one that makes NPV equal or closest to zero.

For two or more competing projects, the project with the highest IRR is more desirable. As such, IRR can be used to rank several prospective projects, assuming all other factors among the various projects are equal.

Formula:

$$IRR \sim NPV = \sum_{t=0}^{n} \frac{C_n}{1 + r^n} - C_0 = 0$$

C_n = Future cash flow from time/period 1 to *n*
n = Time span
r = Discount factor or interest rate
C_0 = Initial cost of investment at time zero

» *Life-cycle cost analysis (LCCA)*

LCCA takes into account the present value of all costs associated with an investment option over its lifetime, that is, the total cost of ownership over a given period. This includes acquisition costs (capital cost, installation costs), replacement costs, operations and maintenance

(O&M), fuel costs, conversion and/or decommissioning costs at the end of the life of the investment. The advantage of LCCA is that it is a familiar tool for decision makers and economists and it provides a means to include time preferences or the opportunity cost of money.

If...	*It means...*	*Then...*
LCC > 0	Over the lifespan of the project, it fails to generate net income.	The project may be rejected.
LCC < 0	Over the lifespan of the project, it generates net income.	The project should be accepted.
LCC = 0	Over the lifespan of the project, it breaks even.	Acceptance or rejection is not a clear-cut matter. This project would break even, i.e. it would add no monetary value. Decision should be based on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

The project with the lowest (or negative) life-cycle cost over its lifespan is more favourable; this means it generates net income. The project with a zero lifecycle cost breaks even, meaning that its costs equal its income, while the project with the most positive life-cycle cost (greater than zero) is a failure, as it fails to generate net income.

Formula:

$$LCC = \sum_{t=0}^{n} \frac{[(C_n + M_n + F_n - R_n) - I_n]}{1 + r^n}$$

C_n = Capital cost at time *n*
M_n = Operations and maintenance cost at time *n*
F_n = Fuel cost at time *n*
R_n = Residual cost at time *n*
I_n = Income at time *n*
n = Time span
r = Discount rate

» *Cost-benefit analysis (CBA)*

Prior to erecting a new plant or taking on a new project, prudent developers will conduct a cost-benefit analysis as a means of evaluating all of the potential costs and revenues that may be generated if the project is completed. A cost-benefit ratio is normally calculated where only the recurrent income is taken as the benefit.

If...	*It means...*	*Then...*
CBR > 1	Costs exceed benefits.	The project may be rejected.
CBR < 1	Benefits exceed costs.	The project should be accepted.
CBR = 1	Benefits exactly equal costs.	Acceptance or rejection is not a clear-cut matter. This project would break even, i.e. it would add no monetary value. Decision should be based on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

Formula:

$$CBR = \sum_{t=0}^{n} \frac{[(C_n + M_n + F_n - R_n) \div I_n]}{1 + r^n}$$

C_n = Capital cost at time *n*
M_n = Operations and maintenance cost at time *n*
F_n = Fuel cost at time *n*
R_n = Residual cost at time *n*
I_n = Income at time *n*
n = Time span
r = Discount rate

» *Payback period (PP)*

Payback period is the time it takes for an investment to generate an amount of income or cash equal to the cost of the initial investment. The shorter the payback period, the better the investment is deemed to be. Developers and investors use payback period to make a quick judgment about a particular investment or capital purchase.

Formula:

$$PP = \frac{Capital\ costs}{Annual\ savings}$$

» *Levellised cost of energy (LCoE)*

LCoE is the ratio of the NPV of total investment/capital costs, fuel costs, operating and maintenance costs of a system to the NPV of the total electricity generated by the system over its economic lifespan. It allows for comparisons to be made between different technology sources based on the electricity cost.

The LCoE gives the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yield a lower return on capital, or even a loss.

Formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in period *t*
M_t = Operations and maintenance expenditures in period *t*
F_t = Fuel expenditures in period *t*
E_t = Electricity generation in period *t*
r = Discount rate
n = Economic life of the system
I_t = Investment expenditures in period *t*
M_t = Operations and maintenance expenditures in period *t*

Example: Financial implication calculation

Example: An off-grid community requires your expert advice on choosing between a water turbine and a solar PV system. For a theoretical lifespan of n = 10 years (120 months) and an assumed equivalent discount rate r = 0.5% per month, the discount factor $D_{nr} = [[1-(1+r)^{-n}]/r\} = \{[1-1.005^{-120}]/0.005\} = 90.073$. Compare the financial implications using net present value, life-cycle cost analysis, cost benefit ratio, and payback period for each of the projects below:

	2 kW water turbine	**_20 kW solar PV plus battery storage_**
Average installed capacity	1,460 kWh/month	14,600 kWh/month
Average availability	0.75	0.07
Average monthly output	1,095 kWh/month	1,022 kWh/month
Generated savings(income)	NGN 43,800/month or NGN 525,600/year	NGN 409,00/month or NGN 490,800/year
Capital cost C (at start of project) including fees, control system, electrical connections, etc.	NGN 3,000,000 including civil works	NGN 2,500,000 including energy storage (batteries) and inverter
O&M costs including insurance, maintenance, spares, etc.	NGN 1,500/month	NGN 4,000/month
	Calculations	
Lifetime net expenditure ($O \times D_{nr}$)	NGN 1,500 × 90.073 = NGN 135,100	NGN4,000 × 90.073 = NGN 360,300
Lifetime net income ($I \times D_{nr}$)	NGN 43,800 × 90.073 = NGN 3,945,200	NGN 40,900 × 90.073 = NGN 3,684,000
Lifetime net electricity generation	1,095 kWh × 90.073 = 98,630 kWh	1,022 kWh × 90.073 = 92,055 kWh
Payback period (PP)	NGN 3,000,000 / NGN 525,600 = 5.7 yrs	NGN 2,500,000 / NGN 490,800 = 5.1 yrs
Net present value (NPV)	NGN 3,945,200 – NGN 3,000,000 = NGN 945,200	NGN 3,684,000 – NGN 2,500,000 = NGN 1,184,000
Life cycle cost analysis (LCCA)	NGN 3,000,000 + NGN 135,100 – NGN 3,945,200 = NGN –810,100	NGN 2,500,000 + NGN 360,300 – NGN 3,684,000 = NGN –823,700
Cost benefit ratio (CBR)	(NGN 3,000,000 + NGN 135,100) / NGN 3,945,200 = 0.795	(NGN 2,500,000 + NGN 360,300) / NGN 3,684,000 = 0.776
Levellised cost of energy (LCoE)	NGN 135,100 / 98,630 kWh = NGN 1.4/kWh	NGN 360,300 / 92,055 kWh = NGN 4/kWh

Based on the calculations for PP, NPV, LCCA, CBR and LCoE, the solar PV project demonstrates better economics and should therefore be recommended.

» *Considerations when making a financial analysis*

When conducting a project financial analysis, a multi-criteria approach is recommended as a source of different valuation mechanisms to inform investment decision-making. Most investors and almost all financing institutions will require some form of multi-criteria analysis or several different key performance indicators (KPIs). While a single analysis technique or KPI tool is sufficient to provide all the investment data needed for an efficient decision, a multi-criteria analysis can be helpful in evaluating future financial performance. It should also be noted that the quality of an analysis tool strongly depends on the quality and level of detail of the input data. Also, renewable energy technologies vary by technology, country, and project, with differences as to the renewable energy resource, capital and operating costs, and technology efficiency/performance. A strong financial analysis considers the following:

YIELD AND DEMAND ANALYSIS

- Can we produce enough power and can we sell all power produced?
- Technology
- Do we have the right technology for this project?
- Is it cost-effective and does it fit into the financial model?

INFRASTRUCTURE

- Substations, roads

Risk (technical, financial and institutional)

- Additional studies

SENSITIVITY

- Financial conditions (tariff rates, engineering procurement and commissioning turn-key costs, payment methods)
- Economic conditions (using SWOT, PEST)
- Ownership structures
- Financing structures

FINANCIAL STATEMENTS

In addition to the financial projection tools, for certain categories of projects, permitting agencies require project developers to provide projections of the following financial statements for the duration of the licence or a minimum of five years.

» *Profit and loss (P&L) account*

The P&L account or income statement reports the financial performance of an entity or a project in terms of net profit or loss over a specified period of time. It takes the difference between the income and expenses to present either a profit or a loss.

Advantage	*Disadvantage*
An updated profit and loss account is a useful tool for measuring performance and expenditures. It can identify: • Sources of financial gain and loss, and how to improve performance • Trends, as well as predictions of future performance	No intrinsic disadvantage. However, as with all financial statements, its utility depends largely on the accuracy of the data used to generate the statement.

» *Cash flow statement*

The cash flow statement presents the inflow and outflow of cash over a period of time.

Advantage	*Disadvantage*
• Shows the actual cash position available. • Helps project the future liquidity position, thereby allowing for arrangements to be made in advance for any cash shortages.	• On its own, a cash flow forecast shows only cash positions and not the company's actual profit and loss.

» *Balance sheet*

The balance sheet is a statement of financial position presented at a given date. It captures the position of assets, liabilities and equity of an entity or a project.

Advantage	*Disadvantage*
• Allows investor to form a well-informed opinion of risk and return prospects. • Financial ratios can be calculated using various balance sheet items to obtain a very thorough summary of the financial health of the project by analysing its cash position, working capital, liquidity and leverage. • Balance sheet items enable the assessment of a project's asset turnover rates – a measure of efficient asset use, key profitability and return measures such as return on equity.	• Balance sheets present a snapshot of the financial position at a given point in time; its figures can be misleading. • Many balance sheet items such as fixed assets are reported at their historical cost basis – the amount an asset was purchased for, which often has little to do with the more meaningful fair market value.

FURTHER READING

1. *Productive Use of Energy – PRODUSE* • ESMAP, GIZ, BMZ, AEI, EUEI PDF (2012)
2. *A Manual for Electrification Practitioners Eschborn* • EUEI PDF/GIZ
3. *From Gap to Opportunity: Business Models for Scaling Up Energy Access* • International Finance Corporation (IFC), World Bank Group, Washington, DC: IFC. (2012). www.ifc.org/wps/wcm/connect/ca9c22004b5d0f098d82cfbbd578891b/energyaccessreport.pdf?MOD=AJPERES (accessed Aug. 30, 2016).
4. *Models of Impact: A Strategic Business-Design Toolkit • www.modelsofimpact.co/ (accessed Aug. 30, 2016)*
5. *"Nigeria's solar projects yield both failure and success"* • B. Omisore; National Geographic, November3, 2011 http://news.nationalgeographic.com/news/energy/2011/11/111102-solar-power-in-nigeria/ (accessed Aug. 30, 2016)
6. *Sankalp Africa interview series 2015 – PowerGen Renewable Energy, East Africa* • PowerGen (2015): www.inclusivebusinesshub.org/page/sankalp-africa-2015-interview-series-powergen-renewable-energy (accessed Aug. 30, 2016)
7. *Community Electricity in Rural South Africa: Renewable mini-grid assessment* • Scottish Power (2003): www.globalelectricity.org/upload/File/South-Africa_Mini_Grid_Assessment.pdf (accessed Aug. 30, 2016)

8. *Renewable Energy in Western Africa: Situation, Experiences and Tendencies* • Vilar (ed.) (2012): www.ecreee.org/sites/default/files/renewable_energy_in_west_africa_0.pdf (accessed Aug. 30, 2016)

9. *Gaviotas: A Village to Reinvent the World. White River Junction, VT* • A. Weisman; Chelsea Green Publishing Company. ISBN 1-890132-28-4 (1999).