A-EES-9813

SMALL-SCALE RENEWABLE ENERGY SOURCES FOR RURAL ELECTRIFICATION

Possibilities and Limitations

Mikael Amelin

VETENSKAP OCH KONST

KTH

DEPARTMENT OF ELECTRIC POWER ENGINEERING
ROYAL INSTITUTE OF TECHNOLOGY
in collaboration with
Swedish International Development Cooperation Agency

SMALL-SCALE RENEWABLE ENERGY SOURCES FOR RURAL ELECTRIFICATION

Possibilities and Limitations

Mikael Amelin

Department of Electric Power Engineering
Kungl Tekniska Högskolan
100 44 Stockholm

December 1998

ABSTRACT

This report is the result of a study of the possibilities of using renewable energy technologies for rural electrification in developing countries. The renewable power sources have been compared with diesel generator sets, which is the most common solution today. The conclusion of the study is that renewables in many cases – but not all – can compete economically with diesel generator sets.

The most important electrical property of a power system is that there must be at least one power plant that can follow the variation of the load. There are four alternatives for this: biomass plants, hydro power stations, diesel generators and batteries. Battery storage of energy is today very expensive and can only be justified for small individual systems or small local networks using low voltage.

The environment impact from small rural power systems will in almost every case be very small. Renewable energy technologies are more environmental benign than diesel generator sets, although there might be problems, for example with biomass usage.

The financing is very important for renewable energy technologies, which generally have a technical life time of 20 years or more. These projects require a low rate of interest and long term financing, if they shall have any chance of competing economically with diesel generator sets.

Most renewable energy technologies are unfamiliar to the local technicians and therefore it is necessary that education of technicians is supported. Also owners of solar home systems must be well informed about the needs of maintenance for their system.

CONTENTS

ACKNOWLEDGEMENTS

First of all I would like to thank Dr. Lennart Söder at the Department of Power Engineering, KTH, for his valuable comments on my work. I have also received useful information from several others, where I would like to mention Jens Schöldström from Ångström Solar Centre, Leif Selhagen from NAPS Sweden AB, prof. Björn Kjellström from Luleå Tekniska Universitet, Sture Holmström from Birka Teknik & Miljö AB and Arne Johansson from Catella Generics.

Mikael Amelin

Stockholm, November 1998

LIST OF ABBREVIATIONS

AC	Alternating Current
Ah	Amperehours
CFL	Compact Fluorescent Lamp
CHP	Combined Heat and Power
DOD	Depth Of Discharge
DC	Direct Current
Hz	Hertz
kVA	kilovoltampere
kW	kilowatt
kWh	kilowatthour
LV	Low Voltage
MVA	megavoltampere
PV	photovoltaics
SEK	Swedish Kronor
TZS	Tanzanian Shillings
USD	US Dollar
V	Volt
VA	voltampere
VAT	Value Added Tax
W	Watt
W_p	Watt (peak)

Chapter 1

INTRODUCTION

This report has been requested by the Swedish International Development Cooperation Agency (Sida) as a technical guideline about the use of renewable energy sources for rural electrification in developing countries. The study has been performed at the Department of Electric Power Engineering at the Royal Institute of Technology in Stockholm. Project leader has been Dr. Lennart Söder.

The report is organised like this: Chapter two describes the basics of power system theory. In chapter three the basics of the renewable energy sources available today are described. For comparison also diesel generator sets are described. In chapter four some schemes for rural electrification are described and evaluated, followed by a discussion in chapter five about what happens when the power system must be expanded due to increased demand. Chapter six contains a summary of the options and a discussion about the impact of different financing of renewable power for rural electrification. Appendices A and B briefly describes batteries, inverters and distribution systems. Appendix C contains some price examples.

1.1 BACKGROUND

Electrification is one of the most important steps to enhance the standards of living in developing countries. With electric power the efficiency of health care can be increased by enabling hospitals to use more advanced equipment and to store medicines and vaccines. Other basic needs, like water supply and education can be improved. Shops, restaurants and industries are also benefited. Electric lighting increases safety and gives people the opportunity to use the dark hours for studies and recreation.

It has been estimated that around 2 billion people live in areas without electric power supply – most of them in rural areas of developing countries.[1] Traditionally electrification of developing countries have been carried out through building large power plants and a national transmission grid. But since developing countries have small resources for such large-scale electrification programmes, it is common that only the major cities are supplied by the national grid and that the expansion to rural areas is progressing very slowly. Small-scale system might therefore be the only alternative to bring electricity to rural areas within the next few decades.

Taking the risk of global warming into consideration, small-scale renewable power plants are also seen as an alternative to large-scale power plants using fossil fuels.

1. [4], p. 1.

1.2 OBJECTIVE OF THE STUDY

The main objective of this study is to describe the renewable technologies that today can be used for rural electrification in developing countries. The descriptions comprises technical advantages and disadvantages of the options as well as environmental and economical aspects.

The term “rural electrification” refers in this report to electrification of small villages and townships with less than approximately 25 000 inhabitants or a total load of less than 1 MW. It also includes electrification of single households or single public buildings.

The focus of the study is the situation in Sub-Saharan Africa, but most parts of the report can be applied to other developing countries as well.

Chapter 2

BASIC POWER SYSTEM THEORY

In this chapter are the most essential properties of power systems described, which is necessary before studying the electric energy sources and possible electrification schemes that are available today.

2.1 POWER AND ENERGY

Any work that shall be done requires energy. The energy consumption is – at least theoretically – a constant for each task. This means that for instance pumping 1 m^3 of water from a depth of 10 m always should require the same amount of energy irrespective of the time used for the work. The time required for the task is reflected by the power consumption. More power is necessary if a work should be performed quickly than if it can be performed more slowly. Mathematically does power equal energy per time unit or the time derivate of the energy.

Power is measured in kilowatt (kW). Energy is – in power systems theory – usually measured in kilowatthours (kWh). A power consumption of 1 kW during one hour equals an energy consumption of 1 kWh.

Electric energy

The absolutely most vital property of electric power systems is that electric energy can not be stored;[1] the generation in a power system must always equal the consumption (including losses in transmission and distribution systems). A result of this is that there must be enough capacity in the system to generate the peak demand. On a longer time basis, we have a second requirement, which is that during a certain time period, ranging from a day to a year, there must be enough energy in the system to cover the total load during the time period.

Renewable energy sources are often *energy limited*. This means that over a longer time period only a certain amount of energy can be produced. How much energy that is available can not be controlled. In the case of hydro power, photovoltaics and wind power is the available energy determined by the weather, since it is proportional to the amount of inflowing water, the insolation and the wind speeds respectively. Biomass plants are also

1. A battery or a hydro reservoir do not store electric energy. Instead it is chemical and potential energy respectively that is stored.

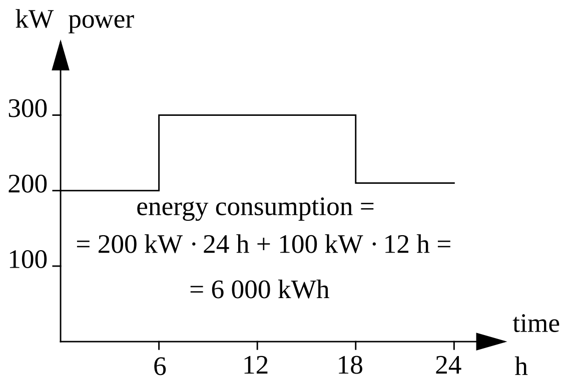

Figure 2.1 *Example of the relation between power and energy.*

energy limited if the amount of bio fuel is limited.

Other energy sources are *power limited*. This is for instance the case with fossil energy sources and some biomass plants. More energy simply means that more fuel is needed, and if fuel not is scarce, then this does not represent a problem.

An example of the demand in a system during one day is given in figure 2.1. Suppose that there are three choices of power systems to cover this demand. System A has an installed capacity of 250 kW which is available during all 24 hours, i.e. the energy limit for system A is 250·24 kWh = 6 000 kWh. System B has an installed capacity of 350 kW which also is available during all 24 hours, which gives an energy limit of 8 400 kWh. Finally, system C has also an installed capacity of 350 kW, but can only use the maximum capacity for 12 hours, i.e. the system has an energy limit of 4 200 kWh. Which of these system can be used? Clearly, system A has not enough capacity to supply 300 kW, which is the peak demand. System C has enough capacity, but the energy consumption is 6 000 kWh and system C can only supply 4 200 kWh. Thus only system B has both enough capacity and enough available energy to meet the demand.

2.2 SYNCHRONIZATION, FREQUENCY AND POWER

All generating units connected together in a AC grid must run with the same frequency. A generator which does not hold the system frequency must be disconnected or it will be damaged. Therefore it is necessary for systems with more than one generating unit that the units are provided with synchronization equipment.

It is also necessary to keep the system frequency stable around the nominal value (normally 50 or 60 Hz). If the power demand exceeds the generation at any moment the system frequency will decrease. To restore the frequency must the total power generation in the system be increased. This is normally done automatically by frequency controllers in some of the generating units. Frequency control presupposes that the unit can regulate its power generation so that it can follow the load. Not all generators in the system need to participate in the frequency control, as long as the capacity in frequency controlling units is large enough. Neither it is necessary that all units that are used for frequency control reacts on momentary changes in the demand; one unit can be used to follow the larger

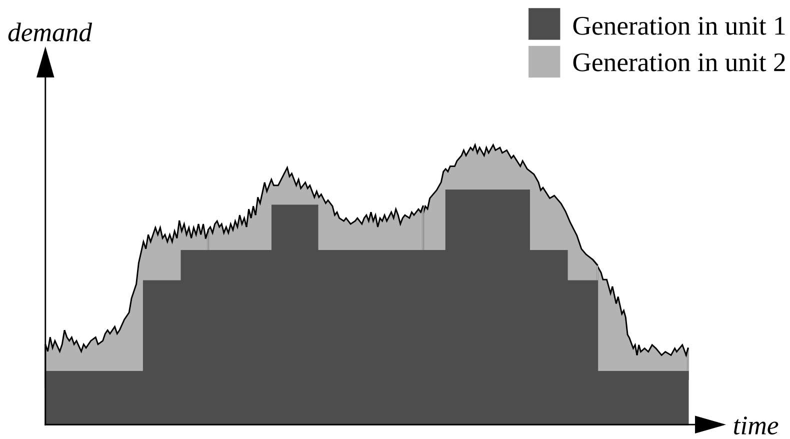

Figure 2.2 *Example of how load following can be divided upon two generating units.*

daily variations and one unit for momentary frequency control, as in figure 2.2. This makes it possible to operate the unit for daily variations at better efficiency.

The frequency can not differ too much from the nominal value. If it is impossible to control the frequency the system must be shut down and restarted. Exactly how large difference from the nominal value that are accepted varies from system to system.

2.3 AVAILABILITY AND ENERGY UTILIZATION

The technical availability is a measure of the reliability of a generating unit. The technical availability is defined by

$$\text{availability} = \frac{\text{part of time when the unit is operational}}{\text{total time}}, \tag{2.1}$$

i.e. as the fraction of time then a power plant can produce power, regardless of if there is a demand for power or not.

The utilization is a measure of if the power is produced when it can be used, i.e. when there is a demand. The energy utilization is defined by

$$\text{energy utilization} = \frac{\text{actual generation of electric energy}}{\text{possible generation of electric energy}}. \tag{2.2}$$

The energy utilization is also called load factor, plant factor or utilization factor.

Note that a low value of the energy utilization can have two explanations: either that the power is generated when the demand is low forcing some power to be wasted, or that the generating unit is used as top power source. A top power source is a unit that is used only when the demand is high or if other units have failed.

The utilization has a large influence of the capital costs. If the utilization factor is low must the annual capital costs be divided over less energy units, and thus will the capital cost per energy unit be high. This is of course of extreme importance for power sources where the capital costs contributes to the major part of the total energy cost, but also for other power sources is the utilization factor important. This can be seen by studying the example in appendix C.1, figure C.1. The capital costs of the petrol generator sets, which have low utilization factors, contributes to a significantly larger part of the total costs, than the capital costs for the diesel generator sets, which have higher utilization factor.

Chapter 3

TECHNOLOGY OPTIONS

In this chapter are the technologies that are available today for rural electrification in developing countries described. Although the objective with this report is to consider renewable energy sources, also diesel generator sets are described. The reason for this is simple; for various reasons are diesel generators the most common electricity source in rural power systems today. This means that it is diesel generator sets that the renewable technologies have to compete with, as well economically as technically.

3.1 DIESEL GENERATOR SETS

Today diesel generator sets are the most common source of electric power in rural areas in developing countries. In many cases have the diesel generator sets been donated by a foreign development aid agency. The reason that diesel generator sets are so common is probably that they are inexpensive to purchase and they can be installed at almost any place that can be reached by a truck. Disadvantages with diesel generator sets are high operation costs and maintenance problems.

Technical description

Internal combustion engines can be used for powering an electrical generator. There are two main types of combustion engines: spark ignition engines which usually uses petrol as fuel and combustion ignition engines which usually uses diesel. Internal combustion engines used for electric power generation are commonly called diesel (petrol) generator sets. Diesel generator sets are often referred to as diesel gensets.

Diesel gensets are available in sizes from about 5 kVA to 30 MVA. Larger units are usually more efficient than smaller. Petrol generators are generally small and have a rating of only a few kVA.

A diesel genset power plant simply consists of a house protecting the gensets and the fuel tank. It is desirable that the power house also has facilities for mechanical repairs, but this is not always the case.

Power system aspects

Most diesel gensets are sold with synchronization equipment, which is necessary if more than one generator should feed a local grid. The power generation in diesel gensets can easily be controlled by the throttle (this can be done automatically), which means that diesel gensets can be used for frequency control. Using diesel gensets for frequency control forces them to continuously follow the load, which increases the fuel consumption. The reason for the increased fuel consumption is that diesel gensets operates most efficiently close to full load.

It is usual in diesel genset powered systems that the installed capacity is much larger than the peak demand, because of the poor availability of diesel generators (see ***Practical experience*** below). It is also common to install more than one diesel genset. A disadvantage with installing many small units is that the efficiency in the smaller units will be less than the efficiency of larger units, but the advantage is that if one of the smaller units fails, only a minor part of the capacity of the plant will be lost. Another advantage with many small units is that it is easier to follow the load, without being forced to operate gensets at low loads, which can be especially valuable if the diesel gensets are used together with wind power or photovoltaics.

Most diesel gensets are equipped with three-phase generators, but the smallest petrol genset usually only generate one-phase power.

Environment aspects

The environment effects of diesel gensets are more or less obvious; diesel is a fossil fuel, which means that combustion leads to pollution of carbon dioxide, nitrogen oxides and sulphur oxides. It must though be stated that the pollution from one diesel genset can be compared with the pollution from a truck, and therefore should a few diesel gensets not be a major threat to the local environment. However, since all combustion of fossil fuels contributes to global warming, if all rural areas in developing countries were to be electrified with diesel gensets, taken all in all could diesel gensets be a problem.

The sound levels within power plants with diesel gensets are usually high, which can be a problem for the staff, especially if ear protection is not available. Another environmental disadvantage is the lubricant oil, which in many cases is not taken care of, but left in holes in the ground.

Costs

Generally the investment cost for installing a diesel genset is low. The maintenance costs are also comparatively low, but the operation costs are high. The operation costs mainly consists of costs for diesel and lubricant oil. Thus the operating cost depend primary on the local diesel price, which in its turn depend on taxes, transportation costs and world market price.

Countries lacking own oil resources have to import the diesel fuel. Import of oil products must be paid with hard currency. A large share of the export earnings might therefore be needed to pay for the oil import. In for instance Tanzania the share was around 50% during the early 80s.[1]

Practical experience

The practical performance of diesel gensets depend on maintenance and supply of spare

1. [8] p. 39.

parts. In many cases are the diesel gensets barely maintained and it can take several weeks – even months – to get spare parts, resulting in very poor availability for the diesel gensets.[2] The poor maintenance does also often leads to a much shorter life span of the genset than stated by the manufacturer.

The fuel consumption is in most cases larger than the nominal fuel consumption stated by the manufacturer. A survey in Tanzania showed that the actual fuel consumption was 10 – 20% higher than the nominal.[3] There are several explanations to this: many diesel gensets are used for frequency control and the maintenance might be insufficient. It also occurs that fuel is embezzled.

Diesel gensets are of course depending on a reliable supply of fuel. If the supply is cut off – due to bad roads, disturbances, war etc. – so is the electricity supply.

Other fuels than diesel or petrol

Spark ignition engines can with minor modifications be fuelled with biomass fuels like producer gas, biogas and ethanol. These biomass fuels can also – after some modifications – be used for compression ignition engines, but in that case it is necessary to use a mix of biofuel and diesel with around 10 – 20% diesel. Compression ignition engines can also use vegetable oils for fuels.[4]

The power rating of combustion engines is decreased when biomass alternatives is used, because of the lower energy content in biomass fuels. The maintenance needs will also increase.

3.2 BIOMASS

Biomass includes a wide range of different fuels and technologies, which all have in common that the basic fuel is derived from biological materials like wood fuel, forest and agricultural residues, energy crops or urban wastes. Biomass already accounts for 38% of the energy use in the developing countries. In rural areas the share is in most cases higher; up to 90% of the energy might be provided by biomass.[5] This biomass is however not used for electricity generation, but primary for cooking and small-scale industrial activities such as brickmaking.

Technical description

There are many technologies for biomass electricity generation available today. An overview is given in figure 3.1. There are basically three principles for the electric power generation: either direct combustion in steam power plants or the biomass can be refined to a more suitable fuel via thermal (pyrolysis or gasification) or biochemical (fermentation or digestion) processes. Which technology that is appropriate in a certain situation is depending on what kind of biomass that is being used. Wood and forest residues can be used for direct combustion and thermal processes. Agricultural residues can be used for

2. See for instance [8] p. 77.
3. [8] p. 75.
4. [4] pp. 241 – 245.
5. [7] p. 595, 607.

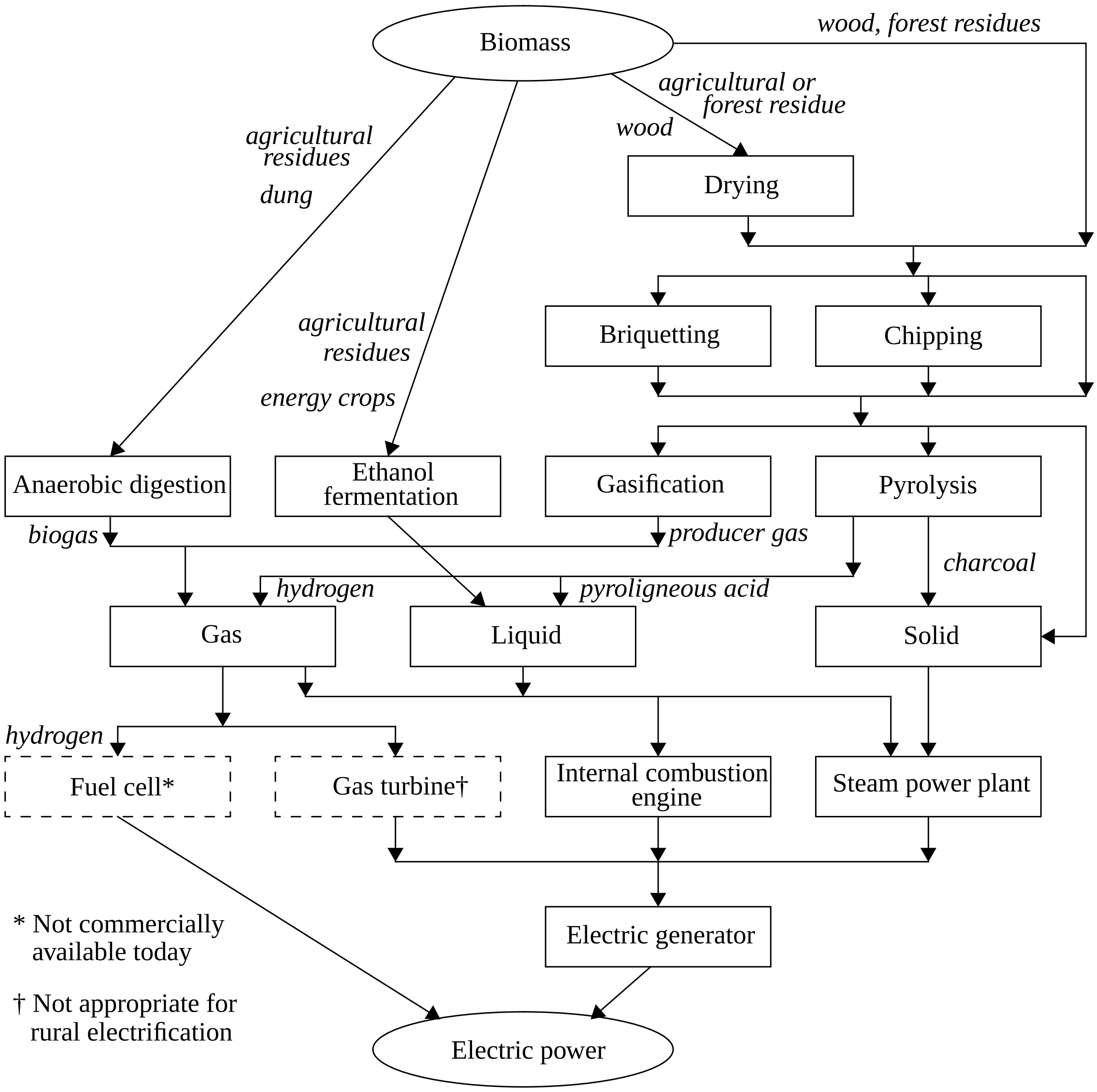

Figure 3.1 *Overview of technologies for biomass fuelled electric power generation. Biogas is a mixture of mainly methane and carbon dioxide ([10] p. 165). Producer gas is a mixture of mainly hydrogen, carbon dioxide, water vapour, methane and nitrogen ([10] p. 192). Pyroligneous acid can be used as a substitute for industrial fuel oil or separated into several chemicals ([4] p. 186).*

thermal or biochemical processing depending on the moisture content of the residues. Animal and human wastes are most suitable for biochemical processing.

Biomass has often a low energy density and is in many cases dispersed, which make it costly and/or energy demanding to collect it. Therefore it is preferable to use biomass fuels that are collected for some other reason, like for instance urban waste and residues from forest or agricultural industries. Animal dung could also be used, provided that the animals are penned and not free ranging.

Gas turbines require well educated personnel and special equipment and is therefore not suitable for rural electrification. Small-scale pyrolysis and fuel cells are still in the developing stage and are not yet commercially available. Fuel cells are further discussed in section 3.6.

Power system aspects

The power generation in biomass plants can be regulated to follow the load, which means that biomass plants can be used for frequency control. The frequency control will reduce the efficiency of the power plant. The size of this reduction is depending on which technology that is used.

There might be some start-up time for biomass power plant, especially for boiler and steam turbine schemes. Biomass plants operated by industries will of course be controlled by the need of the industry.

Environment aspects

The environmental advantages of biomass is that they give no net contribution of carbon dioxide to the atmosphere (and thus do not contribute to global warming), provided that the biomass usage is balanced by regrowth. The sulphur content is usually lower in biomass than in fossil fuels.

There are however also environmental problems with usage of biomass. All combustion in air leads to forming of nitrogen oxides, which causes acidification. Deforestation is a major problem in Africa and many other developing countries and the deforestation can be accelerated by careless use of wood for electricity generation. In some cases it might be preferable to leave the existing forest resources for domestic needs. The opposite is also possible; biomass plants can encourage new plantations of trees for power generation, which might be made in previously deforested land.

At gasification is carbon monoxide formed, which can be a threat to the staff. There is also a risk for explosions if gasifiers are not operated correctly. Tar is formed at both gasification and pyrolysis and has to be taken care of properly.

Costs

The investment cost is higher for biomass power plants than for their fossil equivalents, though the main part of the total energy cost is still the operation and maintenance costs. The maintenance costs are also higher than for fossil fuelled power plants. Biomass power plants can still be profitable compared to a fossil power plant if the biomass fuel is cheap enough.

It is likely that the cheapest biomass can be obtained from industrial (forest or agricultural) residues. In [6] the generation cost of electricity produced in some wood industries in Tanzania were estimated to between 0.08 – 0.14 USD/kWh. The output from such biomass fired plants is around 1 MW, which partly will be used by the industry itself and partly can be used to feed a local grid.

The operation costs decreases if not only the electric power but also the heat can be utilized, so called combined heat and power (CHP). The heat can for instance be used as process heat in some industry.

The life length of biomass power plant is depending on the choice of technology. The investment cost is usually proportional to the life length. Steam power plants have an expected life time of about 30 years. The other technologies are expected to operate for 5 – 15 years.

Practical experience

Most biomass plants demand daily attention from well-trained personnel. Internal combustion engines will require more maintenance when fuelled with biomass fuels than with diesel or petrol.

Many biomass programmes have been started in developing countries, some have been successful, some have not.[6] It seems that one of the most important factors is that the projects have gained approval by the local people.[7]

3.3 HYDRO POWER

This report considers only small-scale hydro power stations, which means that the installed capacity in the station is less than 500 kW.[8]

Building a hydro power station is a large project, which requires proper financing and probably a foreign consultant. Despite this has hydro power a lot of advantages: it is inexpensive in the long run, it is reliable and it can be used as a single energy source in a grid.

Technical description

Hydro power stations can of course not be built anywhere; they require a suitable river within reasonable distance from the consumers. Figure 3.2 shows a principal outline of a small-scale hydro power station. The water is led in a canal to the forebay, which acts as an buffer when the flow through the power station is altered. It is also necessary with spillways so that water can be led away when the turbines are closed. Usually is the original river bed used as spillway. The potential energy of the water in the forebay is converted to electric power as the water falls through the penstock down to the power house, where it turns a turbine. There can be more than one turbine in a hydro power station, but in power stations of the size considered here it is usually enough with one.

The power generation capacity in a hydro plant depends on the height difference utilized in the penstock, and the water flow through the turbine. The utilized height difference is called the head and is here denoted by h. The power generation P equals

$$P = \eta \frac{mgh}{t}, \qquad (3.1)$$

i.e. the potential energy of m kg water divided by the time t and multiplied with the efficiency of the hydro power plant, η. The symbol g denotes the gravitational constant. The mass divided by time is the same as the flow (in m^3/s) multiplied with the density of water, ρ. This gives

$$P = \eta \rho q g h. \qquad (3.2)$$

If the efficiency is assumed to be 75%[9] can the power generation be approximated by

6. [4] pp. 167 – 176.
7. [5] p. 175, [4] p. 180.
8. In other literature is this often referred to as micro or mini hydro.
9. Cf. [1] pp. 7 – 9.

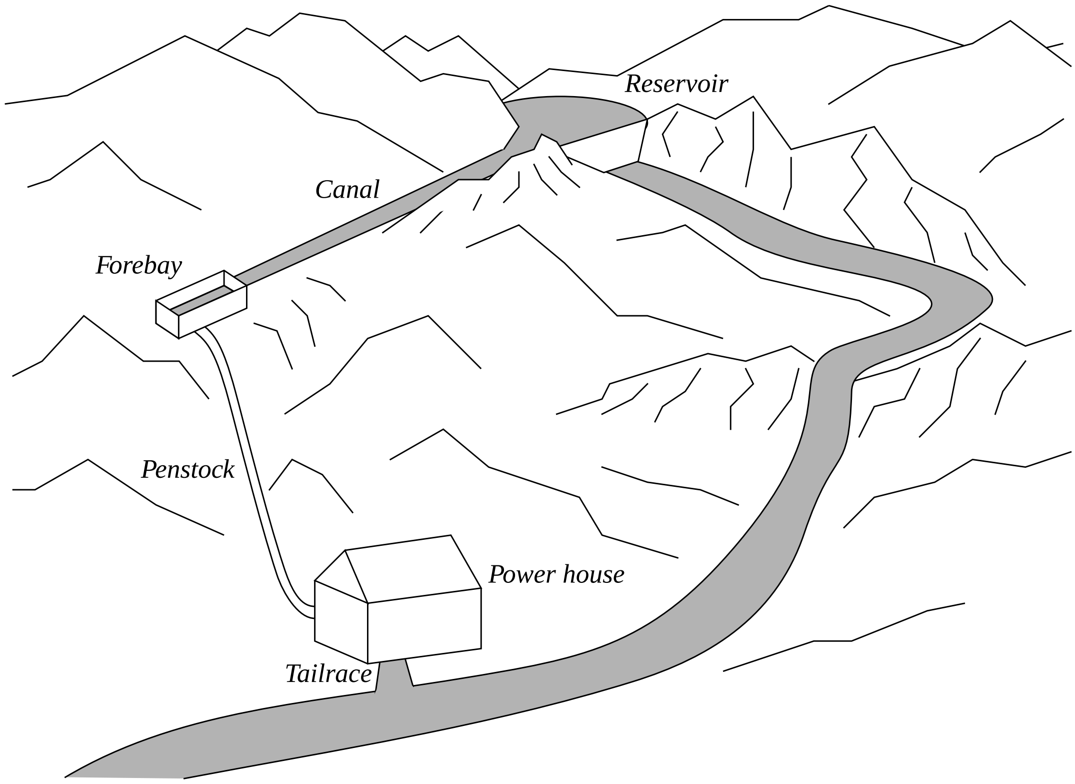

Figure 3.2 *Example of a small-scale hydro power plant.*

$$P \approx 7.5 \cdot q \cdot h. \qquad (3.3)$$

The maximal power generation is thus depending on the maximal flow. The maximal flow through the power station is not necessarily the same as the maximal flow in the river; if there is a reservoir the maximal water flow can be chosen more or less freely.

It is possible to build hydro power plants that also can operate in reverse, i.e. water is pumped from the lower level up to the reservoir. These hydro power schemes are called pump storage units and can be useful if there occasionally is a power overflow in the system. The excess power can then be used to pump water to the reservoir for later usage.

Power system aspects

Hydro power stations can be built with or without a reservoir. If there is no reservoir,[10] water that is not used must be spilled. With a reservoir can this water be stored and used later when the natural flow in the river is smaller or the power demand larger. The proper size of the reservoir varies depending on local factors. If the minimal daily inflow to the reservoir is as large as the daily consumption, but if the power demand is much higher during the evening than during the day, then a reservoir that can store a days energy consumption is enough. If the inflow is significantly smaller during the dry season it might be necessary to build a reservoir large enough to store water for the whole consumption during the dry season.[11]

Frequency control can be done in all hydro power stations, but if a run-of-the-river

10. This is called a run-of-the-river system.
11. Examples on calculations of necessary reservoir size can be found in [1], pp. 27 – 29.

hydro station is the only power frequency controlling unit in the power system it is necessary that the minimum water flow always is large enough to generate power for the peak demand.

The frequency control will reduce the efficiency in the turbine. The size of this reduction will depend on the turbine type, but probably will the efficiency reduction be rather small, making frequency control relatively inexpensive in hydro power stations. If there is more water available than necessary to generate the demand, i.e. if the demand is lower than the energy limit of the hydro power station, the cost for the reduced efficiency is zero, since water will be wasted anyway.

Environment aspects

Hydro power stations of this size are very environmentally benign. The most significant environment effect is that a few hundred meters of the river will be dried out. After the power station is the water led back to the river and can be used by people downstream. Some land will be needed for an eventual reservoir, but the land usage for a reservoir will in most cases be comparatively small. A reservoir might in some cases have a positive environment affect, since the flow in the river will be more even, with less variation between wet and dry season.

Other problems that might occur is an increase in water related diseases caused by the reservoir, or conflicts with farmers upstream the power station who want to use the river water for irrigation. For small-scale hydro power stations it should be quite easy to solve these problems if they arise.

Costs

As most renewable energy sources hydro power has large investment costs and very low costs for operation and maintenance. The investment cost can vary a lot and will depend on the site and the conditions of financing, i.e. interest rate and period of repayment. The investment cost is about 2 000 – 10 000 USD per kW installed capacity.[12] Most hydro power stations has to be located more or less far from the load centre, which means that a transmission line have to be erected. The cost for the transmission line should also be included in the investment cost.[13]

The cost for operation and maintenance should be less than 0.005 USD/kWh.[14]

Practical experience

Hydro power is generally a very reliable power source; a properly maintained hydro power station has an availability of close to 100%. Many missionary stations, farms and small enterprises operate their own hydro power stations without difficulties.[15] The problems with hydro power are probably not technical but management problems. Hydro power projects require proper, long time funding, educated technicians and spare parts must be available.

12. [3], p. 48.
13. Costs for transmission lines are discussed in appendix B.
14. [7], p. 112.
15. [5], p. 196.

3.4 PHOTOVOLTAICS

The development of the photovoltaics can be said to have been started with the U.S. space programme in the early 1970s. The cost of electricity produced in photovoltaics is still quite high, so in industrialized countries, photovoltaics are only used when the distance to grid connection is to large. A lot of research is done in the field and it is likely that the prices will decrease substantially in the future. In developing countries, where energy prices generally are high, and many people live far away from national and local grids, photovoltaics can be an alternative even at current price levels.

Technical description

Photovoltaics produce electric power from solar radiation using the photo-electric effect. Each photovoltaic cell produces a low DC voltage. The cells are connected together into modules that usually produce 12 or 24 V. The power production in a module is depending on the solar irradiation. With photovoltaics commercially available today the efficiency is about 10 – 15%, i.e. 10 – 15% of the energy in the solar radiation is converted to electric power. The efficiency is depending on temperature and decreases with increasing temperature.

A photovoltaic module is usually about 0.5 to 1 m^2 large and can be installed practically anywhere. To gain as much energy as possible out of the module it is necessary to avoid disturbing shadows and to choose the correct tilt angle of the modules.[16] The total energy generation during the year can be increased if the modules are mounted on support structures that follow the sun. The increased generation is in most case not sufficient to motivate the cost for the extra equipment to manoeuvre the support structures. In rural power systems, where skilled technicians are rare, it is also preferable to use as simple technology as possible.

The capacity of photovoltaic modules is specified in peak Watts (W_p) under standard test conditions (STC). Peak Watts refers to the maximum power output and STC means an irradiance of 1000 W/m^2, energy distribution as sun light through 1.5 layers of atmosphere and a cell temperature of 25 ˚C.

Power system aspects

Since photovoltaics only produce power when illuminated, a backup system is necessary. The backup system can either be another power source or batteries. Since the power generation in the photovoltaics is depending on the irradiance and can not be controlled, photovoltaics can not be used for frequency control.

As stated above, photovoltaics produces DC power, but most consumer products are made for AC power.[17] Therefore it might be necessary to have an inverter, which converts DC to AC. Batteries and inverters are further discussed in appendix A.

Photovoltaics can also be used to feed a grid directly, without using batteries. These systems uses several inverters; each inverter serves a group of photovoltaic modules. The inverters are connected together in three groups, where each group is connected to one phase of the grid.

16. How to choose tilt angle is described in [11].
17. See section 4.1 for a further of discussion which applications that can be used in a DC system.

Environment aspects

Photovoltaics generate electricity without any emissions to the environment, but production of photovoltaics is very energy demanding, which can be an environment problem if the energy for the production is generated in fossil fuelled power plants. This does however not seem as an argument against using photovoltaics in developing countries; instead the industrialized countries which produces the photovoltaics should use more environmental benign energy sources.

For the user the main environment problem is eventual batteries, which contain lead and/or other heavy metals. These can cause severe negative environment effects if not disposed or recycled properly.

Costs

As mentioned in the beginning of this section, the price for photovoltaics is rather high, but can be expected to decrease in the future. Today the prices varies between 8 and 14 USD/W_p. Smaller photovoltaic modules are generally more expensive per W_p than larger units, which can be seen in the price examples in appendix C.3.

It should be noted that a customer who buys large amounts of photovoltaics should be able to get a significant discount. Contacts with retailers indicate that the discount might be up to about 40%.

A lot of research is made to develop less expensive photovoltaic cells. One of the most interesting technologies are thin-film photovoltaics. These are already manufactured today, but the efficiency is still poor (only around 8%). When the problem of manufacturing thin-film cells with better efficiency in large quantities is solved, the price is expected to drop substantially.

Practical experience

Photovoltaics have a life span of at least 20 years[18] and require very little maintenance. Batteries have a shorter life time; around 5 years is a common estimation. Theoretically a photovoltaic power system would operate without repairs and with very little maintenance[19] for long periods.

In practice however the experiences seem to vary. At a field visit to Kasulu in Tanzania, two out of four photovoltaic systems were out of order, while the owners of the other two systems were very satisfied and had no complaints. Why these systems had failed was not examined, but the most likely is that the batteries had not been maintained properly.

According to Mr. Leif Selhagen at Neste Advanced Power Systems Sweden the most important with solar systems is that the users are informed about the maintenance needs and that they can be assisted by a qualified technician. Under these circumstances can solar systems perform very well for many years.

18. This figure is an estimation, since the photovoltaics that are sold today have not yet been on the market for 20 years. It is not unrealistic that the photovoltaic modules will last for more than 20 years.
19. Basically the photovoltaic modules have to be cleaned from dust and suchlike, and eventually the battery need to be refilled with water.

3.5 WIND POWER

Very few wind power plants have been set up in Sub-Saharan Africa, although about 30% of the land area has an average wind speed of more than 5 m/s.[20] Almost all wind power plants that have been installed are connected to the national grid.

Wind power is often disregarded because an area is not considered windy enough. For rural power systems, where energy prices tend to be very high, can wind power still be an interesting alternative, even at wind speeds that would not be considered profitable for generation to the national grid.

Technical description

In a wind power plant is the kinetic energy of the wind used to turn a turbine, which generates electric power. The wind speed is of extreme importance, since the generation in a wind power plant is proportional to the cube of the wind speed. This means that if the wind speed increases 10%, the generation increases $1.10^3 = 1.331$, i.e. an increase with 33%. Therefore it is of particular importance to choose a site with as good wind speeds as possible. It is also important that there are no obstacles, like buildings and vegetation, that disturbs the wind.

Smaller wind power generators (less than 1 kW) generate 12 or 24 V DC. These generators are not intended to be connected to a local grid, but to be used for loading a battery and are therefore often called *wind chargers*. Larger wind power plants generate three-phase AC power and are available in sizes from about 50 kW up to 1.6 MW or higher.

Power system aspects

The power rating for wind power plants refers to the size of the generator. The actual power generation will depend on the current wind speed, which of course varies continuously. Therefore a wind power plant always need some kind of backup system, either batteries (for wind chargers) or another energy source (for grid connected wind power plants). Wind power plants can not be used for frequency control, since the power generation in the plants can not be controlled.

Environment aspects

The environment effects of wind power is mainly aesthetic; a wind power plant is high and can be seen from large distance. The blades are rotating faster than the surrounding air, which causes some moderate noise, but at higher wind speeds this noise will be drowned be the sound of the blowing wind. Both these problems should be negligible compared to the benefits of electricity.

There is also a small risk that the blades can break and be hurled away. Wind power plants should therefore be located at some distance from the closest settlements. Sites with very intensive bird life, for instance along main migration routes, should also be avoided.[21]

---

20. [14] p. 153.
21. [14] p. 172.

Costs

The costs for large wind power plants is today around 1 000 USD per kW installed capacity. If a large order is made it is possible that the buyer will get some discount. Transmission lines from the wind power plant to the load centre is not included in the cost estimation above and neither is the cost for purchasing land. Small wind generators for DC generation are usually much more expensive per Watt. Price examples for wind power are found in appendix C.4.

Operation and maintenance costs are generally very small compared to the capital costs. For larger wind power plants it is common to make a service agreement with the manufacturer of the plant. An annual fee includes maintenance and spare parts. The fee is about 4 000 – 8 000 USD depending on manufacturer, size and location of the plant. Maintenance of wind chargers can be done by the owner and the cost is therefore negligible.

Practical experience

In industrialized countries wind power plants usually have a very high availability.[22] Wind power plants are constructed for being operated without supervision and it is therefore reasonable to assume that wind power plants in Africa also will have a high availability.

A difficulty with planning wind power projects is that it might be difficult to find reliable data of wind speeds. Wind speeds from at least one year are necessary for both cost estimations and selecting the best site for the plant. It is possible that no measurements ever have been done in the area, which means that a gauge station has to put up. Automatic wind speed gauge stations can be rented from manufacturers of wind power plants.

3.6 OTHER TECHNOLOGIES

The technologies described in the previous sections are today the most likely to be used for rural electrification in developing countries. All these technologies are already used commercially either in developing or industrialized countries. In this section a few words will be said about other technologies, that either are still under development or that today do not seem appropriate for rural electrification although they are technically possible.

Fuel cells

There are several designs of fuel cells, but all have in common that electric current is generated directly (i.e. without combustion) in a chemical process. The most common process is that hydrogen is oxidated. The waste product of this reaction is ordinary water.

Hydrogen can be produced in several ways. Since most fuel cell designs requires that the hydrogen is more or less free of contaminants as carbon monoxide or carbon dioxide, most fuel cell hydrogen is produced from fossil fuels. It is however also possible to produce hydrogen from biomass.[23]

22. In for instance Sweden the availability was 98.4% in 1997 according to Svensk Vindkraftförening (Association of Swedish Wind Power).

Prices today are too high for commercial use, but fuel cells are still under development. In the future the energy cost might decrease to between 0.10 and 0.30 USD/kWh.[24]

Geothermal energy

Geothermal energy uses the heat of the earth's crust to produce electric energy. Geothermal energy has been used commercially since the beginning of the 20th century. Italy was the first country to use geothermal energy in larger scale, and other countries like the United States, Japan and Iceland have followed. Geothermal energy has also been utilized in developing countries, for instance Philippines, Mexico, Nicaragua, Indonesia and Kenya. Most of the interesting areas for geothermal energy are located in regions distinguished by seismic activity, but also other areas could be used.[25]

Although the costs for geothermal energy are estimated to 0.03 – 0.10 USD/kWh, the minimum size for a profitable geothermal power plant seem to be some MW.[26] This is probably too large for rural systems, which are not likely to have a demand of more than 1 MW. Further, geothermal power plants are advanced and risky projects, which probably need to be carried out through a national energy company.

Ocean energy[27]

The oceans contain energy in form of tidal energy, wave energy, ocean-thermal energy and salt-gradient energy. The only commercially technology today exploits the tidal energy and also this technology is rather expensive, although the prices might be low enough to be competitive in developing countries. However, since this is a not yet a fully developed technology and it is only available in coastal regions, this does not seem to be an interesting alternative for rural electrification.

23. See figure 3.1.
24. [2], pp. 536 – 544.
25. [7] pp. 550 – 552.
26. [7] p. 577.
27. [7] chapter 12.

Chapter 4

ELECTRIFICATION SCHEMES

This chapter is an attempt to describe the options for electrification in some load situations. It must be noted that everything said in this chapter is only guidelines; each site is unique and need special consideration. Differences in local prices can affect the price comparisons. It is also a question about willingness to pay; how much extra may a more reliable or environmental benign solution cost?

The chapter is opened with an exposition of which requirements the power system has to fulfil if it should be possible to use some common loads. Then follows three scenarios, describing certain load situations and the options for electrification in these scenarios.

The three scenarios are individual systems which supply only one consumer, local grids where there only is a power demand during part of the day, and finally local grids that are operated during all hours of the day.

4.1 COMMON LOADS

To determine the power needs that have to be fulfilled by the power system, it is necessary to study the appliances that will be used in the system, since appliances which require a lot of power or energy might be unsuitable in battery depending systems. A guideline is that a battery can store around 0.5 – 1 kWh. Thus an electric iron used for one hour would empty most batteries. Some appliances are not available for DC and thus an inverter is needed if such an appliance should be powered by a battery. Finally, a few appliances require three-phase AC supply.

Below follows a short presentations of the appliances that are most likely to be found in a rural power system in a developing country.[1]

- **Air conditioning and fans.** Air conditioning requires AC voltage. They have a power consumption in the range 500 W to 1 kW. Fans are available for both AC and DC. Typical power consumption for a fan is less than 100 W.
- **Cookers.** Although electric cooking is the most energy efficient way of heating food,[2]

1. Whether appliances are available for DC power or not is based on a brochure, *"Stuga utan el"* (cabin without electricity) from SunWind Energi AB, over DC appliances which are sold in Sweden. These appliances might not be available in all developing countries and the contrary – that some DC appliances are not sold in Sweden – is of course also possible. However, the objective of this section is only to give a basic description over the demands for certain appliances, not to be a complete survey.
2. [7] p. 676.

electric cookers are rather unusual. The reason for this is that electricity is so much more expensive than wood fuel. Electric cooking can though be competitive to kerosine, if the electricity is cheap enough. Electric cookers are made for AC and have a power consumption of about 1 kW per plate.

- **Industrial appliances.** Industrial appliances[3] are different kind of electric motors, battery chargers, welding sets etc. Such appliances require AC voltage (in many cases three-phase AC) and have a power demand of around 1 kW or higher.
- **Hospital equipment.** Some hospital equipment, like microscopes and refrigerators for cooling vaccine, are available for both AC and DC voltage. Others, like sterilization equipment, X-ray machines and developing machines, are made only for AC voltage and consume several kilowatts power.
- **Ironing.** Electric irons are made for AC voltage and they have a power consumption of about 1 kW.
- **Lighting.** Lighting is available for both AC and DC voltage. Bulbs usually have a rated power between 40 and 100 W. Stronger lights, like mercury lamps used for public lighting, can have a power consumption of 250 W or higher, but this kind of lighting is only available for AC voltage.

  Compact fluorescent lamps (CFLs) use less power (about a fifth of the corresponding bulb), but they produce the same amount of light, which makes them more energy efficient than ordinary bulbs. The price for CFLs is higher than for bulbs, but a high quality CFL will last between 8 and 12 times as long as an ordinary bulb. Unless the energy price is very low CFLs will be profitable in the long run. The problem is the high purchase price, which tend to discourage the consumers.[4]
- **Office machines.** Office machines like copiers, computers, duplicating machines, electric typewriters, telefax machines etc. are made for AC voltage. Most machines require less than 250 W, but copiers consume around 1.5 kW when used.
- **Radio and TV.** These appliances are available both for AC and DC voltage. Radios usually have a power consumption of less than 10 W. TV sets consumes between 40 and 100 W. TV sets for DC voltage are usually small (10" screen). Most video recorders require AC voltage, but there are DC versions too.
- **Refrigerators.** Refrigerators are available for both AC and DC voltage. The power consumption of the refrigerator will depend upon outside temperature and how much that is put inside the refrigerator, but a typical power consumption is around 100 W. DC refrigerators are usually smaller and consume around 20 W. Refrigerators do not need power supply during all hours of the day, although it of course is preferable. It is possible to use refrigerators in power systems that are only available fours hours every day.
- **Sewing machines.** Sewing machines require AC power and typically have a power consumption around 100 W.
- **Water pumping.** Special water pumps are available for DC systems. The power consumption is depending on the depth and the desired flow, but it is usually less than 100 W. Water pumps are available for pump depths of about 80 – 100 m.

---

3. This refers to light industrial activities like milling machines, garages, carpentries etc.
4. See [12] for more details about CFLs.

For municipal water supply is standard asynchronous motors, which require three-phase AC power, probably more suitable.

4.2 INDIVIDUAL SYSTEMS

In this report an individual system refers to a household or public building (e.g. a school or a dispensary), which is having an own power system, not connected to any grid. If the distance to other consumers is large enough, it will not be profitable to connect an individual system to others. How large the distance must be to make an individual system more profitable will of course vary with local factors, but as a guideline it can be said that it is not recommended that a low voltage AC grid extends more than 500 m. Building a distribution line with medium voltage seems unreasonable for a single consumer, if the load is not in size of several tens of kilowatts.[5]

Individual systems will probably be used to supply electricity mainly for lighting, but maybe also for water pumping, radios and refrigerators. Thus it is possible to use DC voltage in these kind of systems, but using DC voltage will limit the size of the systems; DC cables may not be too long if the losses on the cable not should be too large. If losses of 10% is accepted[6] and we have a 12 W appliance fed by a 12 V DC system the resistance in the cable may not exceed 1.2 Ω. This corresponds to a cable length of 50 – 150 m, depending on the thickness of the cable.

Solar home systems and wind chargers

These systems use either a photovoltaic panel or a wind charger (or a combination of both) to charge a battery. The battery can then feed the appliances directly or an inverter can be used, converting the DC power provided by the battery to AC power.

It is not easy to say whether a DC or AC system is to prefer. It seems that AC products are cheaper than their DC counterparts, but on the other hand the inverter represents an extra cost. The efficiency of modern inverters is around 90%, which means that the cost for the electric energy produced in the photovoltaics/wind charger will be increased with around 10% due to the losses. On the other hand, some appliances are only available for AC voltage. People who have moved in from electrified areas might already have AC appliances and if the individual system later is connected to a grid, DC appliances will be less useful (see the discussion in section 5.1). Finally the decision has to be made by the consumer, what he or she is ready to pay for.

The major problem with solar home systems or wind chargers is that their performance depend on the weather. In some cases it is so fortunate that sunshine and wind speeds are negatively correlated, i.e. it is likely that the wind speed is high when the sun is not shining and vice versa. If this is not the case, the system must then either be designed for the worst case or it might be necessary to accept a poor reliability. Designing the system for the worst case, for instance adding extra batteries to store power for long periods without sunshine, increases the cost of the system significantly.[7]

5. Cf. cost examples for distribution lines in appendix C.6.
6. This is a large loss percentage. As comparison can be mentioned, that in the Swedish main transmission grid, which extends several hundreds of kilometres, the losses are around 6 – 7%.
7. Cf. the cost calculations for one and two batteries respectively in [1], p. 33.

An advantage of individual systems is that if a fault occurs, only one customer will be affected, in opposite to grid system where a failure in the central power plant can leave all customers without power.

Solar home systems require a minimum of maintenance. The solar panel has to be kept clean and most batteries need to be filled with water occasionally. Wind chargers only require some greasing of bearings.

Batteries are best suited for systems with a peak demand of a few hundred Watts and a daily energy consumption of less than 1 kWh,[8] but by choosing the right kind and number of batteries it is possible to supply almost any load with an individual system. It is of course as always a question about costs: high performance batteries are more expensive than the standard batteries that are designed for usage with photovoltaics and wind chargers. But although it is possible to supply for instance electric motors with an individual system it is probably not the best solution, since the energy cost in individual systems is so high. Besides, consumers with large energy consumption, like small industries and hospitals, are likely to be found in townships, where there probably are many other possible consumers, making a grid solution more interesting.

Petrol generator set

A small petrol or diesel generator set is probably the only alternative to solar home systems or wind chargers for small individual systems. With the high prices for photovoltaics today, a petrol generator set is often less expensive, but this will depend on local fuel price and the utilization factor. If the utilization factor is low will the capital cost for the petrol generator set increase the total energy cost.[9] Therefore petrol generator sets will not be preferable for very small consumers, unless the petrol is really cheap.

Petrol generator sets usually produce one-phase AC power, which means that most appliances can be powered by the petrol generator set, if only the capacity in the generator set is enough. Petrol generator sets also have the advantage that the power is available when needed.

A petrol generator set needs tender maintenance to operate well, which requires a person with at least basic technical skills. It might also be difficult to find spare parts if the engine or generator fails. Another problem is the fuel supply. If the closest petrol station is far away – and this is probably the case for many individual systems – it might be difficult to get fuel. Transporting fuel over long distances using manual labour do not seem realistic and using a vehicle for fuel transports will only make the operation costs of the generator set even higher.

Another disadvantage with petrol generator sets is that they are noisy and produce exhausts.

Combined systems

It is of course possible for a consumer which has both low and high power consuming appliances to have two individual systems; for example a solar home system or wind charger for the low power appliances and a petrol generator set for the high power devices. It is also possible to connect these systems, provided that the solar home system or

8. Cf. with the load descriptions in section 4.1.
9. Cf. the example in appendix C.1.

wind charger system is equipped with an inverter.

There are however some technical disadvantages that makes this kind of schemes less attractive. The inverter can either be grid or self-commutated.[10] A grid commutated inverter will require that the petrol generator set is running even though no high power appliance is used. This will be costly, since the petrol engine will consume fuel without generating electric power. If a self-commutated inverter is used, the petrol generator set must be disconnected when the appliances are to be fed by the inverter and vice versa; the inverter must be disconnected when the petrol generator set is generating power. An inverter that automatically can switch between being grid or self-commutated could of course be designed, but today such inverters are not standard equipment.

If a consumer has a need for a petrol generator set to be able to operate a power demanding appliance it should also be noted that the marginal cost to also generate the power for low power appliances in the petrol generator set is equal to the operation cost of the petrol. Thus, when comparing the costs for supplying low power appliances with a separate battery fed system or with the petrol generator set, the capital costs for the petrol generator set should be excluded, since the generator set will be necessary anyway. This however requires that the high power appliance is used approximately at the same time as there is a need for power to the low power appliances; in other case it might be very bad economics to operate the petrol generator set.[11]

4.3 LOCAL GRID WITHOUT INDUSTRIAL ACTIVITIES

This scenario applies to consumers that are located so close together that it can be profitable to connect them in a local grid. The consumers have basically the same power demand as the consumers in section 4.2, i.e. it is not necessary to supply power during all hours of the day. Since the major part of the load is lighting, it is most important that power is available during the evening.

Weather depending power sources

Photovoltaics and wind power are not very suitable for grids that are only operated during parts of the day, since the power production of photovoltaics and wind power cannot be dispatched to the right time period. It is of course possible to use the same solutions as for individual systems and store energy in batteries, but in most cases will a solution with many individual systems be more expensive than power from a local grid.

Hydro power plants have the same disadvantage as photovoltaics and wind power; to get the lowest energy cost it is necessary that the generation capacity is utilized as much as possible, which means that there is no reason to operate a hydro power plant only during parts of the day. The exception is if the daily inflow is not large enough to provide power during the whole day; it could then be desirable to save water in a reservoir and use it when power is most wanted (usually during the evening), instead of expanding the capacity in the grid with another power plant.

10. See appendix A.2.
11. For example is operating of a 3 kVA petrol generator just to feed 30 W of lighting not reasonable.

Power plants fuelled by biomass or diesel

The operation cost for biomass plants and diesel generator sets is generally large compared to the capital costs. Therefore it is not necessarily preferable to produce as much energy as possible in these units. If the demand is low during part of the day, it might be better to turn off the plant than to operate it during unfavourable conditions, i.e. the increase in capital costs due to lower utilization factor is less than the increase in operation costs, when the plant is operated at low efficiency.

Small local grids which do not need power during all hours of the day are probably suitable for biomass fuelled schemes, because the biomass consumption might be small enough to make it possible to collect it with reasonable efforts.[12]

Low voltage network

In this report a low voltage network refers to a very small grid, which basically connects several individual systems. Such a grid can either use DC or AC power. A DC network should not have any cables longer than 100 – 150 m.[13] The cables in an AC network could be up to around 500 m.[14]

The main difference between a low voltage network and other local grids discussed in this report, is that the low voltage network has no need for transformers, since the power is distributed at the same voltage as it is generated. A low voltage will thus not be very costly and it should not require more than basic electric skills to build it.

The advantage of a low voltage grid is that the costs for increased capacity can be split among the consumers. If the low voltage network for instance is fed by solar home systems or wind chargers can the reliability be increased by adding extra batteries to the system and the cost will probably be less than if each consumer would have his own backup battery. Batteries in low voltage networks should though be connected to only one inverter, since self-commutating inverters can not be connected together.[15]

It is easier to find a petrol or diesel generator size of proper capacity, since the total demand in a low voltage network is higher than the demand in an individual system. When the overcapacity is reduced, the utilization factor will be increased. This means that petrol or diesel generator sets will be more attractive for these systems than for individual systems.[16] If a suitable biomass fuel is available, diesel or petrol can be replaced by alternative fuels.[17]

12. See for instance [4], pp 188 – 189.
13. Cf. that was said about DC cable length in the introduction of section 4.2.
14. Cf. appendix B.
15. Cf. appendix A.2.
16. For an individual system with an average load of only 50 W, even a very small petrol generator with a rated capacity of 500 W will be oversized for the system, resulting in a very low utilization factor. With low utilization will the capital costs increase as can be seen in figure C.1. Further, the efficiency of the generator set will low when the motor is close to idling, which will increase the fuel costs.
17. See sections 3.1 and 3.2.

4.4 LOCAL GRID WITH INDUSTRIAL ACTIVITIES

Industrial activities[18] means that there will be a power demand during all hours of the day Also hospitals have a need for power during all hours, although it of course if necessary is possible to schedule x-ray photographing, sterilization of medical equipment etc. to hours when power is available.

Almost any combination of power plants can be used to supply a local grid operating during all hours of the day, as long as there is enough capacity to operate the frequency control. The most interesting combinations are discussed below.

Hydro power with or without backup

If hydro power is available within reasonable distance[19] this is often the least expensive option for electrification, at least seen over a longer time period. If there is a need for a complementary source,[20] any other source can be used. If the wind speeds are high then wind power is a good complementary energy source; especially if the wind power plant can be located close to the hydro power station, so that they can be connected to the same transmission line. Photovoltaics might also be an alternative. Both wind power and photovoltaics require that the hydro power station has a reservoir, so that the water can be dispatched to time periods when the wind or solar electricity generation is not sufficient.

Diesel generator sets and biomass can always be used as backup for hydro power. Which alternative that is most preferable is depending on local fuel prices and has to be investigated for each site.

Biomass

Biomass power plants require an infrastructure that can supply biomass fuel which is cheap enough to be competitive to diesel or other fossil fuels. The best sites for biomass plants are thus industries generating residues that can be utilized for electric power generation in association with the industry. It is even better if the heat from a steam power plant can be used as process heat in the industry itself.

Diesel generator set

If no suitable site for a hydro power station is available and the local environment cannot support biomass usage or a biomass plant would be too expensive, then a diesel generator set is the only possible option for electrification. However, depending on diesel prices and other local factors, it might be profitable to use wind power or photovoltaics as complementary energy sources. When the wind power plant or photovoltaics generate power is the generation in the diesel generator set decreased. The diesel must though be left

18. Industrial activities refers to light industry as described in section 4.1.
19. Exactly what reasonable distance means depends on the demand, the size of the hydro power plant and the cost for building a transmission line.
20. This could be the case if the maximum power output from the hydro power station is lower than the peak demand or if the energy limit of the hydro power station is lower than the energy demand. A more detailed discussion about power and energy limits is found in section 2.1.

running, since the frequency control must be performed by the diesel generator set.

A diesel generator set in wind-diesel system will usually consume more fuel per kWh than a diesel that is sole power source. This is caused by the continues fluctuations in wind power generations, which has to be compensated by the diesel generator set, forcing it to operate at part load. It might also be more difficult to keep the frequency stable in a wind-diesel system, although a properly designed wind-diesel system actually can have better frequency stability than just a diesel generator set.[21]

Also solar-diesel systems suffer from the same disadvantage; when the photovoltaics are producing the diesel generator set might be forced to operate at part load. The fuel consumption per kWh might then be increased, so that no money is saved by using the photovoltaics.

Complementary energy sources

It is not possible to use photovoltaics or wind power as single power source in a local grid, since they can not follow the load.[22] It must therefore always be at least one other energy source in the system, and the photovoltaics or wind power will only be a *complement* to the other energy sources, i.e. a hydro power station, biomass plant or diesel generator set.[23] How much of the installed capacity that can consist of complementary energy sources is depending on the load in the system[24] and will therefore vary from site to site.

A complementary energy source can either be used to reduce the generation costs in the grid; if the cost for the complementary energy source is lower than the cost in the frequency controlling unit, then it is desirable to generate as much as possible in the complementary sources. If the frequency controlling unit or units are energy limited system, the complementary energy sources can increase the total energy limit in the system.

The energy cost for a complementary solar system will be significantly lower compared to AC solar home system, since there will be no need for batteries and the inverters can be fully utilized, which reduces the capital costs per energy unit for the inverter. Further, a company that buys photovoltaic modules for a 100 kW_p solar system, have good chances of getting a substantial discount on the modules. Thus, if the operation and maintenance costs for a diesel system are high and photovoltaic modules can be bought with a sufficient discount, photovoltaics might already today be profitable for power generation in a local grid.[25]

21. See [9].
22. This is not exactly true; if the generation is *larger* than the demand it is always possible to waste the excess power. This will of course increase the generation cost in the system, since the units are not fully utilized. In some special cases this might still be preferable, but generally it is not.
23. It would of course also be possible to use photovoltaics and/or wind power in combination with batteries and inverters as in individual systems. However, for local grids would such a system be too expensive.
24. The frequency controlling units must have enough capacity to be able to follow the load variations. Cf. section 2.2.
25. Cf. examples in appendix C.1.

Chapter 5

DEVELOPMENT OF RURAL POWER SYSTEMS

As the demand of electric power grows, the power systems must also grow. Local grids will have to be expanded, distribution or transmission lines with higher voltages will have to be erected, new power plants must be constructed etc. It is necessary to consider this development of the power system already when planning the original system, at least if the demand is expected to increase within the economic life span of the original power system.

5.1 CONNECTION TO A LOCAL GRID

For a consumer with an individual system it is of course desirable to be connected to a local grid, especially if the consumer wishes to start using more power and energy demanding appliances as for example an AC motor. As always this is a question of economy. Below the costs and benefits of connection to a local grid are discussed for DC and AC individual systems.

DC individual system

Connection to a local grid means that the consumer has to pay a connection fee. The consumer will of course also have to pay for each consumed kWh according to the local grid prices. Compared to a solar home system or a wind charger, which both have approximately no operation cost, the grid prices will almost certainly be higher. Thus the marginal cost to continue use the individual system will be less than the local grid price, at least until the battery has to be replaced. However, the connection to the grid can be profitable, if only the individual system can be sold to somebody else, who has no possibility to connect to a grid.

The switch to electricity from the local grid will also result in that most of the consumers equipment will be useless. It is of course possible to charge batteries in a grid powered battery charger, and then continue to feed the applications from the battery. This is however a very inconvenient solution. As can be seen in appendix C the batteries are one of the most expensive parts of an individual system and therefore a part that is desirable to get rid of. Further, this system will still suffer from the limitations of batteries.

AC individual system

Connection to the local grid will be less costly for owners of an individual system with an inverter (if the system power source is photovoltaics or a wind charger) or if the system is based on a petrol generator set. The appliances will already be adapted for AC voltage and thus the investment cost for the connection will only be the connection fee.

Petrol generator sets will almost certainly have a higher operation cost than the price for grid electricity and is therefore not profitable to continue operating. Solar home systems and wind chargers will, as in the DC case, have very small marginal costs and it would therefore be preferable to continue to use these systems and only use grid electricity for backup. This is however not possible without buying a new inverter, since inverters for individual systems can not be connected to a grid (see appendix A).

5.2 EXPANSION OF A LOCAL GRID

When the demand is beginning to reach the peak capacity of the local grid either a new power plant can be built or the local grid can be connected to another grid. The latter does usually mean connection to the national grid, which is discussed in the next section. It could however be less expensive to build a transmission line to a nearby local grid with spare capacity. The choice of building a transmission line or a new local power plant is purely economic, and depend on real rate of interest, expected growth rate, costs for new power plants etc.

The cost of expanding existing power plants vary for the different technologies. For photovoltaic systems the cost for new panels will – discounts not regarded – be the same as the cost for the existing system. Also biomass and diesel gensets can be expanded to approximately the same cost or maybe even lower costs if the same buildings can house the new units. Expansion of wind power is most profitable if the new plants can be located close to the existing, so that the same transmission line can be utilized. Finally, hydro power schemes might be possible to expand if not all of the water flow already is used. For instance, a run-of-the-river scheme might be expanded with a reservoir or an additional turbine might be installed. Expansion of existing hydro power stations though requires that the expansion has been planned already at the commissioning; in other case it might be very costly.

Note that the necessary expansion can be postponed by using demand side management, i.e. by encouraging large power consuming appliances to be used when the remaining demand in the system is low. Water pumps could for instance be operated only during the night.

5.3 CONNECTION TO THE NATIONAL GRID

Sooner or later it will be profitable to connect local grids to the national grid, unless the local grid not is located on an island or some other area that is very hard to reach. How large the demand in the local grid must be to make a connection to the national grid profitable depends on how long transmission line that has to be built, if other local grids can be connected with the same transmission line etc. Generally, connection to the national grid is a large project that is coordinated by the government or a national electricity company.

Connection to the national grid means lower electricity prices and higher reliability – at least if the national grid is well maintained and there is enough generation capacity to cover the demand in the national grid. What will then happen to the local generating units after a connection to the national grid? Hydro power stations, photovoltaics and wind power plants have very low operation and maintenance costs and will therefore still be profitable even when they compete with the lower electricity prices in the national grid. Biomass plants might or might not have operation and maintenance costs that can compete with the national grid, depending on the fuel prices and the efficiency of the biomass plant. Diesel generator sets are generally too expensive.

Generating units that are no longer used can in some cases be sold to areas yet unconnected to the national grid. This is primary an option for units that are easy to transport, i.e. diesel generator sets, photovoltaics and depending on local circumstances maybe even wind power or biomass plants. Diesel generator sets and biomass plants can also be kept as reserve power.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

In the previous chapters the most likely options for rural electrification have been presented. This chapter is an attempt to summarize and evaluate these options and to present some general guidelines about when each technology is most suitable. This chapter also discusses some economic issues, as for instance the financing of a local system.

6.1 EVALUATION OF THE AVAILABLE TECHNOLOGIES

Below follows a very brief summary of the advantages and disadvantages of the technologies that have been studied in this report.

Diesel generator sets

The major advantage of diesel generator sets is that they are cheap to buy and can easily be installed at most sites. The disadvantages are that they require a lot of maintenance and that they use fossil fuel and thus are not environment friendly, although the impact on the environment from a few generator sets might not be too harmful.

Maintenance of diesel generator sets is often difficult due to lack of spare parts, resulting in poor availability. The operation cost of diesel generator sets are mainly depending on the price of the diesel fuel. If the price is high – and this is often the case – diesel generator sets can be more expensive than renewable alternatives.

Biomass

Biomass power plants require access to cheap biomass fuel to be competitive to diesel generator sets. It is not only the cost for the biomass itself but also the costs for collecting it and transporting it to the plant that is important.

There are several commercially available technologies for energy generation with biomass as fuel. Generally biomass plants do require well educated personnel, since the operation and maintenance of biomass power plants is usually somewhat more complicated than for the fossil fuelled counterparts.

Biomass can or can not be environmental benign, depending on whether the biomass is grown sustainable or not. Some biomass conversion processes also produce wastes that have to be taken care of properly.

Hydro power

For good locations hydro power is probably the most inexpensive power source, at least in the long run. Small-scale hydro power plants must though be located as close to the consumers as possible, if the transmission costs should not be too high.

It is an advantage if the hydro power scheme includes a reservoir, because this makes it easier to dispatch the hydro power generation, both over the day and – provided that the reservoir is large enough – over the season.

A well designed small-scale hydro power plant should not cause any environmental problems.

Photovoltaics

Photovoltaics is still a rather expensive energy source, but in very remote areas photovoltaics is a profitable option. In some cases, photovoltaics might even be the only option for remote areas.

Photovoltaics can also be used as complementary energy source in a diesel system, depending on the relation between the diesel price and the price for photovoltaics and inverters.

Power generation in photovoltaics causes no pollution to the environment. Possible environment problems are derived from the equipment around the photovoltaics, especially the batteries. Handling the disposal of old batteries should though not be an insoluble problem.

Photovoltaics have practically no operation and maintenance costs.

Wind power

The costs for wind power depend on the wind speeds at the sites. High wind speeds increases the electricity generation significantly and thus reduces the costs, since the operation and maintenance costs are negligible.

Wind chargers together with batteries can be used in individual systems. Larger wind power plants, which are connected to a local grid, can only be used as a complementary power source, for instance to reduce the costs in a diesel system or to increase the capacity in a hydro power dominated system.

6.2 FINANCING

The financing of rural electrification has not been discussed in the previous chapters. Here will a few remarks be given about the special problems of financing renewable energy sources, especially hydro power, photovoltaics and wind power. These energy sources have in common that the investment, and thus the capital costs, contributes to almost all of the total costs and that the operation and maintenance costs are very low in comparison.

Interest sensitivity

When the capital costs dominate the energy price, the rate of interest will of course have a major influence on the total costs. In this report all price estimations have been done with a real rate of interest of 4%, which is a comparatively low interest rate. The reason for using such a low rate of interest is that loans from developing aid authorities, for example the World Bank, usually uses low rates of interest. If the loan is taken in a commercial bank, the rate of interest will of course be higher.

If the interest rate is increased from 4% to 7% the costs for systems with an economic life time of 5 years will increase with about 9%. If the economic life time is 20 years the increase will be about 30% and for an economic life time 30 years the increase will be about 40%. Thus, with higher rate of interest the costs will increase most for hydro power and almost as much for photovoltaics and wind power. Biomass plants and diesel generator sets will not be affected as much, since the main part of the energy cost for biomass and diesel generator sets is operation costs, which are not affected by interest. It will also be more preferable to use individual systems, since batteries, one of the most costly parts of the individual system, have short life time, whereas building of a distribution system is a long-term investment.

Long period of repayment

The period of repayment is also very important for capital cost intensive energy sources. Renewable energy technologies generally have long technical life times; most systems will be operating for at least 20 years without need for major new investments. If the granter of the loan requires that the loan should be repaid in a time period less than the technical life length, the capital costs during the period of repayment will be increased, whereas the capital costs after the period of repayment will be reduced to zero.

If for instance the period of repayment, i.e. the economic life time, is decreased from 20 years to 10 years and the rate of interest is 4%, this will result in an increase of the capital costs with 67%. For a decrease in economic life time from 20 to 5 years, the capital costs increase with 205%! This means that if short periods of repayment are required, hydro power, wind power, most biomass plants and complementary photovoltaics will have no possibility to compete with diesel generator sets, since the costs during the first years of the systems will be too high. Only photovoltaics for individual systems, which can be bought without loans – at least by wealthy people – can under such circumstances compete economically with diesel generator sets.

High initial costs

When energy sources with high investment costs are to be used as a power source in a newly built local grid, another financial problem arises. Most systems will be designed for a larger demand than can be expected to be connected during the initial phase of the electrification – unless the local grid replaces a lot of individual systems, so that there already is a high power demand in the area. If these few first customers should pay the full cost, i.e. so much that the owner of the grid can pay his interest and instalments, the electricity price will be very high. The high price will then of course result in that less people will afford to connect to the grid, and without new customers the electricity price can not be lowered. This is a vicious circle: low prices presupposes many customers and many customers presupposes low prices.

There are two ways out of this dilemma. Either the power company or cooperative has to accept a financial loss during the initial phase. This requires that the company or cooperative can continue to borrow money, although it shows financial losses. This is of course a risky solution; the losses might continue forever if the demand has been overestimated.

The other possibility is to start with a system that is profitably only on short terms, which usually means a diesel generator set, but also could include biomass plants. When the demand has grown so that a more long term renewable solution will be profitable, can the diesel generator sets be phased out or left as spare power. The disadvantage of this solution is that temporary solutions have a tendency of becoming permanent; the more advantageous long-term solution might never be built, because the grid operates properly and nobody is interested in improving it and reducing the electricity price.

Other aspects

Much of the equipment necessary for rural electrification must be imported from industrialized countries, but some parts can also be manufactured locally. Only some of the electrical equipment in hydro power stations (e.g. the turbines) must be imported; the rest of the power station can be built using local materials. There are also several biomass technologies that uses domestic resources.[1] Diesel generator sets, photovoltaics and wind power plants must generally be imported.

It is also common that foreign technical expertise is necessary for planning the project. This might however be a benefit, if the technical knowledge is transferred to local engineers and technicians.

The electrification in itself might give a boost to the local economy by enabling local industries and other economic activities.

6.3 RECOMMENDATIONS

It is never possible to say that one electrification scheme is better than all alternatives without visiting a site. The purpose of this section is merely to show which power systems that generally are the most interesting for different load situations.

In the industrialized countries the power systems have started as many local grids, often built around a power station or an industry, which later have grown as the power demand has increased. At some point it has become interesting to connect the local grids in a national transmission grid, which then expands until all but the most remote parts of the country has been covered by the national grid. There is no reason to believe that this will not be appropriate for developing countries too. However, since developing countries lack resources for a rapid expansion of the national grid, many people will be depending on their own power system or a local grid for many years.

As indicated by the examples in appendix C, power sources for electricity generation in local grids are generally less expensive than individual systems. A well managed local grid will also be much more reliable and it will be possible for individual consumers to connect more power and energy demanding loads. The limitation of the local grid is the

1. See [4] pp. 181 – 200.

distribution system, which will be very expensive if small consumers far away from the load centre should be connected. Therefore individual power systems will be the only possibility for electrification in remote areas, which for a long time are not likely to be reached by the grid, not even by a local grid.

For a group of customers that are too far away to be grid connected, it can still be profitable to connect these customers in a low voltage network. A low voltage system can be seen as a large individual system which serves more than one customer.

The discussion above is summarized in table 6.1. Once again, please note that this are very general guidelines, and that the best choice can differ from site to site.

Table 6.1 *Guidelines for most interesting system.*

Consumers		Power usage	Suggested power system	Most interesting generation technologies[a]
Number	Typical size [kWh/day]			
1	< 0.5	Mainly lighting	Individual system (AC or DC).	Photovoltaics, wind chargers, petrol genset.
1	> 1	Lighting and industrial activity	Individual system (AC) or consider using other power source than electricity.	Petrol/diesel/biomass genset.
< 50	< 1	Mainly lighting	Low voltage network (AC or DC).	Photovoltaics, wind chargers, petrol/diesel/biomass genset.
> 50	< 1	Mainly lighting	Local grid (available part of the day).	Diesel genset, biomass power plant, hydro power.
> 50	> 0.5	Lighting and industrial activity	Local grid (available during all hours of the day).	Hydro power, diesel genset, biomass power plant.[b]
> 1000	> 1	Lighting and industrial activity	Local grid (available during all hours of the day) or connection to the national grid.[c]	For local grids: see above.

a. Cf. comments under ***Individual systems***, ***Low voltage networks*** and ***Local grids*** below.
b. Wind power and photovoltaics can be useful as complementary energy sources.
c. Connection to the national grid is discussed in section 5.3.

Individual systems

The most important factor for choosing power source for an individual system is the local price for petrol. It is not only the petrol price today that is important, but also the future prices: Will the world market price increase or decrease? Will the taxes be changed? etc.

Taking the difficulties (fuel transports, maintenance need and low utilization factor) of petrol generator sets in account, it is likely that solar home systems and wind chargers are preferable.

Low voltage networks

Low voltage networks are basically a number of individual systems that have been connected together by a simple distribution system.[2] Because of the possibility to increase the utilization factor, diesel or petrol generator sets are more interesting in the case of low voltage networks than for individual systems. Also some biomass plants are suitable for these systems. It is of course also possible to use a combination of several power sources, for instance photovoltaics and batteries backed up by a diesel generator set for overcast days. As always, the choice depends on local fuel prices, both for diesel, petrol and biomass.

Local grids

Generally hydro power is the best option for a local grid, if it is available. In other cases it is necessary (for frequency control) with either a diesel generator set or a biomass plant, where the choice between the two depends on the difference between the prices for diesel and biomass. Biomass plants using industrial residues can have very low energy prices, but the electricity generation will be affected by the needs of the industry. In some cases sustainable biomass is not even available, in which case a diesel generator set is almost the only alternative to hydro power.

Photovoltaics and wind power can be used in combination with hydro power or diesel generator sets. For hydro power systems photovoltaics and wind power can increase the energy limit of the system. For diesel generator sets photovoltaics and wind power can reduce the fuel consumption, which of course only is advantageous if the price of the diesel fuel is high enough.

6.4 FINAL CONCLUSIONS

How can rural electrification in developing countries be supported? This is of course a very difficult question to answer, but there are a few remarks that can be made about the special needs of renewable energy technologies:

- **Decrease the capital costs!** Renewable energy sources, especially photovoltaics, hydro and wind power, have higher investment costs than their fossil alternatives. Low real interest rates therefore promotes renewables compared to fossil energy sources. It

2. Note that individual systems using batteries and inverters can not just be connected, because only one inverter in the system may be self-commutating. See appendix A.2.

is also necessary that the period of repayment is long enough. If not, the capital costs during the initial phase of the electrification might simply be insurmountable high.

- **Support education!** Diesel generator sets are familiar technology also in developing countries; renewable technologies are generally not. Especially hydro power plants and biomass plants requires well educated technicians for their daily operation and maintenance. Solar home system might not need a high technical education, but still demand that the users are well informed about the maintenance needs.
- **Support of photovoltaics.** Solar home systems are already today sold commercially in many developing countries. The price is however rather high and there is of course a risk that only wealthy people can afford these systems. By purchasing large volumes of photovoltaic modules better prices can be achieved. The modules can then be resold, preferable without profit, to villagers interested in individual systems.
- **The costs for reducing global warming should not be paid by the rural population in developing countries.** The major drawback with diesel generator set is that the combustion of fossil fuels contributes to global warming. This contribution will though be very small compared to the emissions of greenhouse gases from the industrialized countries. If for some reason a renewable energy source is built in rural power system in a developing country, though a diesel generator set would be cheaper, then it seems unfair if the extra cost should be paid by the villagers. It would be more reasonable if an organization from an industrialized country should pay the extra cost.
- **Investigation of experiences from renewable energy technologies in rural power systems.** The availability of a power plant is important to the economic calculations. Therefore it is desirable to have access to experiences of operation and maintenance from similar projects, when planning future electrification projects. [8] describes the experiences from the Tanzanian rural electrification programme, which so far has been based on diesel generator sets. A similar compilation over renewable technologies would probably be of great value.

Appendix A

BATTERIES AND INVERTERS

Power systems using DC generating units like photovoltaics or small wind generators will usually include batteries and/or inverters. This appendix gives some comments about these components of the power system.

A.1 BATTERIES

Batteries stores chemical energy that rapidly can be converted to electric energy. The design of the battery depend on its purpose. Basically batteries can either be constructed for relative small power output during long time periods or for high power output during short moments. The former construction seem better suited for individual power systems.

The life time of a battery is depending on the depth of discharge (DOD), which is specified as the percentage of the rated storage capacity that can be discharged before the battery need to be reloaded. If the DOD is exceeded the life time of the battery will be reduced. The expected life time of batteries used in photovoltaics systems is usually about 5 years, but if the batteries not are properly maintained can the life time be even shorter.

The storage capacity of batteries is commonly given in Amperehours (Ah). An Amparehour can be converted to kilowatthours by multiplying with the voltage of the battery. A 12 V battery with a capacity of 120 Ah can thus store 1.44 kWh. If the recommended maximal DOD is 70% the battery can deliver about 1 kWh before it needs to be reloaded.

Some batteries loose water from gassing during their operation and therefore need to be refilled occasionally. There are also batteries which need no maintenance at all.

A.2 INVERTERS

Inverters use modern power electronics to convert DC power to one-phase AC power. The conversion is not free of losses; today the inverters have an efficiency of 90 – 95%. The inverter can either be self-commutated (generating its own frequency) or be grid commutated (adjust its frequency after the grid frequency). The former are designed for individual systems, where the inverter is the only unit feeding the system. The grid commutated inverters are made for larger grids, where there has to be some other power source that is controlling the system frequency. If this other power source is failing, the inverters are designed to disconnect themselves.[1]

Inverters are not commonly used in power systems, so the demand for inverters is low. There are however standard inverters available in sizes from around 100 W to some kilowatts.[2] The technology for inverters is still developing, so prices and performance can be expected to improve in the future.

The life length of an inverter can be expected to be the same as for any other industrial electronic appliance, i.e. between 10 – 20 years. If an inverter fails it is usually necessary to have a specialist to repair it.

1. This is for safety reasons; if the grid is turned off for maintenance it would be dangerous if the inverters continued operating.
2. Cf. appendix C.5.

Appendix B
TRANSMISSION AND DISTRIBUTION

For transport of electric power over long distances it is necessary to use high voltages or else the losses would be to high. A power system is therefore usually organized like in figure B.1. The national and regional grids use high voltage (more than 40 kV), whereas the local grids use medium voltage (3 – 33 kV) and most consumers are fed by low voltage (400/230 V). Large industries might be supplied directly from the national or regional grids. In some local systems it might not even be necessary to have a medium voltage distribution network, but it is normally recommended that low voltage lines do not extend further than 500 m.[1]

When local grids are discussed in this report it is usually meant a stand-alone local grid, i.e. a local grid that is not connected to the national transmission grid.

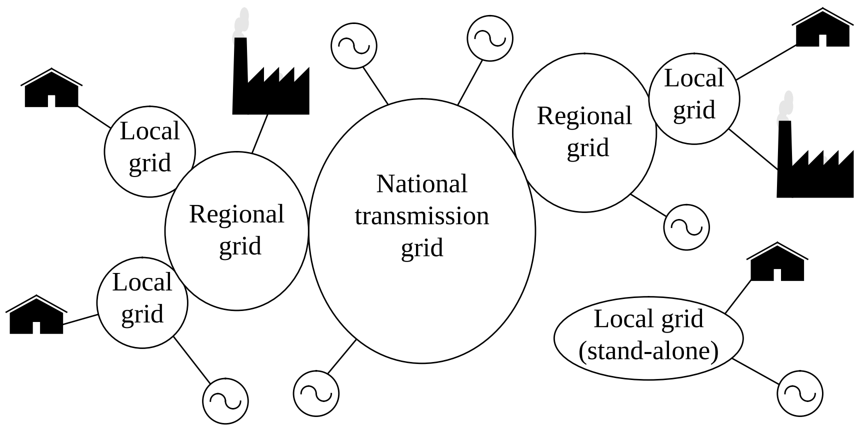

Figure B.1 *General structure of a power network.*

Costs

It is very hard to give a general figure of the costs for building transmission lines and distribution systems, since this is affected by a lot of local factors as

- the size of the power demand,
- the distance between the consumers (i.e. the load density),

1. [13] p. 60.

- the costs for lines, transformers and security systems,
- desired reliability,
- losses.

Some examples of costs for components of distribution systems are found in appendix C.6. Both transmission lines and distribution systems are long term investments, with an expected life time of at least 25 years. It might therefore be wise to build a larger distribution system than necessary for the current load, since this will decrease the cost for future rebuilding of the system when the load has increased.

In table B.1 the total cost (i.e. capital costs, operation and maintenance) has been calculated for two example systems. The calculated costs should not be treated as limits to the costs for distribution systems; the actual cost in a new-built system might be lower or even higher.

Table B.1 *Costs for two example distribution systems.*

Item	"Scarce" system[a]		"Dense" system[b]	
	Quantity	Cost [USD]	Quantity	Cost [USD]
11 kV lines	11.1 km	188 700	3.2 km	54 400
LV lines	25.2 km	378 000	3.2 km	48 000
11/0.4 kV transformers	9 × 1000 kVA	169 200	4 × 800 kVA	54 200
Three-phase customers	50	42 500	10	8 500
One-phase customers	1 200	552 000	330	151 800
Total cost	1 330 400		316 900	
Annual consumption	900 000 kWh		340 000 kWh	
Cost per energy unit[c]	0.17 USD/kWh		0.11 USD/kWh	

a. Based on data of Mpwapwa recorded in [8], tables 2.7, 3.2, 3.10 and 3.11.
b. Based on data of Kilwa Masoko recorded in [8], tables 2.7, 3.2, 3.10 and 3.11.
c. Capital costs with real rate of interest 4% and economic life time 25 years. Operation and maintenance costs are approximated as a fixed annual cost of 5% of the investment cost.

Appendix C

PRICE EXAMPLES

It is of course impossible to specify a general price for a product; prices will vary from country to country depending on VAT, fluctuations in currency exchange rates, distribution chains etc. However, in order to at least give a hint of how the prices of different technologies relate to each other, some price examples are given in this appendix. The prices are from October 1998 if nothing else is stated. The prices are mostly taken from official price lists and all prices exclude VAT. The price in USD has been calculated using the exchange rates listed in table C.1. A real rate of interest of 4% has been used in the energy price calculations.

The total energy cost is the sum of the capital costs and the operation and maintenance costs. The capital costs have been estimated by calculating annual costs with the annuity formula and then dividing the annual cost with the annual energy generation/consumption. The annuity formula reads

$$a = C \cdot \frac{r/100}{1-(1+r/100)^{-n}}, \qquad \text{(C.1)}$$

where

a = annual cost,
C = cost of investment,
r = real interest rate (in per cent),
n = economic life time (in years).

Table C.1 *Exchange rates.*

Currency	1 USD equals
DKK	6.10
SEK	7.75
TZS	640[a]

a. September 1997.

C.1 OVERVIEW

It is impossible to give any general energy costs, since the costs are depending on so many site specific parameters. To get an overview how the costs relate to each other it can though be interesting to compare some of the price examples that are given in sections C.2 – C.5. This is done in figure C.1. Biomass has not been included in the over-

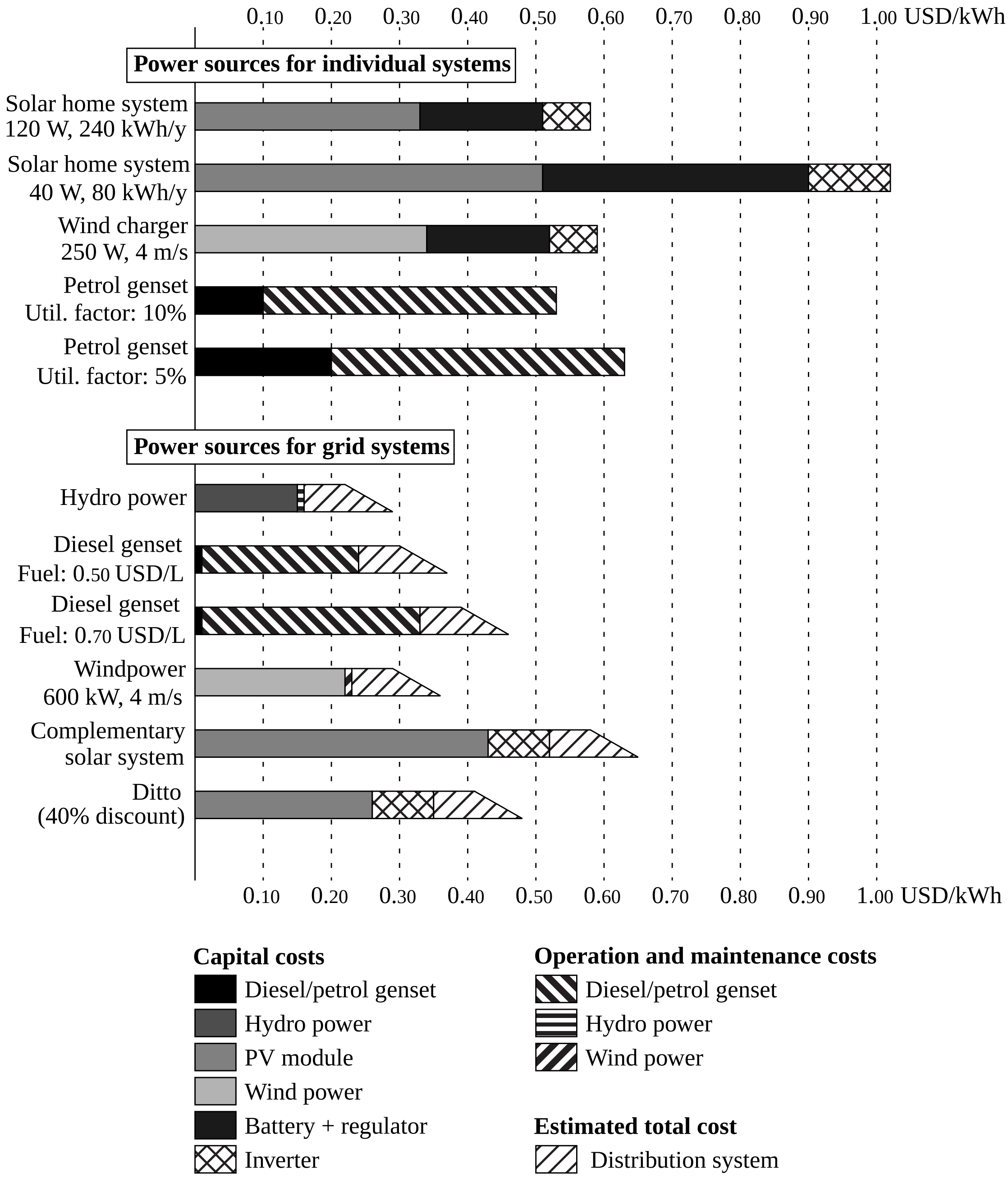

Figure C.1 *Overview over energy costs for some technologies.*
N.B. These costs are only examples and can not be treated as exact values. All costs are depending on a lot of site specific parameters.

view, since the costs for biomass generation are too site specific.

The following assumptions have been done:

- The costs for the solar home systems are based on an insolation of 2 000 kWh/m^2. The battery capacity is 120 Ah for the 120 W panel and 75 Ah for the 40 W panel.
- The load for the wind charger is 240 kWh/year. The battery capacity is 120 Ah.
- The petrol generator set costs are calculated for the 3 kVA petrol generator set. The economic life time is 7 years and the utilization factor is 10% and 5% respectively,

which corresponds to an annual generation of 2 628 kWh and 1 314 kWh respectively. The petrol cost is 0.70 USD/L.

- The cost of distribution systems is based on the two example systems from appendix B. The cost includes capital costs as well as operation and maintenance costs.
- The costs for hydro power is based on capacity of 100 kW, investment cost of 1 000 000 USD, economic life time 25 years and a utilization factor of 50%.
- The diesel generator set costs are calculated for the 450 kVA diesel generator set. The economic life time is 7 years and the utilization factor 25%.
- The 600 kW wind power plant is assumed to have 90% availability and a utilization factor of 100%. The maintenance cost is 3 200 USD/year.
- The complementary solar system uses the 120 W module and the insolation is 1 500 kWh/m^2. The annual energy generation is 180 kWh per module. The cost of mountings has been excluded.
- Losses in inverters and distribution systems have not been included in the cost calculations.

C.2 DIESEL GENERATOR SETS

Table C.2 *Price examples for diesel and petrol generator sets.*

Rated capacity [kVA]	Price per piece [USD]	Price per kVA [USD]	Fuel consumption[a] [kg/kWh]	Estimated energy price[b] [USD/kWh]	
				At fuel cost 0.50 USD/L	At fuel cost 0.70 USD/L
3[c]	1 600†	533	0.315†	0.31	0.43
251	35 500‡	142	0.20‡	0.22	0.30
450	63 950‡	142	0.22‡	0.23	0.32
Sources: † SunWind Energi AB ‡ Martinsson Kraft/Teknik (Data from 1997)					

a. Nominal consumption for cos φ = 1, stated by the manufacturer.

b. Neglecting capital costs and assuming that cos φ = 0.8, that the fuel consumption is 15% higher than the nominal consumption (cf. ***Practical experience*** in section 3.1) and that the cost for lubricants and other maintenance is 25% of the cost for fuel (cf. [8] p. 98).

c. This is a petrol fuelled generator set.

C.3 PHOTOVOLTAIC MODULES

In Sub-Saharan Africa the irradition varies between 4 and 6 kWh/m^2 per day,[1] which means that the annual total insolation can be estimated between 1 500 and 2 100 kWh/m^2. In table C.3 have the energy prices been calculated for a yearly insolation of 1 500 and 2 000 kWh/m^2 respectively. If a discount is given on the photovoltaic

1. [11], figure 8.4.

modules the energy price will be decreased by approximatly the same percentage as the discount.

To calculate the relation between insolation and energy generationa it is necessary to know the area and efficiency of the module. From the definition of standard test conditions we have

$$\hat{P} = 1000 \text{ W/m}^2 \cdot A \cdot \eta_{STC}, \quad \text{(C.2)}$$

where

$\hat{P}$ = rated capacity in W_p,
A = area of the module,
η_{STC} = efficiency at STC.

If we assume that the efficiency of the module does not differ very much from the efficiency at STC, then the annual generation can be approximated by

$$W_{PV} = I \cdot A \cdot \eta \approx I \cdot \frac{\hat{P}}{1000}, \quad \text{(C.3)}$$

where I is the annual insolation.

Table C.3 *Price examples for photovoltaic modules.*

Capacity [W_p]	Price per piece [USD]	Price per W_p [USD]	Estimated energy price[a] [USD/kWh]	
			At yearly insolation 1 500 kWh/m^2	At yearly insolation 2 000 kWh/m^2
40	557‡	13.94	0.68	0.51
75	702†	9.36	0.46	0.34
120	1 063†	8.86	0.43	0.33
Sources: † NAPS Sweden AB ‡ SunWind Energi				

a. Assuming that the utilization factor and availibility are 100%. The ecomic life time is assumed to be 20 years. The energy price only refers to the cost for the modules, i.e. the cost for batteries, inverters etc. is not included.

C.4 WIND POWER GENERATORS

When no specific data about wind speeds are available it is common to assume that the wind is Rayleigh distributed, which means that it has the duration curve

$$F_w(v) = e^{-(v/\alpha)^2}, \; v \geq 0, \quad \text{(C.4)}$$

where

$F_w(v)$ = the probability that the wind speed is higher than v,

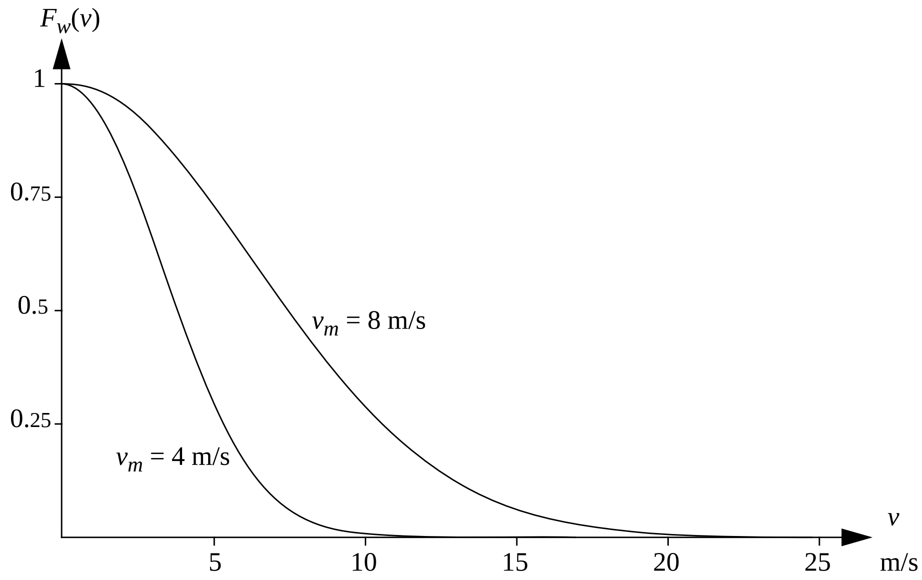

Figure C.2 *Examples of the Rayleigh distribution for two average wind speeds.*

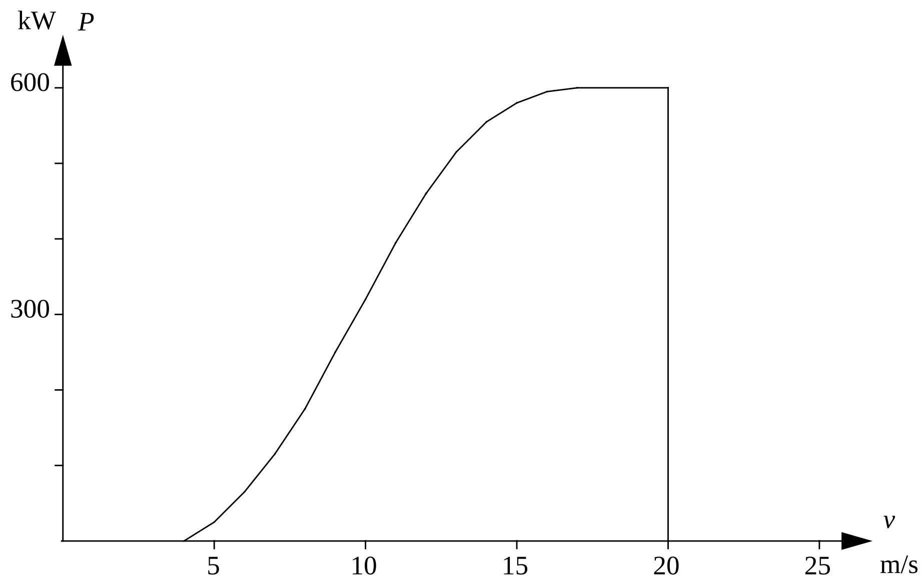

Figure C.3 *Power function for Vestas V44-600 at an air density of 1.06 m^3/kg. At wind speeds higher than 20 m/s is the plant switched off.*

α = a scaling parameter.

In figure C.2 are two examples of the Rayleigh distribution shown. The average wind speed is equal to the area below $F_w(v)$, i.e.

$$v_m = \int_0^{\infty} e^{-(v/\alpha)^2} dv = \frac{1}{2}\alpha\sqrt{\pi} \approx 0.89 \cdot \alpha. \tag{C.5}$$

To calculate the expected annual generation it is necessary to know the duration curve of

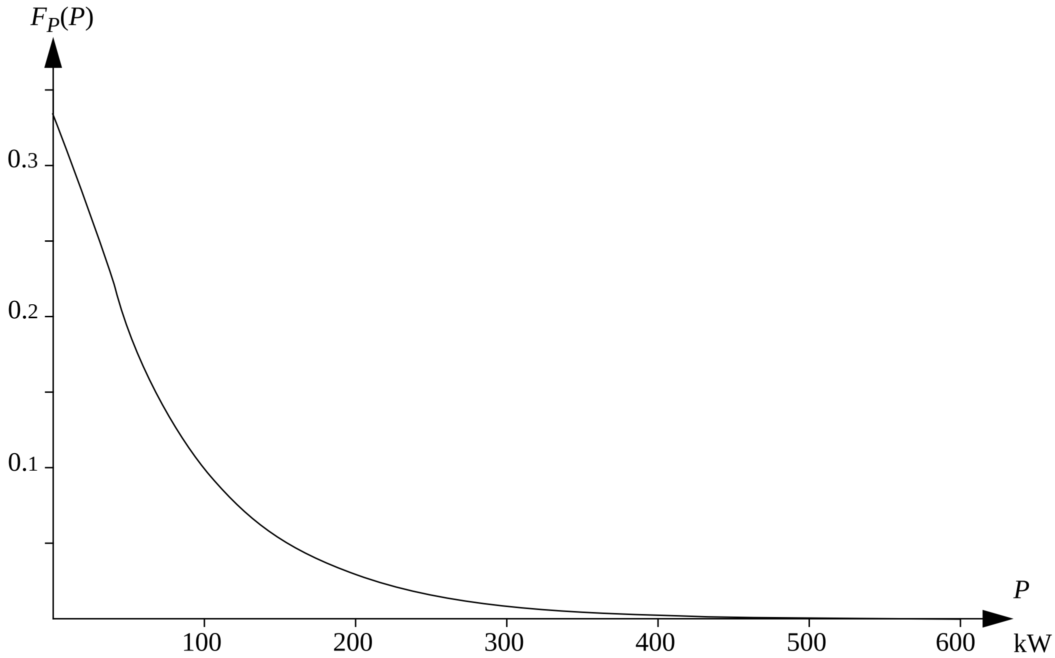

Figure C.4 *Power generation distribution function for a Vestas V44-600 at average wind speed 4 m/s. Notice that the probability that the generation is zero is more than 65% – this illustrates why wind power plants need a backup power source.*

the power generation. The probability that the power generation in the plant exceeds P equals the probability that the corresponding wind speed is exceeded, i.e.

$$F_P{'}(P) = F_w(v(P)) = e^{-((v(P))/\alpha)^2}, \tag{C.6}$$

where

$F_P{'}(P)$ = the probability that the power generation is higher than P (ignoring that the plant is turned off at high wind speeds),

$v(P)$ = the wind speed that is necessary to produce a power of P.

The function $v(P)$ can be obtained by inverting the power function, which is supplied by the manufacturer. An example of a power function is shown in figure C.3. As can be seen in the figure are wind power plants usually turned off when the wind speed is too high. When this wind speed, denoted v_{co}, is exceeded the power generation is zero, which means that probability for this must be subtracted from $F_P{'}(P)$. The probability for a certain generation level is also reduced due to the risk that the power plant is unavailable. Therefore we should also multiply with the availability p, which gives the expression

$$F_P(P) = p\left(e^{-((v(P))/\alpha)^2} - e^{-(v_{co}/\alpha)^2}\right). \tag{C.7}$$

If an utilization factor of 100% is assumed the estimated annual generation can be calculated through

$$W_w = T \cdot \int_0^{P_r} F_P(P)\,dP\,, \qquad \text{(C.8)}$$

where
T = number of hours in a year (i.e. 8760),
P_r = rated capacity of the wind power plant.

If the utilization factor is less than 100%, i.e. if there is a risk that the power generation in the power plant is higher than the demand, the estimated annual energy must be calculated using probabilistic production simulation. This method is briefly explained in [1].

Table C.4 *Price exemples for wind power generators.*

Rated power [kW]	Price per piece [USD]	Price per kW [USD]	Estimated energy price[a] [USD/kWh]	
			At average wind speed 4 m/s	At average wind speed 8 m/s
0.072	770†	10 695	0.78	0.21
0.25	1 806†	7 226	0.34	0.20
600	660 000‡	1 100	0.20	0.03
1 650	1 575 000‡	955	0.17	0.03
Sources: † NAPS Sweden AB ‡ Vestas Wind Systems A/S				

a. Assuming that the utilization factor and availibility are 100% and excluding operation and maintenance costs. The economic life time is 20 years.

C.5 BATTERIES AND INVERTERS

Table C.5 *Price examples for inverters (12 VDC to 220 VAC).*

Capacity [W][a]	Price per piece [USD]	Price per W [USD]	Cost per energy unit[b] [USD/kWh]	
			At annual generation 80 kWh[c]	At annual generation 240 kWh[d]
140	77†	0.55	0.12	0.04
200	129†	0.65	0.20	0.07
500	253†	0.51	0.39	0.13
3 400	5000‡	0.66	0.09 at annual generation 5 MWh[e]	
Source: † SunWind Energi AB ‡ Birka Teknik & Miljö AB				

a. The capacity refers to continuos loads. For short time periods can most inverters double their power output.
b. Assuming that the economic life time is 10 years.
c. Approximatly corresponding to the electric energy generated by a 40 W_p panel at yearly insolation 2000 kWh/m^2. Average power during the year is 9.1 W.
d. Approximatly corresponding to the electric energy generated by a 120 W_p panel at yearly insolation 2000 kWh/m^2. Average power during the year is 27.4 W.
e. Approximatly corresponding to the electric energy generated by twentyeight 120 W_p panels at yearly insolation 1500 kWh/m^2.

Table C.6 *Price examples for batteries and regulators.*

Equipment	Capacity [USD]	Price per piece [USD]	Cost per energy unit[a] [USD/kWh]	
			At annual consumption 80 kWh[b]	At annual consumption 240 kWh[c]
Battery	75 Ah	115	0.18	0.06
Battery	120 Ah	209	0.32	0.11
Regulator	10 A[d]	135	0.21	0.07
Source: NAPS Sweden AB				

a. Assuming that the economic life time is 5 years.
b. Approximatly corresponding to the electric energy generated by a 40 W_p panel at yearly insolation 2000 kWh/m^2.
c. Approximatly corresponding to the electric energy generated by a 120 W_p panel at yearly insolation 2000 kWh/m^2.
d. Maximum load current at 12 V.

C.6 DISTRIBUTION

Table C.7 *Price examples for customer connections.*

Item	Price [USD]
One phase service line	400
One phase meter	60
Three phase service line	700
Three phase meter	150
Source: Working paper from Tanzanian Electric Supply Company Ltd, August 1997.	

Table C.8 *Price examples for transmission and distribution lines.*

Voltage [kV]	Conductor	Price [USD/km]
0.4	AAC-PVC 50 mm^2	14 000
0.4	AAC-PVC 100 mm^2	15 000
11	ACSR 50 mm^2	15 000
11	ACSR 100 mm^2	17 000
33	ACSR 50 mm^2	16 000
33	ACSR 100 mm^2	20 000
66	ACSR 150 mm^2	38 500
132	ACSR 150 mm^2	60 000
Source: Working paper from Tanzanian Electric Supply Company Ltd, August 1997.		

Table C.9 *Price examples for transformers.*

Voltages [kV]	Rating [kVA]	Price [USD]	Voltages [kV]	Rating [kVA]	Price [USD]
11/0.4	50	2 900	33/0.4	50	3 125
11/0.4	100	3 750	33/0.4	100	3 800
11/0.4	200	6 000	33/0.4	200	6 200
11/0.4	500	9 200	33/0.4	500	9 600
11/0.4	800	12 750	33/0.4	800	13 550
11/0.4	1000	15 500	33/0.4	1000	18 800
11/0.4	2000	25 500	33/0.4	2000	26 000
Source: ABB Tanelec, July 1997.					

REFERENCES

[1] M. Amelin & E. Hersoug, "*Options For Rural Electrification in Developing Countries. A Case Study in Kasulu, Tanzania.*" Diploma thesis, B-EES-9705, Department of Electric Power Engineering, Royal Institute of Technology, Stockholm 1997.

[2] L. M. J. M. Blomen, M. N. Mugerwa, et. al., *"Fuel Cell Systems"*. Plenum Press, New York 1993.

[3] G. Foley, "*Electricity for Rural People*"*.* Panos Publications Ltd., London 1990.

[4] W. Hulscher, P. Fraenkel et. al., *"The Power Guide"*. Second edition, Intermediate Technology Publications, London 1994.

[5] T. Jackson, et. al, *"Renewable Energy – Prospects for Implementation"*. Stockholm Environment Institute 1993.

[6] K. Johansson, J. Kabedi & A. Martinsson, *"Biomass Fuelled Steam Power Plants in the Wood Industries of Tanzania"*. Master's thesis, 1996:116E, Luleå University of Technology, Luleå 1996.

[7] T. B. Johansson, H. Kelly, A. K. N. Reddy, R. H. Williams et. al., "*Renewable Energy*"*.* Island Press 1993.

[8] B. Kjellström, M. Katyega, H. Kadete, D. Noppen & A. Mvungi, *"Rural Electrification in Tanzania. Past Experiences - New Approaches.*" Energy, Environment and Development Series no. 15, Stockholm Environment Institute 1992.

[9] Å. Larsson, *"Grid Interaction and Power Quality of Wind Turbine Generator Systems"*. Licentiate thesis, Chalmers University of Technology, Göteborg 1997.

[10] J. Pasztor, L. A. Kristoferson, et. al., *"Bioenergy and the Environment"*. Westview Press Inc. 1990.

[11] S. Roberts, "*Solar Electricity: A Practical Guide to Designing and Installing Small Photovoltaic Systems*"*.* Prentice Hall 1991.

[12] I. Vorwerk, *"Electric Energy Efficiency in Urambo Power System (part two)"*. Diploma thesis, B-EES-9602, Department of Electric Power Engineering, Royal Institute of Technology, Stockholm 1996.

[13] "*Dimensionering av landsbygdsnät*" (Design of rural power sys-

tems). Svenska Elverksföreningen (Association of Swedish Electric Utilities) 1985. In Swedish.

[14] "*New Renewable Energy Resources: A Guide to the Future.*" World Energy Council, 1994.

INDEX