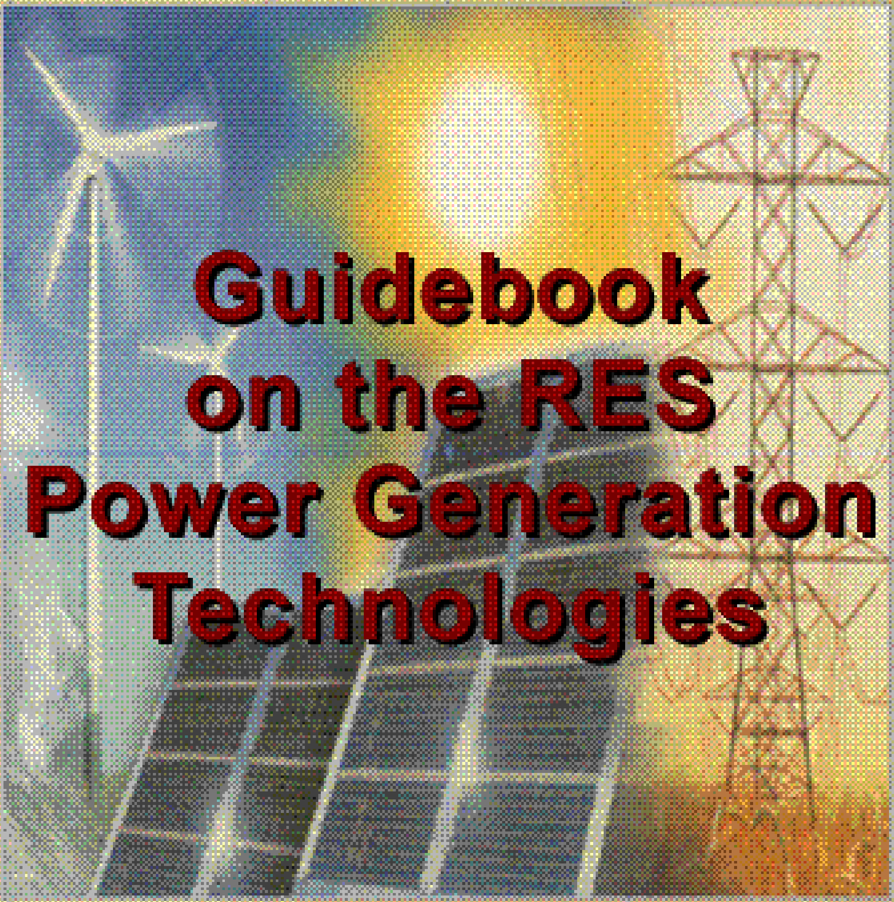
European Commission

Education and Culture

Leonardo da Vinci



Guidebook on the RES Power Generation Technologies

ZREU

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ECOLE DES MINES DE PARIS

Preface

On the 10th of May 2000 the European Commission adopted a proposal for a "Directive of the European Parliament and of the Council" on the promotion of electricity from Renewable Energy Sources (RES) in the EU's internal electricity market. The strategic objective of the proposal is to create a framework for the medium-term significant increase of renewable sourced electricity in the EU and to facilitate its access to the internal electricity market.

Promotion of electricity from RES is a high priority. The 1997 White Paper on Renewable Energy Sources highlighted the key role of renewables in terms of the security of supply, employment, and the environment, and it suggested an indicative target of doubling the share of RES from 6% to 12% in the energy balance of EU by 2010. This objective was endorsed by the Council in 1998. As concerns in particular the environmental aspects, the increased use of electricity from RES would also constitute an important part of the actions which will be necessary in order to meet the commitments to reduce greenhouse gas emissions made by the EU in Kyoto.

The 12% share of total RES in the gross inland energy consumption of the White Paper has been translated into a specific share for consumption of electricity produced from RES (22.1% - 12.5% without large hydro), and it is this specific share to which the promotion of RES-E must contribute. Member States have to fix national targets (the proposal contains quantitative indications for the targets to be chosen by individual Member States) and the measures needed to achieve them no later than one year after the entry into force of the Directive. The Commission has an obligation to propose amendments to the national objectives if they are inconsistent with the Community ones.

Under this frame, the partnership of the D.G. for Education and Culture Leonardo Da Vinci 1999 project with the acronym TEPRES produced the "Guidebook on the RES Power Generation Technologies", in an attempt to facilitate the RES penetration procedure both in a national and European level. The present edition is the Guide's English version, followed by the relevant French, Greek and German ones. The three TEPRES partners, namely ARMINES-Centre d' Energétique, the Centre for Renewable Energy Sources (CRES – Project Contractor) and the Zentrum für rationelle Energieanwendung und Umwelt GmbH (ZREU), prepared all material.

The aim of these publications is to comprise a useful and practical tool for Engineers and other scientists that are going (or wish) to be occupied in the field of Power Generation with the exploitation of RES. The following technologies are presented in a comprehensive enough way:

- Small Hydro Power (Chapter 1),
- Wind Energy (Chapter 2),
- Photovoltaics (Chapter 3),
- Concentrating Solar Power (Chapter 4),
- Geothermal Energy (Chapter 5),
- Biomass Power (Chapter 6),

while two more Chapters, more specifically Chapter 7: "Enabling Technologies", and Chapter 8: "RES Integration", complement the whole material.

CRES was in charge for Chapters 2, 5 and 6 (by Dr. Ch. Malamatenios, Mr. P. Choustoulakis, and Mr. St. Mengos – Training Dept., respectively). ARMINES – Centre d' Energétique (France) prepared Chapters 4, 7 and 8, all by Dr. Didier Mayer (Ass. Director, CENERG Sophia Antipolis). ZREU (Germany) carried out Chapters 1 and 3, whose authors were Mr. Johann Fenzl, Dr. Alexandra Babeck, Mr. Klaus Grepmeier, and Mrs. Beate Bender. The unification of all texts in order to be presented as a continuous script, together with all corrections and additions needed, was made by Dr. Ch. Malamatenios (Head of CRES Training Dept.).

This edition constitutes part of a series of four Training Guides produced by the partnership of the Leonardo Da Vinci 1999 Project with Contract No: EL/99/2/011015/PI/II.1.1.b/FPI and acronym TEPRES, entitled: “Guide for the Training of Engineers in the Electricity Production Technologies from RES - TEPRES”. More specifically, this is the English version of the Guide, which is completed with the relevant French, Greek and German versions prepared by ARMINES-Centre d’ Energétique, the Centre for Renewable Energy Sources (CRES) and the Zentrum für rationelle Energieanwendung und Umwelt GmbH (ZREU), respectively. CRES was the TEPRES Project (implemented from December 1999 to August 2001) Contractor and Coordinator, and the coordination of all project activities was made by Dr. Charalambos Malamatenios (Head of CRES Training Dept.).

The LEONARDO DA VINCI Community Vocational Training Action Programme

On December 6, 1994, the Council of Ministers of the European Union adopted the Leonardo da Vinci programme for the implementation of a Community vocational training policy. This programme, adopted for a period of five years (1995-1999), had a key objective of supporting the development of policies and innovative action in the Member States, by promoting projects in the context of transnational partnerships that involve different organisations with an interest in training.

The adoption of the Leonardo da Vinci programme also represented a rationalisation of Community action in the area of vocational training, providing the basis to enhance the value of the acquits. Leonardo da Vinci facilitated the taking forward of initiatives successfully developed under COMETT, PETRA, FORCE, LINGUA and EUROTECNET and added new dimensions. The programme was open to the 15 Member States, the 3 States of the European Economic Space and progressively to Cyprus, the Czech Republic, Estonia, Hungary, Lithuania, Latvia, Romania, Poland and the Slovak Republic.

The programme came at a time when the *White Paper on "Growth, Competitiveness and Employment"* forcefully emphasised the crucial importance of vocational training as a key factor in combating unemployment and strengthening the competitiveness of European enterprises. The programme aimed at responding to the demand for new skill needs which are generated by the evolution of our societies and tackles concretely the problem of employment in Europe which is also the priority target of the *White Paper on "Teaching and Learning - Towards the Learning Society"*, approved by the Commission on November 29, 1995.

Education and Culture

Leonardo da Vinci

LEONARDO DA VINCI 1999 PROGRAMME

Project title: "Guide for the Training of Engineers in the Electricity Production Technologies from Renewable Energy Sources"

Contract No: EL/99/2/011015/PI/II.1.1.b/FPI

Guidebook on the RES Power Generation Technologies

Produced by:

ΚΑΠΕ
CRES

ECOLE DES MINES
DE PARIS

ZREU

ATHENS
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CONTENTS

1.1. INTRODUCTION

1.1.1. The concept

Nearly a quarter of the energy from the sun that reaches the Earth's surface causes water from the seas, lakes and ponds to evaporate. Some of this energy is used to make the water vapour rise (against the gravitational pull of the Earth) into the atmosphere, where it eventually condenses to form rain or snow. When it rains in the hills or snows in the mountains, a small proportion of the solar energy input remains stored. Thus, water at any height above sea level represents stored "gravitational" energy.

This energy is naturally dissipated by eddies and currents as the water runs downhill in "babbling brooks", streams and rivers until it reaches the sea. The greater the volume of water stored and the higher up it is, then the more available energy it contains. For example, water stored behind a dam in a reservoir contains considerable "potential" energy since, given the chance, if the dam burst the large volume of water would rapidly run downhill. This would cause devastation in its wake as a result of the sudden release of a large amount of energy.

To capture this energy in a controlled form, some or all of the water in a natural waterway can be diverted into a pipe. It can then be directed as a stream of water under pressure onto a water wheel or turbine wheel so that the water striking the blades causes the wheel to turn and create mechanical energy. In water mills, large wooden water wheels rotate slowly to turn the millstones to grind the grain. Similar principles have been used to pump water, saw wood and drive simple machinery in factories. Today a modern turbine is connected to a generator to produce electricity, which is then transmitted to the place where the energy is required.

Hydropower is the largest and most mature application of renewable energy, with some 678,000MW of installed capacity, producing over 22% of the world's electricity (2564 TWh/yr) in 1998. In Western Europe, hydropower contributed 520TWh of electricity in 1998, or about 19% of EU electricity (avoiding thereby the emission of some 70 million tonnes of CO_2 annually). Despite the large existing hydropower capacity, there is still much room for further development as most assessments assume this is only around 10% of the total world viable hydro potential.

This chapter deals with Small Scale Hydro Power (SHP) systems, since large-scale hydropower plants are usually not considered as being RES exploitation systems by ecologists. In general, there is a myth that large dams damage/change ecosystems. They hood and silt in natural stream areas and deplete oxygen from the water. Their reservoirs are dead-water or slack-water pools whose water is hostile to native fish species. Downstream, they create alternating periods of no water followed by powerful surges that erode soil and vegetation.

Small scale Hydro Power (SHP) is mainly "run of river", i.e. not involving significant impounding of water and therefore not requiring the construction of large dams and reservoirs, though where these exist and can be utilised easily they do help. There is no general international consensus on the definition of SHP; the upper limit varies between 2.5 and 25 MW in different countries, but a value of 10MW is becoming generally accepted and has been accepted by ESHA (the European Small Hydro Association).

The definition for SHP as any hydro systems rated at 10MW or less will therefore be used herein. SHP can be further subdivided into “mini hydro”, usually defined as those systems with capacity <500kW, and “micro hydro” for systems with capacities <100kW. Whichever size definition is used, SHP is one of the most environmentally benign forms of energy generation, based on the use of a non-polluting renewable resource, and requiring little interference with the surrounding environment.

It also has the capacity to make a significant impact on the replacement of fossil fuel, since unlike many other sources of renewable energy, SHP can generally produce some electricity at any time on demand (i.e. it needs no storage or backup systems), at least at times of the year when an adequate flow of water is available, and in many cases at a competitive cost with fossil fuel power stations. For example, a 5MW SHP plant typically displaces 1400 tonne/year of fossil fuel, and avoids the emission of 16000 tonne of CO_2 and over 100 tonne of SO_2 per year, while supplying the electricity needs for over 5000 families.

1.1.2. Planning small hydro projects

Planning of small hydro projects requires many stages of technical and financial studies to determine if a site is technically and economically feasible. The viability of each potential project are very site specific. The power output depends on flow of water and the height of the drop of the available water. The amount of energy that can be generated depends on the quantity of water available and the variability of flow throughout the year.

The economics of a site depends on the power (capacity) and energy a project can produce, if the power can be sold, and the price paid for the power sold. In a remote community the value of power generated for consumption is generally significantly more than for systems that are connected to a central grid. However, remote communities may not be able to use all the available energy from the small hydro plant or may be unable to use the energy when it is available, because of seasonal variations in water flow and energy consumption.

Planning studies are essentially an iterative process whereby project benefits and costs are continuously compared. However, developers must proceed through the following steps in the process of reaching a decision on whether to proceed or not with a full feasibility study:

1. Identification of the site.

2. Evaluation of the water resources available for the plant and consequently its annual energy production.
3. Preliminary definition and cost evaluation of the plant.
4. Preliminary evaluation of economics of the scheme, after researching financial alternatives, benefits available from national governments or from the EC, tax incentives, etc.
5. Review of regulatory requirements and administrative procedures.
6. Decision to proceed or not with a feasibility study.

1.2. THE WATER RESOURCE AND ITS POTENTIAL

1.2.1. Hydrology

An essential requirement for hydropower generation is a stream with a combination of adequate flow and head - the vertical distance that the water falls through in generating power, i.e. between the upper and lower surface levels. The power to be generated is proportional to the product of these two variables. The head can be easily measured with a surveyor's level and staff or even with a tachometer or a clinometer, and once established can be assumed to remain unchanged over time.

The flow, on the other hand, is affected by factors such as rainfall, nature of the soil, vegetation cover, temperature and land use patterns in the catchment area. In fact, measuring the flow at one point in time is of little use in planning, because that flow may not be representative of the flow available most of the time. Accordingly, the study of any potential hydroelectric scheme involves the science of hydrology, that is the study of rainfall and stream-flow, the measurement of drainage basins, catchment areas, evapo-transpiration and surface geology, all of which influence the quantity of flow and its variability.

The first essential step in formulating a small hydroelectric scheme is to obtain records of rainfall and stream-flow for as long a period of time as possible in the particular catchment area and drainage basin involved. Surface water and rainfall records are collected in every country and published annually, although often with a considerable delay, by one or more government agencies. The World Meteorological Organization maintains a database (HYDROINFO), which, among other data, gives a list of the agencies responsible for this task, in the countries that are part of the organization.

With the help of a hydropraph (figure 1.1) supplied by the appropriate agency, a flow duration curve (FDC) as the one shown in figure 1.2 may be obtained, by organising the data by magnitude instead of chronologically. This makes it possible to estimate the potential of the site. It is foreseeable that, in the relatively-near future, anyone will have access to well developed, computerized hydrological data bases, which will enable obtaining flow duration curves for any potential site.

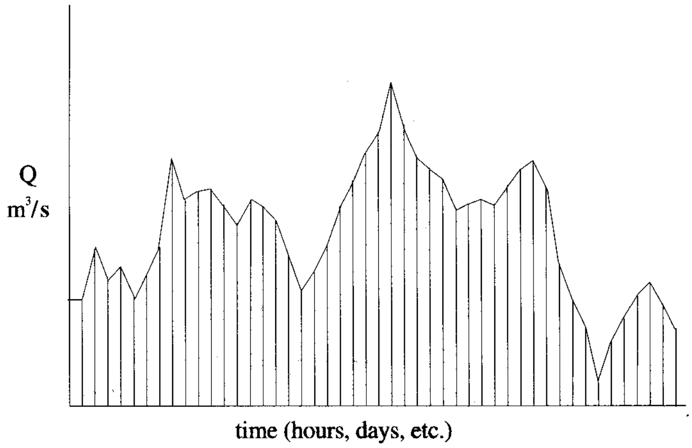


Figure 1.1. A typical hydrograph[1]

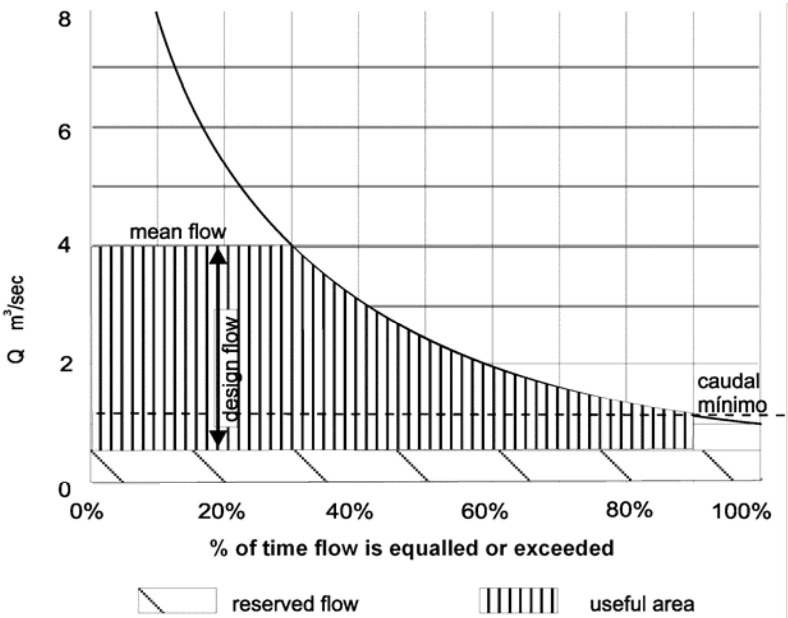


Figure 1.2. Flow duration curve (FDC)

1.2.2. Sizing a power plant

The FDC shows the proportion of time during which the discharge equals or exceeds certain values and provides a mean of determining quickly how much of the available water resource can be used by turbines of different sizes. Referring to figure 1.2 above, which is the FDC for a river at a proposed hydropower site, the power (P) available from the flow obviously varies in time, since Q is varying.

Assuming, at first, an overall efficiency of the electro-mechanical equipment of 0.81, P is given by the equation:

$$P=8QH \qquad (1.1)$$

[1] Most figures contained in this Chapter have been reproduced from the: "Layman's guidebook on how to develop a small hydro site – Part I", a handbook prepared under contract with the Commission of the European Communities (DG XVII) by the European Small Hydropower Association (ESHA), 1994.

where Q is the discharge (m^3/s), and H is the net head (m). If head is constant or nearly so, the power equation (1.1) can be written as:

$$P=cQ \qquad (1.2)$$

where c is a constant. So every ordinate of the FDC represents a potential power capacity.

However, not all of this power can be used. Firstly, the reserve flow must be removed from the FDC since it is to be allowed at all times to continue to flow naturally. The un-shaded band at the base of the FDC in figure 1.2 represents this flow. The usable flow is the remaining area above this. If a turbine large enough to use all of this area were to be installed it would have to be very large and expensive, yet it would operate at its full capacity for a very short time.

The energy gained, compared with some lesser capacity, would not be worth the additional cost of the machinery and pipeline. There is a further reason for choosing a lower capacity. No turbine can operate from zero flow to its rated discharge. Many can operate only upwards from about 60% of rated discharge. Even the best, in this respect cannot be used below one fifth. Therefore, the larger the rated discharge chosen the larger the cut-off at low flow.

The figure 1.3 below illustrates this for a turbine whose cut-off is estimated at 30% of the nominal or design flow. Area A and area B are unusable, so although the generating plant in the first case is 25% larger than the capacity of the second, it can be seen that it produces little more energy, for a much larger investment.

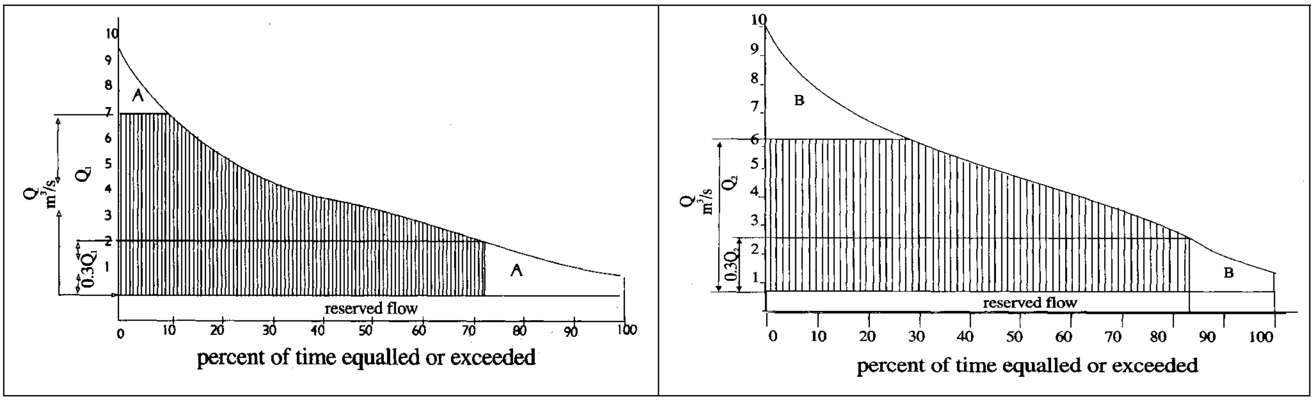


Figure 1.3. Different flow duration curves for a turbine

1.2.3. Annual energy production

Annual energy production can be estimated to a first approximation by measuring the usable area under the FDC, converting it to an actual quantity of water in a year, multiplying that by 9.8 (the specific weight of 1 m^3 of water in kN), by the net head and by the mean efficiency (estimated at 0.81). The result is the annual energy expressed in kJ (kilojoules) that is converted to kWh by dividing by 3600. This kind of preliminary estimate is usually sufficient to enable a decision to be made about a more detailed feasibility study.

1.2.4. Site selection and basic layout

As adequate head and flow are necessary requirements for hydro generation, site selection is conditioned by the existence of both requirements. Since there are so many inter-related factors, it is difficult to give a clear-cut procedure for selecting a site. A preliminary reconnaissance study should include definition of power potential, estimation of power output, identification of physical works needed, identification of critical issues (environmental and social constraints), and a preliminary study of economic feasibility.

Small hydropower schemes can be either high-head or low-head depending on the geographical characteristics of the available site. In general high-head sites are less expensive to develop than low-head sites, because for the same power output the flow through the turbine and required hydraulic structures will be smaller. In a river with a comparatively steep gradient over part of its course, the level difference can be utilised by diverting all or part of the flow and returning it to the river once it has passed through the turbine. The water can be brought from the intake directly to the turbine through a pressure pipe.

Unfortunately, pressure pipes are expensive so what may be a cheaper alternative is shown in figure 1.4. The scheme comprises a dam or a weir, a river intake, and an almost-level open canal running along the side of a river valley ending in a fore bay, from where a pressure pipe conducts the water to the turbine in the powerhouse. If the topographical or geotechnical characteristics of the ground are unfavourable the open canal may not be the best solution. A low pressure pipe, although usually more expensive, may provide a more economic solution in such circumstances.

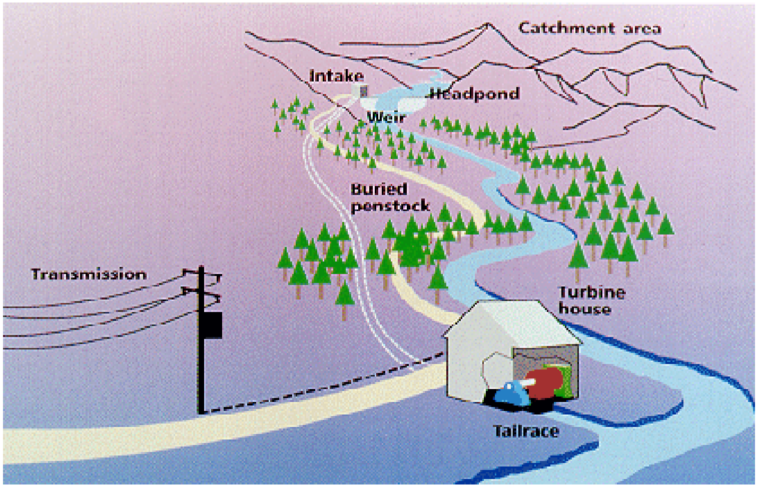


Figure 1.4. High head small hydropower scheme

When all the power conduits, including the forebay, are covered in one way or another, surge shafts to reduce possible sudden pressure surges are normally used.

In low-head schemes two configurations are possible. One uses a diversion weir and its layout is very similar to the above in high heads, although the canal is usually short and the penstock short or non-existent (figure 1.5 left). The other involves a dam with an integral intake and powerhouse (figure 1.5 right).

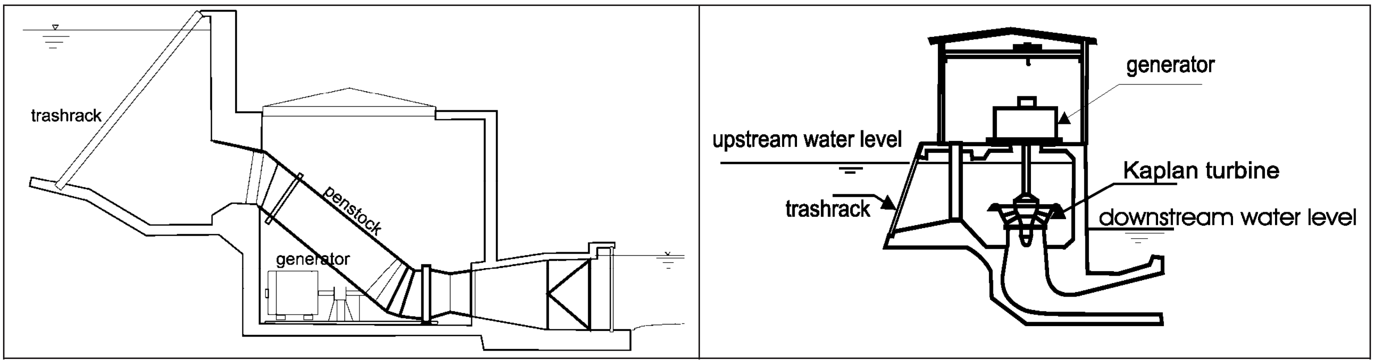


Figure 1.5. Low head small hydropower configurations

Another possibility is to install a power plant on an existing conventional dam, built for multiple purposes (flow control, irrigation, water abstraction etc.). Water enters the turbine through a penstock previously constructed as an integral part of the dam structure or, if the dam is not too high, through a syphon intake (figure 1.6). In the syphon solution the penstock runs over the dam before sloping down to the turbine, which can be located either on top of the dam or, more generally, on the downstream side. Although the head in most syphon installations varies from 1.8 to 11 m, there are a few examples with heads as large as 30 m.

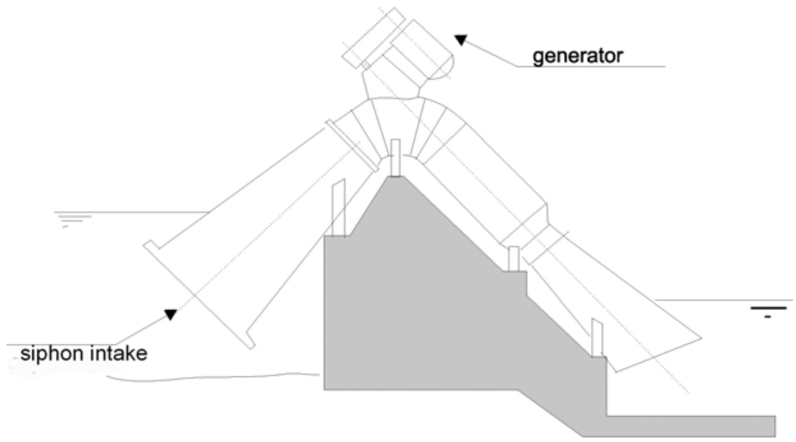


Figure 1.6. Power plant scheme on an existing conventional dam

1.3. CIVIL ENGINEERING WORKS

Once the site has been selected and the basic layout decided, it is necessary to develop the scheme in detail. The following section describes the function of all the possible basic components and shows how they may be designed.

1.3.1. Dams and weirs

Dams are an intrinsic part of large-scale hydroelectric projects and are used to increase the available head and/or to create a reservoir to store water. When the terrain is relatively flat, a dam raising the level of water behind it may provide enough head to generate the required power. A dam can also be used to store water in times of high flow and make it available at times of low flow. Due to the high costs involved in their construction, dams are rarely used in small-scale systems.

However, provided topographical conditions are favourable, the construction of a small gravity dam to store water during periods of low demand, to make it available in peak hours, when electricity prices are higher, can be justified. In diversion schemes, a weir, made of mass concrete or stone masonry, with a crest one meter or more above the river bed (see figure 1.7), will be enough to create an adequate depth of water at the intake of the canal or pipeline.

Figure 1.7. Weir of a small hydro diversion scheme

1.3.2. Intakes

The function of the intake structure is to conduct water into the penstock or power canal under controlled conditions. The intake serves as a transition between a stream, which can vary from a trickle to a raging torrent, and a flow of water controlled both in quality and quantity. Its design, based on geological, hydraulic, structural and economic considerations, requires special care to avoid unnecessary maintenance and operational problems that cannot be easily remedied and would have to be tolerated for the life of the project.

The most important criterion in the design of an intake is its orientation with respect to the stream, as a means of controlling the quantity and quality of watering entering. Rivers tend to deposit sediments in the inner sides of bends. Therefore the intake should not be located on the inside of the bend, to avoid the entrance blocked by sediments. Nor is the outside of a bend recommended, because water borne debris can impair its functioning. The ideal diversion site will be a relatively straight section, stabilized by rock outcropping, if possible, where the weir could be founded.

The orientation of the intake entrance with respect to the stream has a definite influence on the trash accumulation in front of the trash-rack, which can be the cause of considerable downtime and expensive maintenance. The best orientation is to have the centre-line of the intake entrance parallel to or at a shallow angle with the axis of the spillway so that trash is automatically removed by the frequent flood flows passing over the spillway (figure 1.8).

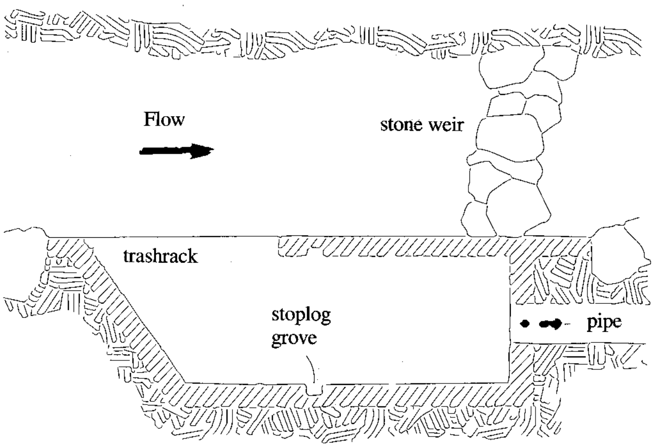


Figure 1.8. Optimum orientation of the intake entrance

One of the major functions of the intake is to minimize the amount of debris and sediment carried by the incoming water, so trash-racks are placed at the entrance to the intake to prevent the ingress of floating debris and large stones. A trash-rack is made up of one or more panels fabricated from a series of evenly spaced parallel metal bars. Recently, trash-racks fabricated from hard plastics have been introduced.

Since the plastic bars can be made in aerofoil sections, less turbulence and lower head losses results. The bar spacing varies from a clear width of 12 mm for small high head Pelton turbines to a maximum of 150 mm for large propeller ones. Trash-racks can be either bolted to the support frame with stainless steel bolts or slid into vertical slots, to be removed and replaced by stop-logs when closure for maintenance or repair is needed.

Trash-racks can be cleaned by hand, and a horizontal platform above high-water level should be provided to facilitate the operation. On intakes for rivers that contain large amounts of debris it is usually preferable to use mechanical rakers (figure 1.9). When significant quantities of suspended sediments are expected to enter the intake it is important that large-size particles are removed, using a sediment-excluding structure.

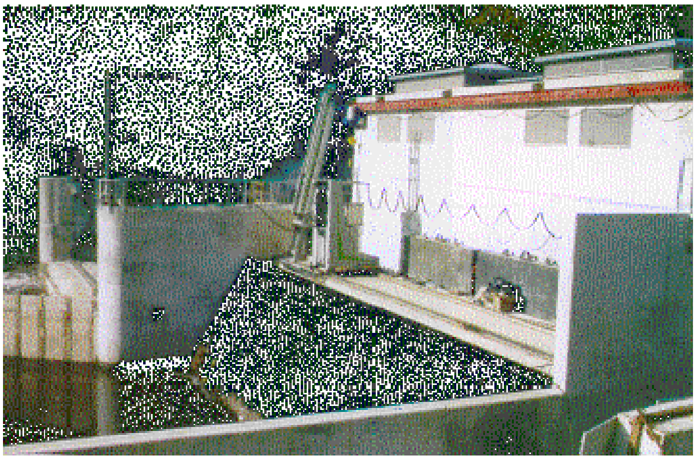


Figure 1.9. Mechanical raker at the intake of a small hydro site

The sediment-trap can be located immediately downstream of the intake, where the flow velocity is reduced. Well designed it should be able to remove all particles over 0.2 mm and a considerable portion of those between 0.1 mm and 0.2 mm. Such a structure is essential for heads over 100 m. The intake should incorporate a well-designed spillway to keep the water level in the canal thereafter relatively constant.

1.3.3. Canals

From the intake the water is conveyed either directly to the turbine through a pressure pipe or by a canal. In a canal the flow is a function of its cross-sectional profile, its slope, and its roughness. The application of hydraulic theory yields reasonably accurate results to man-made canals where the cross-section is regular in shape and the surface roughness of the construction materials - earth, concrete, steel or wood - is well-documented.

The velocity of water in a canal should be kept above a minimum value to prevent sedimentation and aquatic plant growth, but below a maximum value to prevent erosion, especially in unlined canals. To keep silt in suspension after the intake, the flow velocity should be at least 0.3-0.5 m/s. If the canal is unlined and built in sandy soil, the velocity should not exceed 0.4-0.6 m/s. Concrete lined canals may have clear water velocities up to 10 m/s without danger. Even if the water contains sand, gravel or stones, velocities up to 4 m/s are acceptable.

Along the alignment of the canal obstacles may be encountered, and to bypass them it will be necessary to go over, around or under them. The crossing of a stream or a ravine requires the provision of a flume, a kind of prolongation of the canal, with the same slope, supported on concrete or steel piles or spanning as a truss. Steel pipes are often the best solution, because a pipe may be used as the chord of a truss, fabricated in the field. Inverted siphons can also solve the problem. An inverted siphon consists of an inlet and an outlet structure connected by a curve pipe.

At the end of the canal, just before the entrance to the penstock, there is the forebay. Although it can be designed to provide water storage, a forebay normally provides only enough storage to provide extra volume needed during turbine start-up. It should include a spillway, a purging outlet, a trash-rack and an air vent.

1.3.4. Penstocks

From the forebay the water is conveyed to the turbine via a pressure pipe or penstock. Penstocks can be installed over or under the ground, depending on factors such as the nature of the ground itself, the penstock material, ambient temperatures and environmental requirements. A flexible and small diameter plastic penstock for instance, can be laid on the ground, following its outline with a minimum of grade preparation. Otherwise larger penstocks should be buried, provided there is not too much rock excavation.

The sand and gravel surrounding the pipe provide good insulation, and eliminate anchor blocks and expansion joints. Buried penstocks must be carefully painted and wrapped to protect the exterior from corrosion, but, provided the protective coating is not damaged when installed, further maintenance should be minimal. From the environmental point of view, this solution is optimal because the ground can be returned to its original condition and the penstock does not constitute a barrier to the movement of wildlife.

Variations in temperature are especially important if the turbine does not function continuously, resulting in thermal expansion or contraction. The movement can be accommodated with expansion joints or by designing the pipe layout with bends free to move. Usually the penstock is built in straight or nearly straight lines, with concrete anchor blocks at each bend and with an expansion joint between each set of anchors. The anchor blocks must resist the thrust of the penstock plus the frictional forces caused by its expansion and contraction, so when possible they should be founded on rock (fig. 1.10).

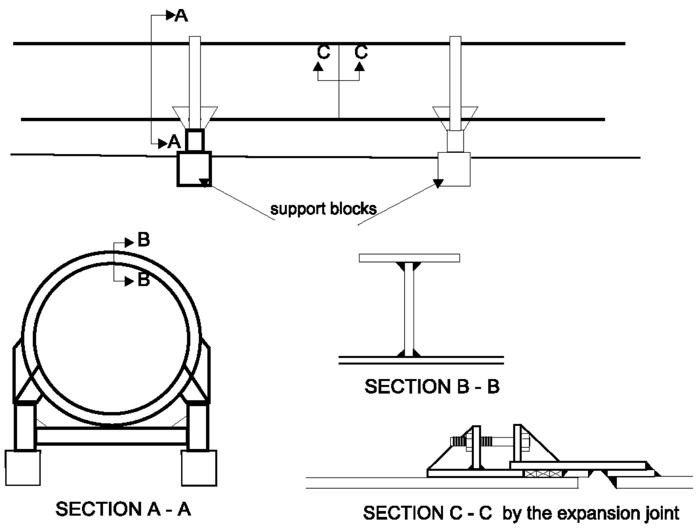


Figure 1.10. SHP penstock scheme

There is a wide choice of materials for penstocks nowadays. For large heads and diameters, fabricated welded steel is probably the best option. Nevertheless spiral machine-welded steel pipes should be considered, due to their lower price, if they are available in the required sizes. At medium and low heads steel becomes, for low discharges, less competitive, because the layer foreseen for risk of corrosion is the same, independently of the wall thickness.

In those cases plastic pipes constitute a very attractive solution, because they are cheaper, lighter and more easily handled than steel pipes and do not need protection against corrosion. For smaller diameter pipes, there is a choice between manufactured steel, supplied with spigot and socket joints, and rubber “O” gaskets, which eliminate field welding, or with welded - on flanges, bolted on site, plain spun or pre-stressed concrete, ductile iron spigot and socket pipes with gaskets, cement-asbestos, glass reinforced plastic (GRP), PVC or polyethylene (PE) plastic.

The materials, diameter, wall thickness and type of joint characterize a penstock:

- the material is selected according to the ground conditions, accessibility, weight, jointing system and cost;
- the diameter is selected to reduce frictional losses within the penstock to an acceptable level;
- the wall thickness is selected to resist the maximum infernal hydraulic pressure, including transient surge pressure that will occur when the flow is rapidly increased or decreased.

The diameter is selected as the result of a trade-off between penstock cost and power losses. Head losses increase rapidly with the increase in water velocity. To convey a certain discharge, a small diameter pipe will need a higher water velocity than a larger diameter one, and therefore the head losses will be greater. Small diameter pipes are cheaper but the power losses are higher than those generated in larger diameter pipes.

Wall thickness depends on the pipe material's ultimate strength (and yield strength), pipe diameter and operating pressures, including transitory surge pressures due to rapid valve closures in the operation of the plant. Commercial pipes are often rated according to the maximum working pressures under which they are designed to operate. Safety factors and surge pressure allowances depend on the standard being used to manufacture the pipe. In Europe, unless a spiral welded pipe of the required diameter and wall thickness is available, penstocks are fabricated by welding steel plates previously curved at the required dimensions.

1.3.5. Tailraces

After passing through the turbine the water returns to the river through a short canal called a tailrace. Impulse turbines can have relatively high exit velocities, so the tailrace should be designed to ensure that the powerhouse will not be undermined. Protection with rock rip-rap or concrete aprons should be provided between the powerhouse and the stream.

The design should also ensure that during relatively high flows the water in the tailrace does not rise so far that it interferes with the turbine runner. With a reaction turbine the level of the water in the tailrace influences the operation of the turbine and more specifically the onset of cavitation. This level also determines the available net head and in low head systems may have a decisive influence on the economic results.

1.4. ELECTROMECHANICAL EQUIPMENT

1.4.1. Hydraulic turbines

All the above-mentioned structures are designed to convey water to the turbines where the power carried by the water is harnessed. The economic feasibility of a projected power plant in a site with a given flow duration curve (FDC) primarily depends on the right selection of the hydroelectric equipment, an iterative process that depends, inter alia, on the shape of the FDC, the quantity of reserved flow, the value of the energy, the cost of the equipment, its ease of operation and its reliability.

A hydraulic turbine is a rotating machine that converts the potential energy of the water to mechanical energy. There are two basic types of turbines, denoted as “impulse” and “reaction”. The “impulse turbine” converts the potential energy of water into kinetic energy in a jet issuing from a nozzle and projected onto the runner buckets or vanes. The “reaction turbine” uses the pressure, as well as the velocity, of water to develop power. The runner is completely submerged and both the pressure and the velocity decrease from inlet to outlet.

Most existing turbines may be grouped in three categories:

- Kaplan and propeller turbines.
- Francis turbines.
- Pelton and other impulse turbines.

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads (usually under 16 m). The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide-vanes (figure 1.11). If both runner blades and guide-vanes are adjustable it is described as 'double-regulated'. If the guide-vanes are fixed it is ‘single-regulated'.

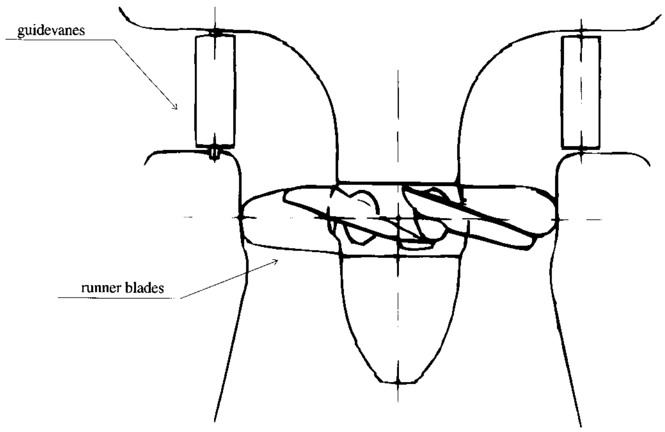


Figure 1.11. A Kaplan turbine

In the conventional version the Kaplan turbine has a scroll case (either in steel or reinforced cast concrete); the flow enters radially inward and makes a right-angle turn before entering the runner in an axial direction. When the runner has fixed blades the turbine is known as a propeller turbine. Propeller turbines can have mobile or fixed guide-vanes. Unregulated propeller turbines are only used when both flow and head remain practically constant.

Bulb and tubular units are derived from propeller and Kaplan turbines, where the flow enters and exits with minor changes in direction. In the bulb turbine multiplier and generator are housed within a bulb submerged in the flow. Tubular turbines permit several arrangements, namely right-angle drive, S ducts Straflo turbines, belt driven generators etc. Right-angle drives constitute a very attractive solution but are only manufactured up to a maximum of 2 MW.

Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. The runner is composed of buckets formed of complex curves. A Francis turbine usually includes a cast iron or steel fabricated scroll casing to distribute the water around the entire perimeter of the runner, and several series of vanes to guide and regulate the flow of water into the runner. Figure 1.12 illustrates a schematic view of this type of turbine.

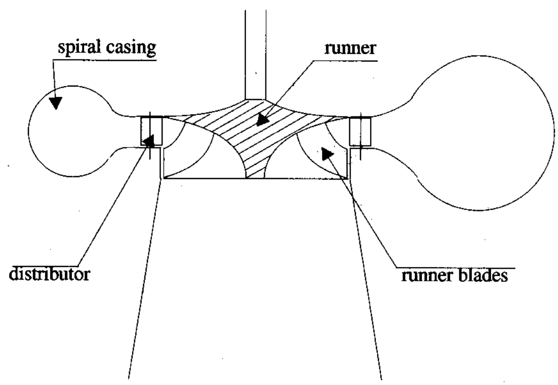


Figure 1.12. Schematic view of a Francis turbine

Pelton turbines are Impulse turbines with single or multiple jets, each jet issuing through a nozzle with a needle valve to control the flow. They are used for medium and high heads. Figure 1.13 illustrates the scheme of a vertical Pelton turbine and figure 1.14 shows the axis of the nozzles placed on the same plane as the runner. Certain manufacturers have developed special types of machines, with a limited range of discharge and output, but which may be advantageous under certain circumstances.

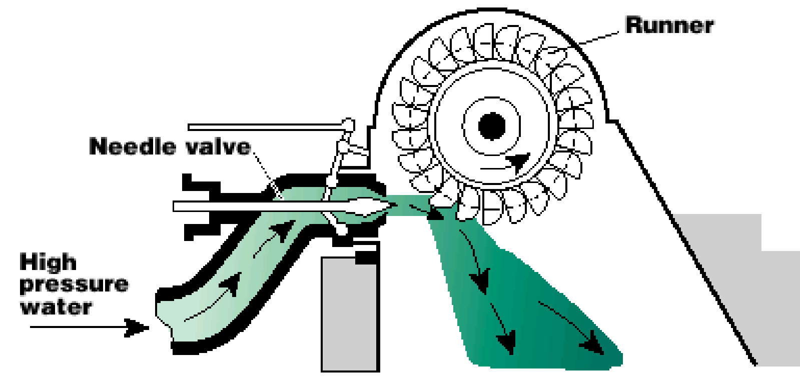


Figure 1.13. Vertical Pelton turbine

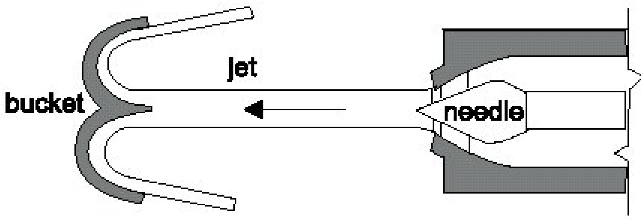


Figure 1.14. The bucket shape of a Pelton turbine

The cross-flow turbine (figure 1.15), also sometimes called as the Ossberger turbine, after a company that has been making it for more than 50 years, or Michell turbine is used for a wide range of heads overlapping those of Kaplan, Francis and Pelton. It is specifically suitable for a high-flow, low-head stream.

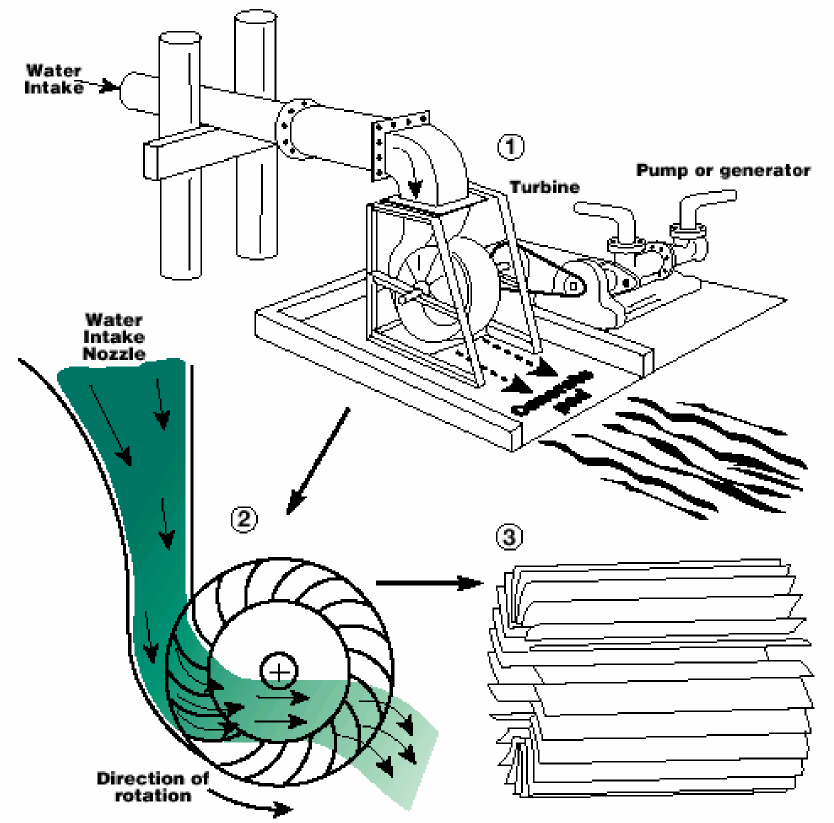


Figure 1.15. (1) The crossflow (Michell) turbine, (2) Cross-section through the turbine, (3) Arrangement of crossflow turbine blades

[Source: Energy-wise Renewables – 4, EECA, October 1997]

The Turgo turbine can operate under a head in the range of 30-300 meter. Like the Pelton it is an impulse turbine, but its buckets are shaped differently and the jet of water strikes the plane of its runner at an angle of 20°. Water enters the runner (fig. 1.16) through one side of the runner disk and emerges from the other. The higher runner speed of the Turgo, due to its smaller diameter compared to other types, makes direct coupling of turbine and generator more likely. A Turgo may prove appropriate at medium heads where a Francis turbine might otherwise be used. However, unlike in the Pelton, the water flowing through the runner produces an axial force, requiring the installation of a thrust bearing on its shaft.

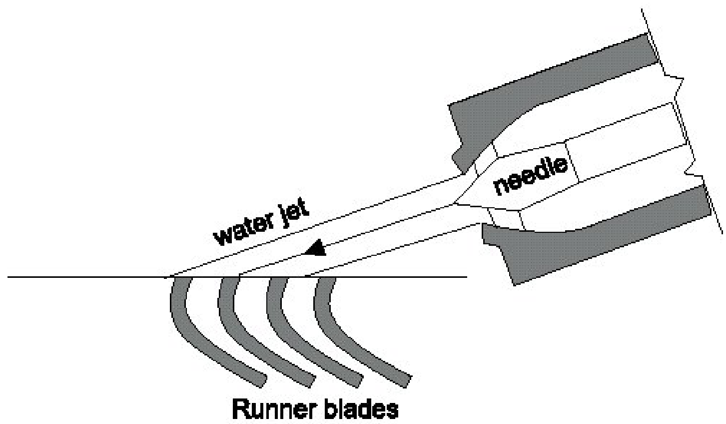


Figure 1.16. Turgo runner blades and water jet

The selection of type, geometry and dimensions of the turbine depends primarily on the head, the discharge and the runner speed. Figure 1.17 presents the operating ranges of the different types of turbines as a function of the head and the discharge. The head by itself constitutes the first criterion in the choice of the type of turbine to install. Table 1.1 indicates the range of suitable heads for the different types of turbines.

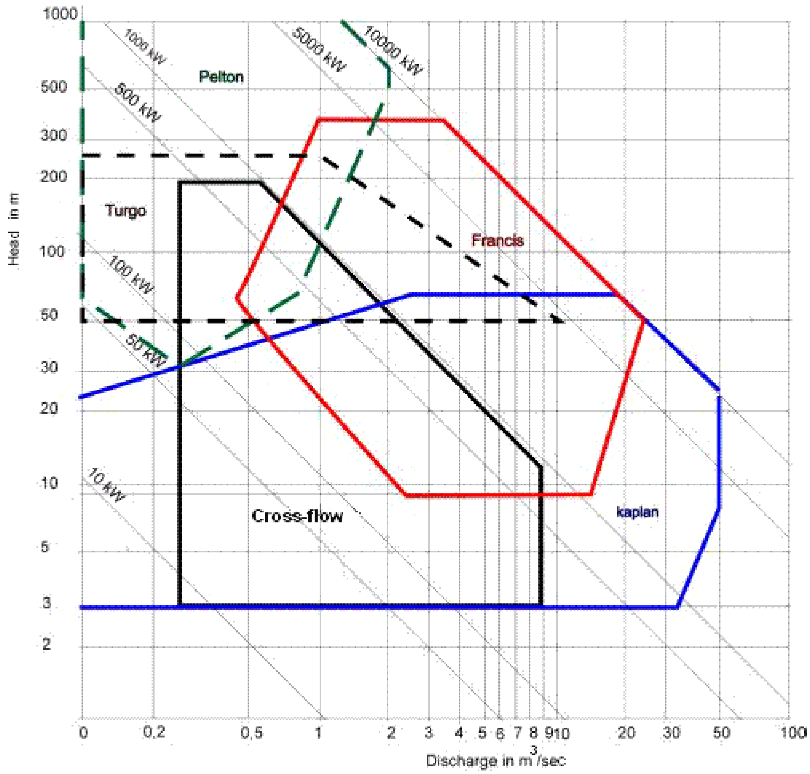


Figure 1.17. Operating ranges of different types of turbines

Table 1.1. Range of heads
[Source: Layman's guidebook on how to develop a small hydro site]

Types of turbine	Range of head in meters
Kaplan and propeller	2 < H < 40
Francis	10 < H < 350
Pelton	50 < H < 1300
Cross-flow	3 < H < 250
Turgo	50 < H < 250

For the same head, certain turbines are more difficult to manufacture than others and consequently they are more expensive. For instance, for low heads, a propeller turbine is cheaper than a Kaplan designed for the same rated discharge. In a medium head scheme, a cross flow turbine will be cheaper than a Francis, whose runner is more complex, although its efficiency is higher.

Regarding discharge it must be remembered that turbines cannot operate from zero flow to rated discharge. As can be seen in figure 1.18, that shows the mean efficiency for several types of turbine, the efficiency decreases rapidly below a certain percentage of the rated discharge. The best, in this respect, cannot be used below 1/6 and many can operate only upwards from about 40% of rated discharge.

The range of discharges to be used, consequently the generated energy, varies if:

a) the scheme has to supply electricity to a small network

b) the scheme has been designed for connection to a large distribution network

In the first case a discharge must be selected which enables generation of electricity almost all the year. In the second, the rated discharge should be selected so that the net revenue from the sale of electricity is maximized.

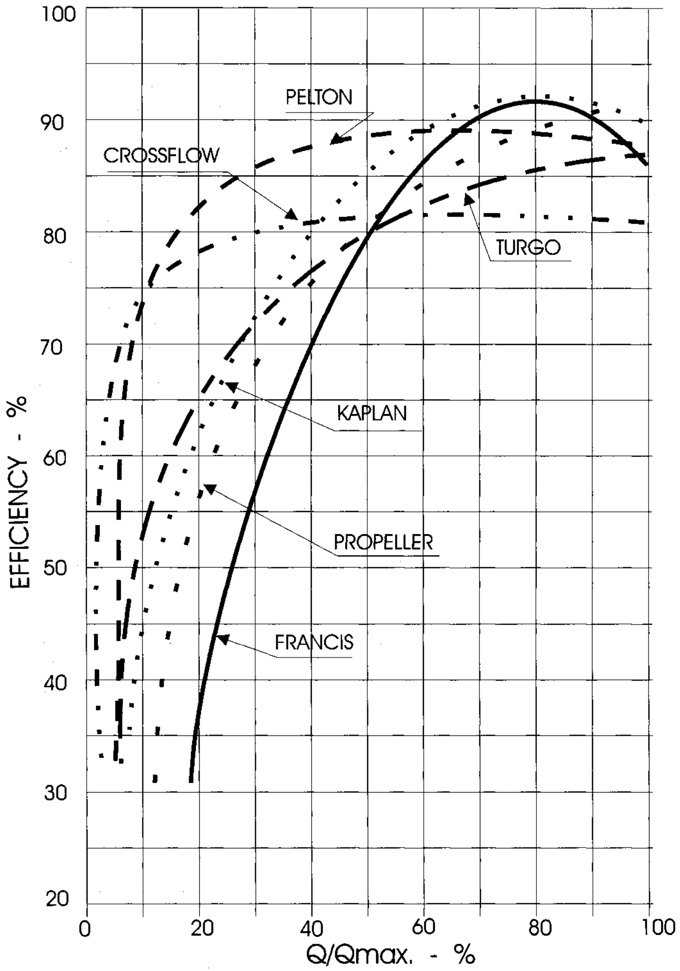


Figure 1.18. Mean efficiency of different types of turbines

1.4.2. Gearboxes and other speed increasers

When the turbine and the generator operate at the same speed and can be placed so that their shafts are in line, direct coupling is the right solution; virtually no power losses are incurred and maintenance is minimal. Turbine manufactures will recommend the type of coupling to be used, either rigid or flexible, although a flexible coupling that can tolerate certain misalignment is usually recommended. In many instances, particularly in the lowest power range, turbines run at less than 400 rpm, requiring a speed increaser to meet the 1000-1500 rpm of standard alternators.

In the range of powers contemplated in small-scale hydropower projects this solution is usually more economical than the use of a custom-made alternator. The speed increaser can be chosen from the types commercially available in the market:

- Parallel-shaft gearbox,
- Epicyclical gearbox,
- Right angle gearbox with bevel gears,
- Belt drives.

Gearboxes substantially increase the noise level in the powerhouse and require additional maintenance. Moreover the friction losses may amount to 2 per cent of the output power. Flat belts or V shaped belts constitute the simplest and cheapest solution.

1.4.3. Generators

Generators transform mechanical energy into electrical energy. Although most early hydroelectric systems were of the direct current variety to match early commercial electrical systems, nowadays only three-phase alternating current generators are used in normal practice. Depending on the characteristics of the network supplied, the producer can choose between:

- *Synchronous alternators*, equipped with a DC excitation system (rotating or static) associated with a voltage regulator, to provide voltage, frequency and phase angle control before the generator is connected to the grid and to supply insignificant proportion of the reactive energy required by the power system when the generator is tied into the grid. On disconnection of the paralleled connection, the synchronous alternator will continue to generate at a voltage and frequency determined by its control equipment. Synchronous generators can run isolated from the grid and produce power since excitation power is not grid-dependent.
- *Asynchronous generators*, that are simple electric squirrel-cage induction motors, with no possibility of voltage regulation, which operate at a speed directly related to system frequency. They draw their excitation current from the grid, absorbing reactive energy. The absorbed reactive energy can be compensated for by adding a bank of capacitors. They cannot generate when disconnected from the grid because they are incapable of providing their own excitation current.

Synchronous alternators are more expensive than asynchronous generators, at least for powers up to about 2 MW, and are used in power systems where the output of the generator represents a substantial proportion of the power system load. Asynchronous generators are used in large grids where their output is an insignificant proportion of the power system load. Their efficiency is 2 to 4 per cent lower than the efficiency of synchronous generators over the entire operating range.

1.4.4. Control equipment

A governor that usually controls a turbine is a combination of devices and mechanisms that detect speed deviation and convert it into a change in servomotor position. A speed-sensing element detects the deviation from the set point; this deviation signal is converted and amplified to excite an actuator, either hydraulic or electric, to control either the turbine discharge or the electrical load.

Governors can be mechanical or electronic. In the mechanical type, the speed sensor is a fly-balls mechanism that controls a hydraulic oil system to operate, through servomotors, the guide vanes and/or the runner blades. Electronic governors control the turbine through power amplification stages, which normally incorporate a hydraulic power unit. Their main advantages are increased reliability, accuracy of control and versatility. Figure 1.19 illustrates a scheme of an electronic governor unit.

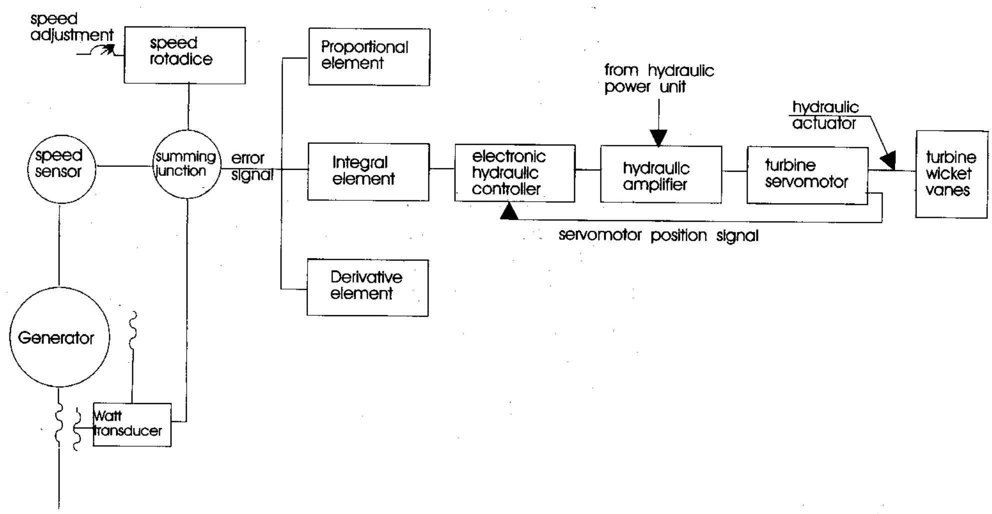


Figure 1.19. Schematic of an electronic governor unit

For small water turbines feeding an isolated system, load governing constitutes a simpler and more inexpensive solution. At full load, constant head and flow, the turbine will operate at design speed, so maintaining full load on the generator; this will run at a constant speed. Reliable and inexpensive electronic load governors, that switch on and off present resistances and so maintain the system frequency accurately, are available. If the generator is connected to a large network, the network provides frequency regulation and a governor is unnecessary.

1.4.5. Switchgear panel and protection equipment

In every country the electricity supply regulations place a statutory obligation on public electric utilities to maintain the safety and quality of electricity supply within defined limits. The independent producer must operate his plant in such a way that the utility is able to fulfil its obligations. Therefore various associated electrical devices are required inside the powerhouse for the safety and protection of the equipment.

Switchgear is required to control the generators and to interface them with the grid or with the isolated load. It must provide protection for the generators, main transformer and station service transformer. A switchgear panel typically contains a generator breaker, potential transformers (PTs), current transformers (CTs), generator control devices, a fused circuit breaker for the station service power and the copper bus bars.

The independent producer is responsible for earthing arrangements within his installation. The independent producer's earthing arrangement must be designed in consultation with the public utility. The earthing arrangement will be dependent on the number of units in use and the independent producer's own system configuration and method of operation.

Figure 1.20 shows a single-line diagram for a power plant with a single unit; the line circuit breaker in the high voltage side can be seen together with the generator circuit breaker and metering in the low voltage side. Greater complications can be expected in multi-unit stations where flexibility and continuity of service are important requirements.

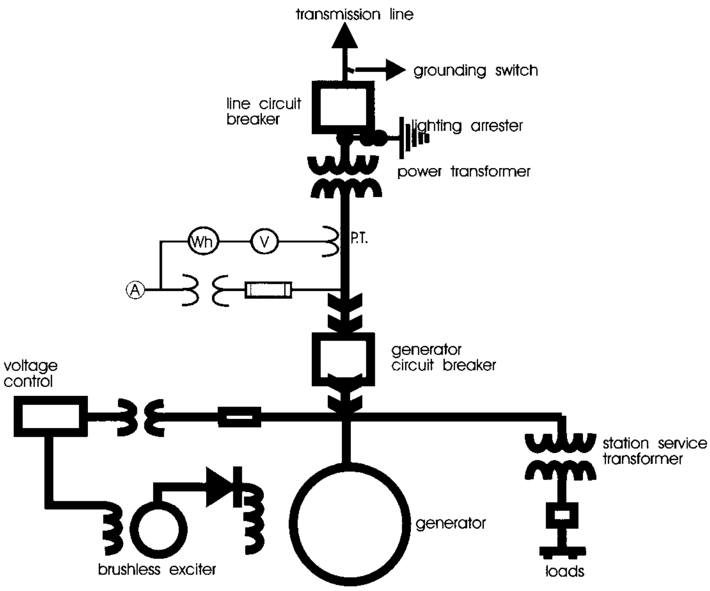


Figure 1.20. Single-line diagram for a power plant with a single unit

1.4.6. Automatic control

Small hydro schemes are normally unattended and are operated through an automatic control system. Because every power plant is different, it is almost impossible to determine here the extent of automation that should be included in a given system. Some requirements are, notwithstanding, generally accepted:

a) All equipment must be provided with manual controls and meters totally independent of the programmable controller (PLC), to be used only for initial start up and for maintenance procedures.

b) The system must include the necessary relays and devices to detect malfunctioning of a serious nature and then act to bring the unit or the entire plant to a safe de-energized condition.

c) Relevant operational data of the plant should be collected and made readily available for making operating decisions, and stored in a database for later evaluation of plant performance.

d) An intelligent control system should be included to allow for full plant operation in an unattended environment.

e) It is convenient, though not essential, to access the control system from a remote location and override any automatic decisions, provided the plant shuts down safely in the event of malfunction.

f) Ideally, the system should be able to communicate with similar units up- and down-stream for the purpose of optimising operating procedures.

g) Fault anticipation constitutes an enhancement to the control system. Using, an expert system, fed with baseline operational data, it is possible to anticipate faults before they occur and take corrective action so that the fault does not occur.

Automatic control systems can significantly reduce the cost of energy production by reducing maintenance and improving reliability, while running the turbines more efficiently and producing more kilowatts from the available water.

1.4.7. Power station auxiliary electrical equipment

Generating auxiliary loads, lighting and station mechanical auxiliaries may require from 1 to 3 percent of the station capacity; the higher percentage applies to micro hydro (less than 500 kW). If available, two alternatives supplies, with automatic changeover, would ensure the service in an unattended plant. Plants with larger than 500 kW capacity, especially if they are remotely controlled, require a DC System including a battery charger, station batteries and a DC distribution panel. The ampere-hour capacity must be such that, on loss of charging current, full control is ensured for as long as is required to take corrective action.

1.5. SMALL HYDRO-POWER ISSUES OF CONCERN

1.5.1. Environmental impact

SHP is in most cases 'run-of-river'; in other words any dam or barrage is quite small, usually just a weir, and generally little or no water is stored. The civil works purely serve the function of regulating the level of the water at the intake to the hydro-plant. Therefore run-of-river installations do not have the same kinds of adverse effect on the local environment as large hydro. Of course there are some environmental problems, notably where the water is extracted some distance from where it is discharged back into the river. Then, the short stretch of bypassed river can run dry or look unsightly unless adequate compensation flow is allowed. In most cases, new hydro installations are designed to leave sufficient water bypassing the turbines - which is not difficult except in times of low flow.

Another area that requires care is the need to avoid harming fish and riverine flora and fauna, but modern turbine installations are designed with this problem in mind. Some low head systems allow fish to pass through the turbine generally unscathed, but various forms of screening (either physical screens or even electrical and ultrasonic) are also used. Fish ladders, a set of small waterfalls set in a channel, are provided to ensure that migrating fish such as salmon can safely bypass the hydro-plant.

Turbines also need to be protected from all the debris that is commonly found in rivers, whether natural (such as leaves, branches, even tree trunks) or man-made (supermarket trolleys, plastic fertiliser bags or general garbage); this is done using screens. A major operating cost element is cleaning these screens, especially in low head situations where large flow rates pass through. Understandably, though slightly unjustly, the hydro-plant operators are usually prohibited by law from returning the rubbish collected on their screens back into the river. Therefore garbage collection and disposal carried out at a hydro installation can serve to clean up a river considerably for the benefit of everyone downstream, but usually at considerable expense to the operator.

There are a few other environmental impact issues relating to oxygenation (or lack of oxygenation) of the water, disturbance of the river bed or erosion immediately downstream of the turbine draft tubes, electrical machinery noise, electrical cables, the general appearance of an installation, etc. However, all these problems are capable of being mitigated by using suitable design techniques and the end product is a remarkably long-lasting, reliable and potentially economical source of clean energy.

1.5.2. Economics of SHP

The last sentence used the phrase 'potentially economical' for good reason; paradoxically, using modern conventions for financial and economic appraisal, most new SHP installations appear to produce rather expensive electricity as the high up-front capital costs are usually written off over only 10 or 20 years (yet such systems commonly last without major replacement costs for 50 years or more). In contrast, an older hydro site where the capital investment has been written off is cheap to run as the only costs relate to occasional maintenance and replacements.

As an example, the unit cost of owning a typical small low head hydro site in the UK might be typically 5 pence/kWh (€0.07/kWh) during the first ten years while the capital investment is being repaid, but subsequently, because of the low running costs, the unit costs should fall to around one tenth of this level - say 0.5 pence/kWh (€0.007/kWh). Clearly the output for the first decade will be more costly than power bought from the grid in most cases, although after the capital investment has been paid off, the hydro plant power prices become exceedingly attractive. Unfortunately, the majority of potential users take a short-term view on investment and are put off by the initial decade or so of high costs.

Decisions to use a technology are generally driven primarily by economics, so naturally there is a need to drive down the costs of SHP. Least cost hydro is generally high head hydro, since the higher the head, the less water is required for a given amount of power - so smaller, less costly equipment is needed. Therefore, in mountainous regions even quite small streams, if used at high heads, can yield significant power levels at attractively low costs.

However, high head sites tend to be in areas of low population density where the demand for electricity is small, and long transmission distances to the main centres of population can nullify the low cost advantages of remote high head systems. High head sites are also relatively rare, with most of the best ones in Europe and other developed regions being already exploited. Therefore, the greatest scope for expanding the use of SHP is with low head sites, although there are of course still many good high and medium head sites waiting to be developed.

Unfortunately, at present most low head sites are at best only marginally attractive economically compared with conventional fossil fuel power generation and for this reason many potential sites remain to be exploited. For example, the UK has some 20,000 disused water mill sites, all low head, which were used in the past but which have so far not been redeveloped; many other countries have a similar situation.

1.5.3. Barriers to the development of SHP

The development of SHP has been handicapped by a general failure to receive similar support that has been given for R&D and for pioneering operation of other forms of renewable energy. This is possibly true because:

- There is a widely held, but faulty, perception that SHP technology is mature and fully developed and that market forces alone will be sufficient to take it forward – so it does not need any significant level of institutional encouragement or support. For this reason SHP is usually excluded from (or given a minor share in) programmes designed to assist other forms of renewable energy development. In reality, there is probably more potential - at least in the short term and on the global scale - for development and improvement of lower cost SHP than for any other form of clean energy development, yet it does need support.
- Economic analysis of hydropower projects generally gives no significant credit for the exceptionally long useful life and low running costs of SHP, and the high 'upfront' costs tend to make it seem financially unattractive compared with conventional energy unless low discount rates are available.
- There has been a tendency to develop SHP in exactly the same way as large hydro, which leads to high design overheads and sometimes to faulty optimisation of systems so as to maximise energy capture rather than to optimise cost-effectiveness.

- There are many other institutional barriers mainly resulting from the difficulties inherent in gaining permission in most countries to abstract water from rivers, and also due to perceptions that hydro plant might adversely effect fishing, boating and other riverine leisure interests (although in practice well designed hydro systems can avoid causing any serious environmental impact for fish or anything else).
- Last but not least, much of the responsibility for the development of SHP lies with small and medium sized enterprises lacking the lobbying capability and influence that other industries such as PV or wind farm developers have on governments.

Hydro power has had a long and significant past; it ought also to have at least as important a future - especially in the light of the growing realisation that it is necessary to bring large-scale methods of clean power generation on stream as quickly as possible in order to avoid some form of climatic catastrophe. It also offers one of the most promising energy resources for the long-term sustainable development of many of the world's poorer countries.

2.1. THE POWER IN THE WIND

2.1.1. Formation of winds

Wind energy is the kinetic energy of moving air. The uneven heating of the earth's surface by the sun causes the winds. The heat absorbed by the ground or water is transferred to the air, where it causes differences in air temperature, density and pressure. In turn, these differences create forces that push the air around. According to fluid mechanics, the air moves from the high-pressure to low-pressure areas of the world.

On a global scale, the temperature difference between the tropics and the poles drives the trade winds, which act as a giant heat exchanger to keep the equator from becoming even hotter and the poles from becoming even colder. On a much smaller scale, temperature differences between land and sea and between mountains and valleys often create strong breezes. Wind direction and speed are also affected by other factors, such as the earth's rotation, local topographical features and the roughness of terrain.

2.1.2. Wind power density

Wind contains energy that can be converted to electricity using wind turbines. The amount of electricity that wind turbines produce depends upon the amount of energy in the wind passing through the area swept by the wind turbine blades in a unit of time. This energy flow is referred to as the wind power density. More specifically, wind turbines rotors reduce the wind velocity from the undisturbed wind speed v_1 far in front of the rotor to a reduced air stream velocity v_2 behind the rotor (figure 2.1).

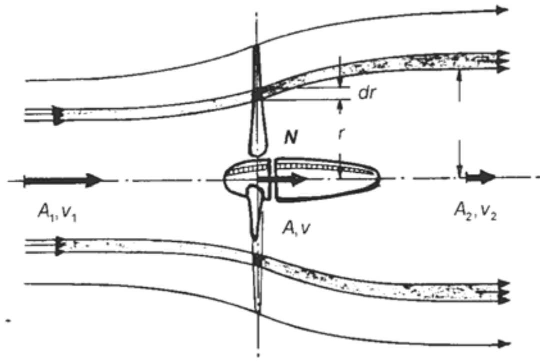


Figure 2.1. Wind flow through a WT

The difference in wind velocity is a measure for the extracted kinetic energy that turns the rotor and, at the opposite end of the drive train, the connected electrical generator. The power theoretically extracted by the wind turbine (WT) can be described by the equation:

$$P = c_P \cdot \eta \cdot \frac{\rho}{2} v_1^3 \cdot A \qquad (2.1)$$

where ρ is the air density (kg/m³), c_p the power coefficient, η the mechanical/electrical efficiency, and A the rotor disk area.

In ideal conditions the theoretical maximum of c_p is 16/27 = 0.593 or, in other words, a wind turbine can theoretically extract 59.3% of the airflow energy content. This is the so-called "Betz limit". Under real conditions the power coefficient reaches not more than c_p=0.5, because it includes all aerodynamic losses of the WT. In most of the technical publications the c_p value includes all losses and is in fact the shortcut for $c_p \cdot \eta$. Different power contents and extractions dependent on the power coefficient and the efficiencies of a WT are shown in figure 2.2.

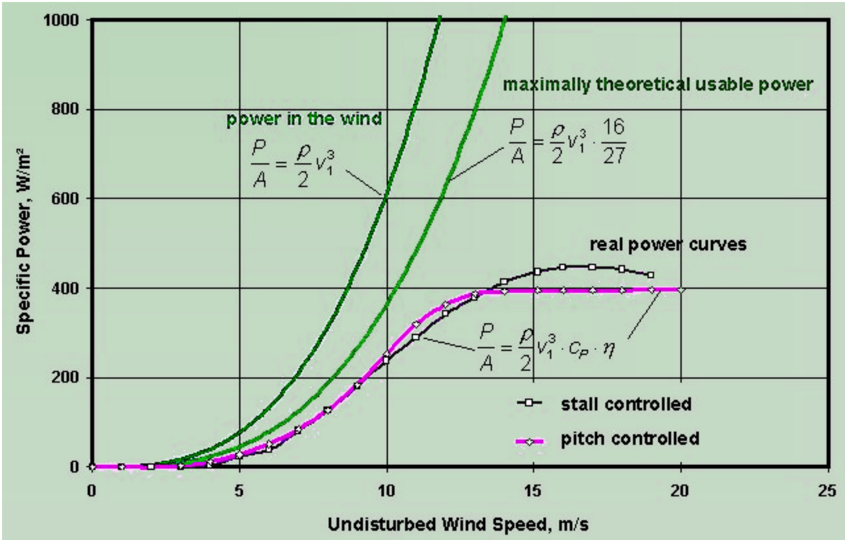


Figure 2.2. Power extraction per rotor disk area versus wind speed

As is evident from eq. (2.1), a key aspect of wind power density is its dependence on wind speed cubed. This means that, if the speed doubles, the power contained in the wind increases by a factor of eight. In practice, the relationship between the power output of a WT and wind speed does not follow a cubic relationship (real power curves of figure 2.2). A WT power curve is usually described in terms of four distinct wind speed regions, which are presented in table 2.1 (with illustrative values referenced to figure 2.2).

Table 2.1. The four regions of the wind turbine power curve

Operating Region	Operational Description: Power output vs. wind speed	Illustrative wind speed range (with reference to figure 2.2)
Region 1	Wind speeds too low to produce useable electric power.	0 to "cut-in" wind speed; 0 to 4 m/s.
Region 2	Production of electric power increasing with wind speed.	"Cut-in" to "rated" wind speed; 4 to 13 m/s.
Region 3	Production of electric power at constant, rated power level. WT blades purposely made less efficient as wind speed increases.	"Rated" wind speed to "cut-out" wind speed; 13 m/s to 20 m/s (or more).
Region 4	No electric power output. Winds too energetic to justify added strength and cost for the small number of hours/year beyond cut-out speed.	"Cut-out" wind speed to "survival" wind speed; 20 m/s (or more) to rated survival wind speed.

Of the four regions, the WT generates and delivers power only in the wind speed ranges defined by regions 2 and 3. In region 1 (below cut-in wind speed), there is not enough energy in the wind to produce useable power. In region 4 (beyond cut-out wind speed), the turbine's output levels-off or begins to decline, while in very high winds the turbine may even be shut down to prevent damage to it. There, the winds are too energetic to justify the added structural strength and cost relative to the small number of hours per year that wind speeds occur within region 4.

Wind power density also depends on air density. At higher altitudes, air density decreases and, as a result, so does the available power. This effect can reduce the power output of wind turbines on high mountains by as much as 40% compared to the power that could be produced at the same wind speeds at sea level. Air density depends inversely on temperature; therefore, colder temperatures are favourable for higher air densities and greater wind power production.

2.1.3. Variability of winds

2.1.3.1. Variation with time

To accurately predict the performance of wind turbines, one needs to know not only the average wind speed at a particular location, but also how the wind speed varies over time. If a long time series of wind speed is transformed to the frequency domain as a power spectrum, then the time scale of the energy in the wind can be identified (figure 2.3). It is useful to distinguish between variations on three time scales: short (seconds to minutes), medium (hours to days) and long (weeks to years).

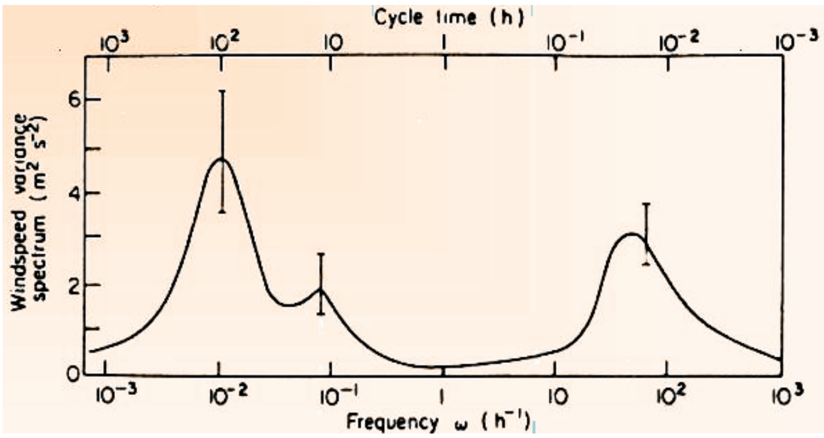


Figure 2.3. A typical wind speed variance spectrum

Variations in the short time scale usually are not very important for evaluating the wind resource unless the wind is very turbulent or frequently changes direction. For single WTs, abrupt wind speed changes can cause large fluctuations in power output (and extra wear on WT components, therefore increased repair and maintenance costs). However, in wind power plants that contain many WTs, this effect tends to average out because the machines at different locations experience gusts at different times. For this reason, wind speed measurements intended to evaluate a potential wind power site are normally averaged over a period of 10 minutes to one hour.

Variations occurring over hours to days are very important for the wind resource evaluation. Wind speed records typically show large upswings and downswings that persist for up to several days, reflecting passing storms and weather fronts. In addition, many locations experience a daily pattern of wind speed variation, with peak winds often occurring in the afternoon. Monthly and seasonal variations also have a significant effect on wind power plant performance. The degree and timing of the seasonal variations depend upon the region.

There may even be changes in the annual average wind speed from year to year related to regional climate phenomena. At least one year of measurement is essential to capture seasonal wind behaviour. Beyond that, the benefits of extended measurement diminish quickly, and one to two years of measurement usually will suffice to predict long-term average wind speeds and wind speed variability with acceptable accuracy. The time scales, the group having most interest and the reasons for that interest are listed in table 2.2.

Table 2.2. Time scales for wind electricity-generation systems

Time scale	Of interest to	Reason for interest
Tens of seconds or less	Wind turbine designers	Structural strength against wind-induced loads, structural vibrations and flexural failure of components; possible voltage and frequency fluctuations.
Tens of minutes to hours	Power system operators	Ability to follow or compensate for the varying power contributed by the wind system; wind forecasting.
One day	Power system operators	Predictability of a diurnal cycle and output in some wind regimes; correlation with the diurnal load profile.
Month-to-month	Power system planners and operators	Predictability of seasonal variations and output in most wind regimes; correlation with the seasonal load profile.
One year	Power system operators and the financial community	Predictability of annual output in most wind regimes; ability to cover debt in an average wind year.
Year-to-year	Financial community	Inter-annual variability and ability to cover debt in a substandard wind year.

2.1.3.2. Wind speed dependence on height

The equation for the power extraction by a WT shows that the energy generation of a WT depends on the wind speed distribution of the site, the air density, the rotor size and the technical design. Especially the tower height affects considerably the energy extraction, because the wind speed increases with the height above ground level, a phenomenon known as wind shear. The degree of wind shear depends mainly upon on two factors, namely atmospheric mixing and the roughness of the terrain.

Terrain roughness affects wind shear by determining how much the wind is slowed near the ground. In areas with a high degree of roughness, such as forests or cities, near-surface wind speeds tend to be low and wind shear high, whereas the converse is true in areas of low roughness, such as flat, open fields. Wind shear may be greatly reduced or eliminated where there is an abrupt change in terrain height, such as a sea cliff or mountain ridge. Figure 2.4 gives an impression of a possible shape of such a wind velocity boundary layer.

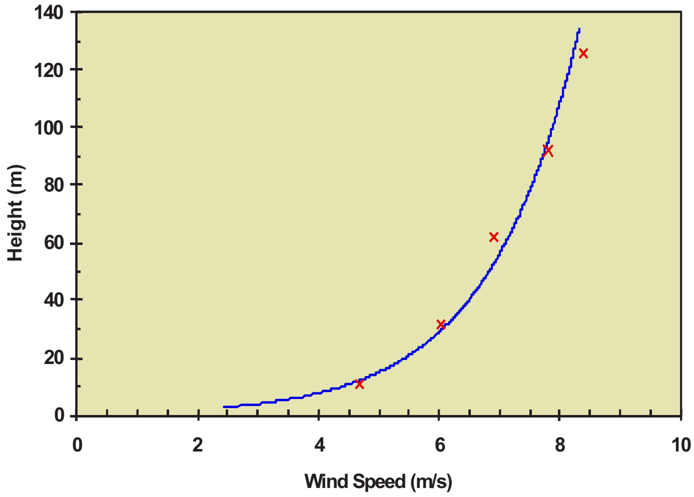


Figure 2.4. Measured typical wind speed profile

A usual assumption for the wind speed distribution over height is the logarithmic one:

$$v = \frac{v_\tau}{\kappa} \ln\left(\frac{h}{z_0}\right) \tag{2.2}$$

where v is the wind speed at height h, v_τ the friction velocity, κ the von Karman constant (equal to 0.4), and z_0 the roughness length, which is related to the vegetation cover of the area. Tables of roughness length are available from several sources. Sometimes a power law is also used for the description of the wind profile:

$$v = v_R \left(\frac{h}{h_R}\right)^{\alpha} \tag{2.3}$$

with v_R the wind speed at reference height h_R. The exponent α is dependent on the roughness elements of the ground and a value of 1/7 is often quoted as reasonable.

Atmospheric mixing typically follows a daily cycle driven by solar heating. At the hub height of a WT, this cycle often causes wind speeds to increase in the daytime and decrease at night. However, the range of variation between night and day typically diminishes as hub height increases. At a height of about 10 metres the diurnal variation can be very pronounced, but as the height increases to around 50 metres, it weakens or may even disappear.

The log law wind profile [equation (2.2)] may still be used in the lowest 100 metres with appropriate corrections in order the above changes in atmospheric stability to be taken into account. To save money, wind measurements sometimes are taken at a lower height than the WT tower. In that case, it is essential to measure wind shear at different times of day and in different seasons to accurately predict the performance of a wind power plant. The shear can be measured by monitoring wind speeds at two or three heights on a tower.

2.1.3.3. Spatial variations

To further complicate matters, wind resource characteristics can differ greatly between nearby locations. For obvious reasons, the strongest winds usually are found in well-exposed locations. In addition, terrain features such as hills and ridges can accelerate the wind as it passes over them. A ridge oriented perpendicular to the prevailing wind direction and with a moderate slope is usually ideal. However, strong winds may sometimes occur in unexpected places.

For example, broad mountain passes may be ideal for wind power plants because they channel winds passing over a mountain range and because breezes may be created by cold air sinking from mountain tops into valleys. A variety of tools for predicting wind speeds in complex terrains, over buildings and other obstacles, and the site orography have been developed, including sophisticated computer models. There is no substitute, however, for direct measurement.

2.1.4. Global wind power resource

Global winds are a good energy resource and are well distributed over large areas of the world. Estimates of the resource suggest that the present world energy demand is equivalent to approximately 1% of the total energy in the world's winds. In order to evaluate the resource it is necessary to provide some estimate of how much of the resource is accessible given the technology and constraints on land use in any area.

The World Meteorological Organisation (WMO) performed a study of the global wind resource (1981). A preliminary estimate of the available resource was presented as a map of wind energy in Watts/m^2 at 10m above the ground. Data from the global network of meteorological stations were used to construct the estimate. These stations were not designed to evaluate wind energy, so the data were supplemented by upper air and topographical information to aid with the extrapolation. This provides a broad picture of the global wind energy resource.

Not all areas of high wind speed potential are highlighted, some because they cover too small an area, some because there is little data, and others due to local effects that are not fully accounted for. The presentation of the data also makes no allowance for any constraints on the land use and so no estimate of an accessible resource is given. Many countries have performed their own wind resource analysis. Various studies of the whole USA and selected areas have been completed.

The European wind resource has been estimated in the European Wind Atlas. Maps for the whole of Europe have been compiled, showing the wind speed in m/s and the wind power in Watts/m^2, at 50m above the ground and for various terrain types. The initial wind data were taken from meteorological stations with long records and good exposure. The data were then corrected for topography, terrain and any local shelter before being extrapolated to other areas.

The data spread again means that some localised areas of high wind speed are not resolved. In addition, some areas of low wind speed, e.g. sheltered valleys in a high wind speed area, are also not resolved. No judgement on the accessible resource is made, but many European countries have performed their own national or regional surveys. Many other countries are also now assessing their wind resource, especially India and China, which are already making commitments to utilising wind energy.

2.1.5. Historical perspective and current development of wind energy

The pioneering installations in Europe were principally in Denmark. The configuration of grid-connected wind systems has evolved from the early Danish model of the seventies to that of the large Californian and later European wind-farm installations. As the California wind-farms were being designed and installed during the early eighties, the Danish installations of the 1970s and later typically consisted of small clusters of machines geographically dispersed throughout much of the country. Typically, a grid-connected wind installation consisted of at most three or more WTs.

Local farmers, manufacturers, and other citizens formed cooperatives to own and operate the wind turbines, and to use and sell the power produced by the machines. By contrast, the California model has been the formation of wind-farms, that is, the commercial aggregation of large numbers of machines in close geographical proximity. While there are differences in sizes of installations (due principally to differing land use constraints), the more recent European installations have followed the Californian model.

In 1999, a record-breaking total of 3,900 MW of new wind energy generating capacity were installed globally. About 2,500 MW came online in 1998. During the year 2000, 3,800 MW of new wind energy generating capacity were installed worldwide, representing annual sales of $4 billion and boosting total installed capacity to about 17,300 MW, enough to generate some 37 billion kWh of electricity each year. This year's growth remained concentrated in Europe, since some 3,500 MW of new installed capacity went online in Europe, of which half (1,668 MW) were in Germany.

Since 1993, the market for new WTs to generate clean power from wind in Europe has grown at over 40% per year. This forced the European Wind Energy Association (EWEA) to raise its goal for the region by 50%, from 40 GW to 60 GW of installed capacity by 2010, of which 5 GW are expected to be offshore. A new target of 150 GW was also set by EWEA for 2020, which would provide electricity for 75 million people. Moreover, over 20,000 Europeans are employed in the wind energy industry, which in 1999 produced more than 90% of the total worldwide sales in that year.

Manufacture and installation of WTs employs, on average, six people per year for every MW of newly manufactured turbines. For operation and maintenance, between 100 and 450 people are employed per year for every TWh of electricity produced, the number varying according to the age and type of turbines. For every job in WT manufacture, installation, operation and maintenance, there is at least one more in associated sectors of the industry. This includes consultancy, legal work, planning, research, finance, sales, marketing, publishing, and education.

2.2. DESCRIPTION OF WIND TURBINES

2.2.1. General layout

Figure 2.5 shows a generic Horizontal Axis Wind Turbine (HAWT) system. A Vertical Axis Wind Turbine (VAWT) is an equally viable alternative design, but it is not as common as the HAWT one in recent projects. Although there is no standard system for classifying WT subsystems, the components shown in figure 2.5 could be divided into four (4) basic subsystems:

1. a rotor, usually consisting of two or three blades, a hub through which the blades attach to the low speed drive shaft, and sometimes hydraulic or mechanically-driven linkage systems to pitch all or part of the blades;
2. a nacelle, generally including a gearbox and generator, shafts and couplings, a cover for the entire nacelle, and often a mechanical disk brake and a yaw system;
3. a tower and foundation that supports the rotor and the drive train (nacelle);
4. electrical controls and cabling, and instrumentation for monitoring and control.

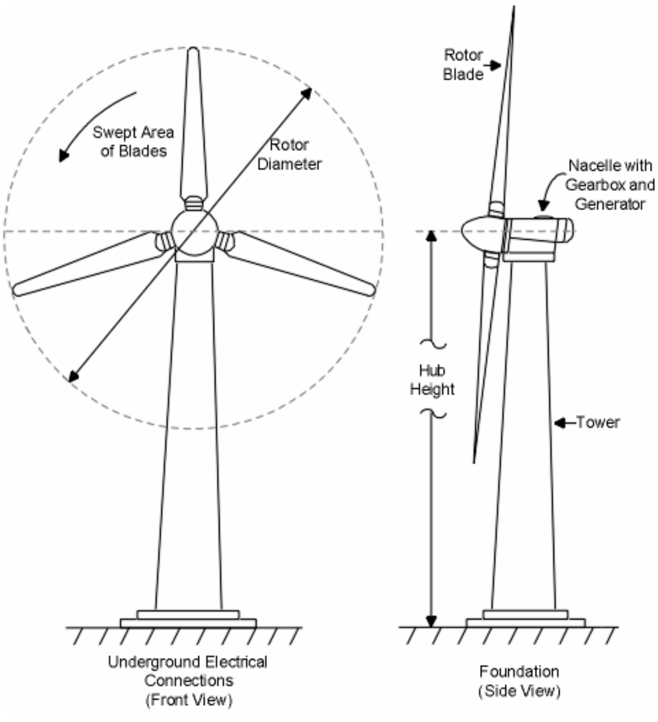


Figure 2.5. Horizontal axis wind turbine schematic

The sequence of events in the generation and transmission of wind power can be summarised as follows:

a. A torque is produced as the wind interacts with the WT rotor.
b. The relatively low rotational frequency of the rotor is increased via a gearbox, and the gearbox output shaft turns a generator.
c. The electricity produced by the generator passes through the WT controller and circuit breakers and is stepped up to an intermediate voltage by the transformer.
d. The site cabling system delivers the electricity to the site transformer via the WT control and circuit breaker system, which steps up the voltage to the grid value.
e. The grid system transmits the electricity to the locality of its end use.
f. Transformer substations reduce the voltage to domestic or industrial values, while local low voltage networks transmit the electricity to homes, offices and factories.

2.2.2. Rotor

With large wind turbine rotors of up to 66m diameter now in commercial production for megawatt scale wind turbines, and rotors of up to 100m diameter (Growian, MOD 5B) having been operated, a rotor blade technology has developed that is quite unique to the wind industry. Rotor blade design has advanced with knowledge from wing technology, and utilises the aerodynamic lift force that an airfoil experiences in a moving stream of air. The shape of the blade and its angle in relation to the relative wind direction both affect its aerodynamic performance.

The rotor assembly may be placed either “upwind” of the tower and nacelle, so receiving wind unperturbed by the tower itself, or “downwind” of the tower, which enables self-alignment of the rotor with the wind direction (yawing), but causes the wind to be deflected and made turbulent by the tower before arriving at the rotor (tower shadow). WTs can have different numbers of rotor blades. The rule is: the lower the number of blades the faster turns the rotor. The measure for this is the tip speed ratio λ, defined as the rotor tip speed divided by the wind velocity.

Modern WTs are designed for the generation of electricity, which means their rotors drive electrical generators with normally high rotational speeds. Therefore, rotors of WTs should have rotational speeds as high as possible in order to reduce the masses of transmission gears and generators. Consequently, the number of rotor blades should be low and in general no more than three. Only the well-known western type windmills are using 12 to 20 blades or even more, but they are applied for directly driven water piston pumps with their high mechanical torque.

Normally, 3-bladed rotors have design tip speed ratios in the order of 6 to 8, 2-bladed rotors of 10 to 12, and 1-bladed rotors above of these values (see figure 2.6). On the other hand, commercial WTs with high blade tip speeds have the disadvantage of high noise emissions of the rotor. In principle, the noise power level of the rotor increases with the sixth power of the blade tip speed; that is the reason why the designers of commercial WTs not exceeded 70 m/s up to now.

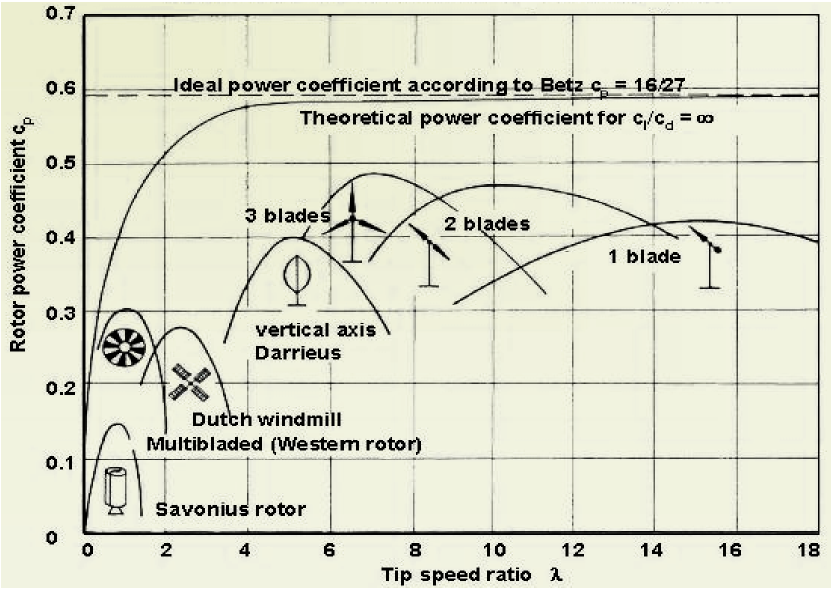


Figure 2.6. Typical c_P–λ diagrams for a variety of WT configurations/blades

The lifetime of a rotor is related to the variable loads and environmental conditions that it experiences during its operation. Therefore, the rotor's inherent mechanical properties and design will affect its useful service life. The materials used in modern wind turbine blade construction may be grouped into three main classes:

1. wood (including laminated wood composites);
2. synthetic composites (usually a polyester or epoxy matrix reinforced by glass fibres); and
3. metals (predominantly steel or aluminium alloys).

2.2.3. Nacelle

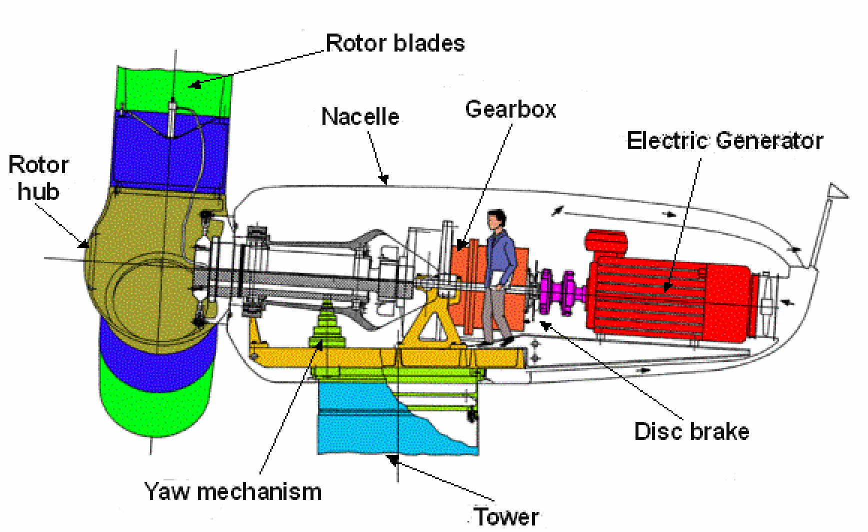


Figure 2.7. Schematic representation of a WT nacelle

The nacelle houses the turbine's drive train and generator assemblies, plus the yaw mechanism and any control components. A view of the machinery in the nacelle of a medium/large-scale wind turbine is shown in figure 2.7. Service personnel may enter the nacelle from the tower of the turbine. A brief presentation of the equipment that is housed in a typical WT nacelle is provided in the following.

2.2.3.1. Main shaft

Transferring the primary torque to the gear train from the rotor assembly, the main shaft is usually supported on journal bearings. Due to its high torque loadings, the main shaft is susceptible to fatigue failure. Thus, effective pre-service non-destructive testing procedures are advisable for this component. On a modern 600 kW WT the rotor rotates relatively slowly, with about 19 to 30 revolutions per minute (RPM).

2.2.3.2. Disc brake

This may be situated either on the main shaft before the gearbox, or on the high-speed shaft after the gearbox. The latter arrangement requires a smaller (and cheaper) brake assembly in order to supply the necessary torque to slow the rotor. However, this arrangement does not provide the most immediate control of the rotor, and in the event of a gearbox failure, braking control of the rotor is lost.

2.2.3.3. Transmission

The electrical output of wind turbines has to be compatible with the frequency (50 - 60 Hz) and voltage of the local distribution grid. The rotor's frequency is typically about 0.5 Hz, and so the increase in frequency is obtained by a combination of a gearbox and a multi-pole generator. Most commercial generators have 4 or 6 pole pairs, and so a step-up gear ratio of about 25:1 is required. The simplest method to drive the generator is directly via the main shaft from the rotor without a gearbox, which eliminates gearbox losses and energy conversion efficiency is optimised.

Then, special slow-speed generators are required, which need large rotor and stator diameters having about 50 poles in order to provide the required frequency (now offered on a commercial basis by a small number of manufacturers). Small sized (50-150 kW) turbines utilise one or two stage parallel shaft transmissions (with helical gears to minimise noise and power losses). Larger commercial turbines (150-750 kW) commonly use epicyclical or planetry transmissions, which have output shaft in line with the main shaft (thereby reducing stress and power losses in the drive train), with a corresponding reduction in size.

2.2.3.4. Generator

The generator converts the mechanical energy of the input shaft to electrical energy. WT generators are a bit unusual, compared to other generating units ordinarily found attached to the electrical grid. One reason is that they must be compatible at input with the rotor and gearbox assemblies, but at the output with the utility's power distribution (if connected to the grid) or to local power requirements (if the WT is part of a stand alone system). If a grid-connected turbine is fitted with an AC generator, this must produce power that is in phase with the utility's grid supply.

Many grid-connected turbines use capacitor excited induction AC generators, whose magnetising current is drawn from the grid, ensuring that the generator's output frequency is locked to that of the utility, and controlling the rotor speed within limits. Synchronous generators produce electricity in synchronization with the generator's rotating shaft frequency, and the rotor speed must exactly match the utility supply frequency. Very small WTs may have generators producing DC power, which is then used to power low voltage loads (usually 12 volts), to charge a bank of batteries, or through an inverter system to supply higher voltage AC power to a grid network.

2.2.3.5. Yaw assembly

In order to extract as much of the wind's kinetic energy as possible, the rotor axis should be aligned with the wind direction. Small upwind WTs (up to 25 kW) typically use tail vanes to keep the machine aligned with the wind. However, larger WTs with upwind rotors require active yaw control to align the machine with the wind. When a change in wind direction occurs sensors activate the yaw control motor, which rotates the nacelle and rotor assembly until the turbine is properly aligned. Downwind machines of all sizes may possess passive yaw control, which means that they can self-align with the wind direction without the need for a tail vane or yaw drive.

2.2.4. Tower

The tower of a WT supports the nacelle assembly (which may weigh many tonnes), and elevates the rotor to a height at which the wind velocity is significantly greater and less perturbed than at ground level, due to the wind shear effect. In areas with high terrain roughness it is an advantage to have a tall tower, since the rotor blades on turbines with relatively short towers will be subject to very different wind speeds (thus different bending) when a rotor blade is in its top and bottom positions, which will increase the fatigue loads on the turbine. Manufacturers often deliver machines where the tower height is equal to the rotor diameter.

Therefore, the tower’s structure must withstand significant loads, originating from gravitational, rotational and wind thrust loads. In addition, the tower must be able to withstand environmental attack for the entire design life of the turbine, which may be 20 years or more. The price of a WT tower is generally around 20% of the turbine’s total price. For a tower around 50 metres height, the additional cost of another 10 metres of tower is about €17,500. It is therefore quite important for the final cost of energy to build towers as optimally as possible.

2.2.4.1. Fixed tubular towers

These are manufactured from tapered steel or concrete. Most large WTs today are delivered with tubular steel towers, which are manufactured in sections of 20 to 30 metres with flanges at either end and bolted together on the site. The towers are conical (i.e. with their diameter increasing towards the base – fig. 2.8 left) to increase their strength and, at the same time, to save materials. Spun-concrete towers are generally less flexible than steel ones, and so offer improved sound deadening qualities (they do not transmit or amplify rotationally-induced vibrations).

2.2.4.2. Fixed latticed towers

Lattice towers (figure 2.8 right) are manufactured using welded steel profiles. They are relatively cheap to erect, and require less substantial foundations than tubular towers, due to their spreading of the structure loads over a wider area. Thus, their basic advantage is cost, since a lattice tower requires only half as much material as a freely standing tubular tower with a similar stiffness. The basic disadvantage of lattice towers is their visual appearance, although that issue is clearly debatable.

Figure 2.8. Photographs of WTs with tubular steel tower (left) and lattice tower (right)

2.2.4.3. Erectable-guyed towers

These towers have a significant cost advantage compared to other types, since they may be raised or lowered using a gin pole, without the need for a crane. Therefore ground-level rotor and nacelle maintenance is possible. The diameter of guyed towers is, in practice, much less than fixed towers. Guyed towers, along with latticed designs, give less of a tower shadow effect than tubular towers. However, they utilise more ground area due to the need to spread the guy cables quite widely, which may be a handicap if machines are used for cultivating crops around the wind turbine bases. On the other hand, animal farming is not so affected.

2.2.5. Power control

With increasing airflow speed, the aerodynamic lift forces on the rotor blades grow with the 2nd power and the extracted energy of the turbine with the 3rd power of the wind speed, a situation which needs a very effective, fast acting power control of the rotor to avoid mechanical and electrical overloading in the wind turbine's energy transmission system. Modern WTs use two different aerodynamic control principles to limit the power extraction to the nominal power of the generator. The most passive one is the so-called "stall control", the active one being "pitch control".

In the first case, it is the inherent aerodynamic properties of the blade that determine the power output; there are no moving parts to adjust. The twist and thickness of the rotor blade vary along its length in such a way that turbulence occurs behind the blade whenever the wind speed becomes too high. This turbulence causes some of the wind's energy to be shed, minimising power output at higher speeds. Stall control machines also have brakes on the blade tips to bring the rotor to a standstill, if the turbine needs to be stopped for any reason.

In the second case, the angle of the rotor blades can be actively adjusted by the machine control system. The pitch control system has built-in braking, as the blades become stationary when they are fully "feathered". In the past, most of the small and medium sized WT generator systems used the simple stall control, but nowadays, with the growing size of the WTs, the manufacturers more and more prefer a pitch control system, which offers more possibilities to influence the operation of the WT.

Only the last years a mixture of stall and pitch control appeared, the "active stall". In that case the rotor blade pitch is turned in direction towards stall and not towards feathering position (lower lift) as it is done in normal pitch systems. The advantages of this system are:
- very small pitch angle changes necessary;
- power control under partial power conditions (low winds) possible;
- feathering position of rotor blades for low loads at extreme winds.

2.2.6. Rotor speed

Modern wind turbines have two types of electrical connections to the grid. With the simple direct synchronisation of an induction generator the rotor operates with nearly constant speed because the strong grid keeps the generator's frequency. The slip range of the generator gives the only rotational speed variation. With the help of an inverter system between the wind turbine generator and the grid the turbine is decoupled from the grid frequency and is able to rotate at variable speeds.

For a long period, directly grid coupled WTs dominated the world market due to their technical simplicity, but several positive aspects of the variable rotor speed mode changed the current development status. As was mentioned, the aerodynamically optimised lay-out of wind turbines is based on a fixed relationship between wind and rotor tip speeds, the tip speed ratio λ. In order to keep the maximum aerodynamic efficiency the rotor must change its rotational speed according to the wind speed; in other words, low winds with low rotor speeds, high winds with high rotor speeds.

As a result, the large new megawatt WTs more and more use variable rotor speed to profit by the technical advantages. To better adapt the WT rotor operation to the aerodynamic design point (see figure 2.6), the manufacturers often use two-speed induction generators that allow changing the rotor speed in two steps. At low wind speeds the generator operates with a low rotational speed (higher number of poles), and at high wind speeds with a high rotational speed (lower number of poles).

2.3. WIND TURBINES PERFORMANCE CHARACTERISTICS

2.3.1. Range of wind turbine applications

2.3.1.1. Application classes

Electricity-generating wind turbines can be applied in a variety of contexts. These range from individual, isolated installations to large arrays of turbines. They may be connected to an existing grid or be integrated with other non-grid-connected power sources. The range of applications may be grouped into three classes. Wind-farms, i.e. large arrays of WTs interconnected to the utility grid, form one end of the application spectrum. In terms of installed capacity and economic impact, wind-farms currently are by far the largest application class of wind turbines.

The other two application classes typically utilize a smaller number of WTs of smaller unit size. These are wind turbines used as grid-connected, distributed generation, and WTs closely integrated with other power sources and capable of operating without the presence of a larger utility grid. These are the so called “hybrid power” systems. Both classes have historical precedents in both the U.S. and Europe.

2.3.1.2. Wind-farms

The wind-farms are comprised of arrays of WTs interconnected electrically so as to deliver their power to the utility grid. From an electrical power flow perspective, a wind-farm acts in parallel with the utility's conventional generating capacity to supply the power demands of the connected load. The arrays can consist of hundreds of machines with a combined wind-farm power rating of hundreds of megawatts. The conventional sources almost always supply the larger fraction of the power required by the load.

In general, the ratio of wind generating capacity to that of the total capacity (wind plus conventional) serving a utility load at any given moment is measured by the wind penetration *WP*:

$$WP = \frac{Wind\,Capacity}{Wind\,Capacity + Conventional\,Capacity} \tag{2.4}$$

For example, suppose that at a given time of day the utility load is 1,100 MW, and that this demand is being met by a combination of wind and conventional generating sources. If the wind capacity on-line is 100 MW and the conventional capacity is 1,000 MW, then the wind penetration value at this time would be 0.0909 or 9.1%.

With current WT electrical technology, the maximum value of wind penetration with which most utility systems are comfortable lies in the range of 10 to 15%. This upper limit on the amount of wind that can be accommodated by a utility system reflects concerns about the technical characteristics of the power supplied by the wind system, that is the power quality. Specifically, the concern is over the impact of the time-varying, wind-generated electrical power on the short-term voltage and frequency stability of the combined power supplied to the load.

The acceptable penetration value depends on a number of factors, including the details of the wind technology, the operating characteristics of the conventional generation sources, and the capacity and length of the transmission lines connecting the sources to the load. The upper boundary on the amount of wind power that can be integrated with conventional sources is not a hard and fast limitation, and its value will increase as more operating experience is gained, the technology changes and as the control systems of the wind and conventional sources are more tightly integrated.

Intensive development of these systems during the past 15 years resulted in the increment of their unit size (currently, the power ratings of WTs designed primarily for wind-farm use range from approximately 300 kW to 1.5 MW, with corresponding rotor diameters ranging from 35 to 65 m), and the dramatic improvement of their reliability and economics. As was mentioned, the economics of grid-connected, large-scale wind systems now approach those of some conventional power generation systems.

In case that c_p reaches its theoretical maximum ("Betz" limit), the wind velocity v_2 behind the rotor is only 1/3 of the velocity v_1 in front of it (figure 2.1). Therefore, wind turbines situated in a wind farm produce less energy due to the wind speed reduction caused by the WTs in front of them. The energy loss can be diminished by increasing the distance between the WTs because the wind behind a WT will be accelerated again by the surrounding wind field. A proper designed wind farm can have less than 10% losses caused by mutual interference effects.

As there is a range of WT sizes, there is also a range of wind-farm sizes. The large Californian farms form one end of this range, the other end being a small cluster of WTs serving a municipal utility, a farm or ranching cooperative, or an industrial facility. Regardless of the size, the defining characteristics of a wind-farm are:

1) the wind turbines are connected to a utility grid,
2) the wind generating capacity usually is a small fraction of the conventional capacity supplying the utility system load (low values of wind penetration), and

3) the wind turbines require some level of electrical support from the utility grid.

Depending on the details of the generator and other electrical technology employed in WT, the support can range from a simple frequency reference (for synchronization of the wind-generated electricity to that of the conventional sources) to the consumption of reactive power (required for operation of the WT generators). Regardless of the wind-farm size, standard utility techniques and components (e.g., transformers and protective switchgear) are used to connect the wind turbines to the grid. The WT is the only non-standard utility component.

2.3.1.3. Distributed generation

As the discussion concerns wind turbines, the very early water-pumping windmills used extensively in the first half of this century in ranches and farms worldwide are likely to be recalled. These early, small-scale WTs have been supplanted by their modernized, more efficient equivalents used mainly to generate electricity. Although there are no technical reasons why larger units cannot be used, the unit size of these systems typically ranges from 1 to 50 kW. They are intended for use individually or in small clusters, while they may or may not be connected to the existing utility grid.

When connected to the grid, these systems are called distributed wind generation systems. From both utility and customer perspectives, distributed generation can be useful in providing end-of-line voltage support to an extensive grid. Distributed wind systems also can be used as an alternative to extension of the grid to distant loads. As can be noticed, wind system applications form a continuum, so in many instances the distinction between a wind-farm and a distributed system may not be clear. The only difference may be the size or the number of the WTs used.

When not connected to the grid, the electric power is unregulated. Only the load and the output of the WT determine the power quality and delivery characteristics. Thus, the load must be capable of using such unregulated power without damage to either the load or the wind turbine generator. Development work is under way to improve this situation. Of particular interest is the work aimed at successfully connecting an induction motor directly to a non grid-connected WT. Application examples include wind turbines used for water pumping, ice making and refrigeration.

2.3.1.4. Hybrid power systems

Hybrid power systems employ wind turbines and possibly other renewable power sources together with diesel generators to form the equivalent of a miniature grid. While the unit size of WTs in these applications typically ranges from 1 kW to 50 kW, much larger machines and hybrid power systems have been fielded. They may be used with diesel generators, energy storage (e.g. batteries), and, where appropriate, other renewable power sources, such as photovoltaics or hydropower.

Used in this mode, these systems are often called hybrid power systems. They are typically used where there is no utility grid. Because of the close coupling and control of all generation sources and some (or all) of the connected load, the wind energy component of hybrid power systems can achieve 100% penetration. That is, given suitable wind conditions, the wind energy system can supply nearly all of the power demanded by the load.

2.3.2. Wind system energy productivity

2.3.2.1. Overview

During the year, there are times when the wind does not blow, or blows at speeds below the cut-in wind speed of a turbine. Obviously, wind systems do not produce energy during all of the 8,760 hours in a year. Even when a wind system does produce energy, it does not always do so at its full rated power. What is required is a measure of the energy productivity of the wind system. This measure is the capacity factor *CF*, a descriptive parameter defined and used in the utility industry.

This parameter, as a ratio of energies, says nothing about the physical processes associated with the conversion of power carried by the wind into electric power. Required is a description of the relationship between the power output of a WT as a function of wind speed (power curve) and the variation of wind speeds during a given period (the wind speed frequency distribution). These functions together describe the matching of the WT power generation characteristics to those of the wind regime in which the WT is situated, and are used to predict or estimate its energy production.

After accounting for losses in the electric power collection system, interactions between wind turbines in a wind-farm, and other losses, the individual WT outputs can be summed to form an estimate of the wind-farm energy production. These estimates or projections are most often cast in terms of a calendar year and are referred to as the annual energy production of the wind turbine or wind-farm.

2.3.2.2. Estimates of the annual energy production

The strength of the wind resource is described quantitatively by the wind speed distribution. The WT power curve is the quantitative relationship between the electric power output and the incident wind speed. Together, the wind speed distribution and the WT power curve determine the annual energy production (*AEP*). These functions and this relationship are illustrated below. The discrete version of a hypothetical/ measured wind speed distribution at the WT site is graphed in figure 2.9.

The wind speed distribution function $F(v)\cdot\Delta v$ gives the number of hours per year that the wind speed lies within the wind speed interval or bin of width Δv, located between the values v and $v+\Delta v$ (in the case of figure 2.9, Δv=0.5 m/s). The integer index k identifies the wind speed bins. Thus, the bin k=21 corresponds to the bin bounding the range 10 to 10.5 m/s, with a mean speed equal to v_k=10.25 m/s. The height of the bar for k=21 indicates that the wind speed lies within this interval for about 275 hours/year. The sum of all bars is 8,760 hours (the number of hours in a year).

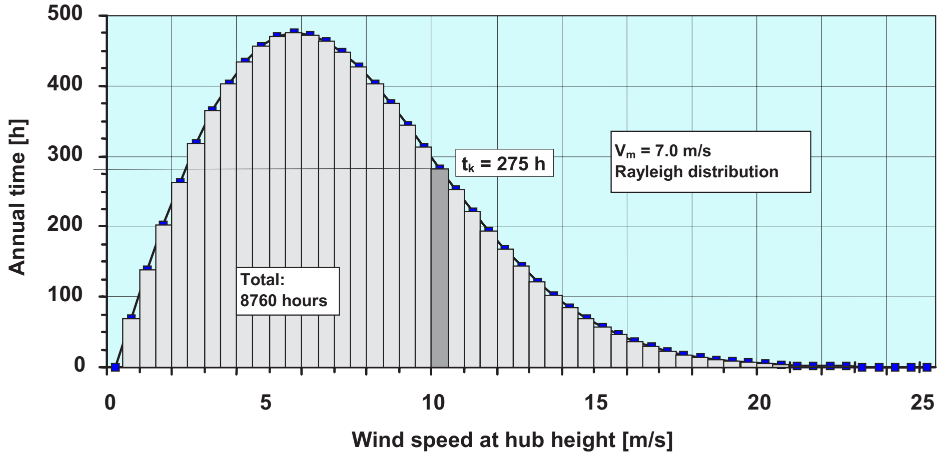


Figure 2.9. Annual wind speed histogram (v_k=10.25 m/s; t_k=275 h)

The power curve for a hypothetical 500 kW WT at standard air density (1.225 kg/m³) is plotted in fig. 2.10. The power curve *P(v)* is the continuous function that specifies the wind turbine's electric power output as a function of the wind speed. The discrete version, indicated by the small square symbols, is denoted by P_k where the integer index k is the same as that used for the wind speed distribution.

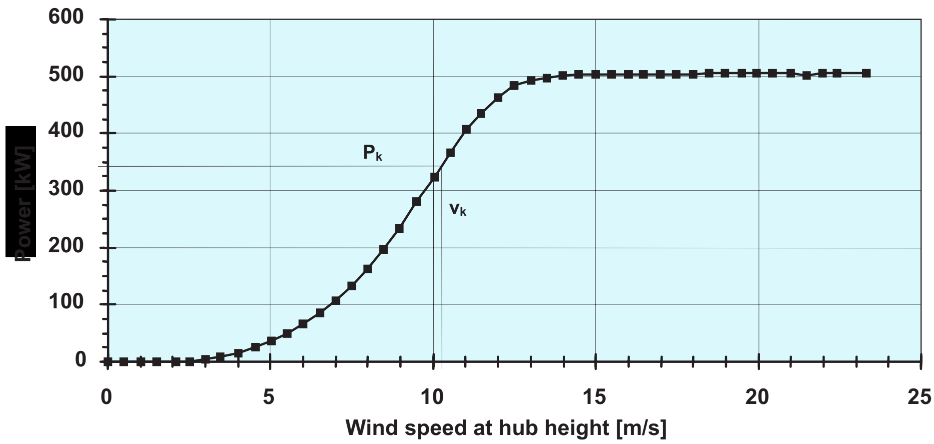


Figure 2.10. Power curve of a 500 kW wind turbine (P_k=345 kW; v_k=10.25 m/s)

The above two functions, namely the wind speed frequency distribution and the WT power curve, when multiplied together (fig. 2.11) and summed over all wind speeds (all values of the index k) provide an estimate of the annual energy production:

$$AEP = (hours/Yr)\cdot\Delta v\cdot\sum_{k=1}^{N}(F_k\cdot P_k) = (8760\,hrs/Yr)\cdot(0.5\,m/s)\cdot\sum_{k=1}^{N}(F_k\cdot P_k) \qquad (2.5)$$

where N is the total number of bins. Relationship (2.5) can be used to estimate the annual energy production (in Wh/year) to be expected from the WT with a specific power curve operating in the wind regime described by the wind speed distribution.

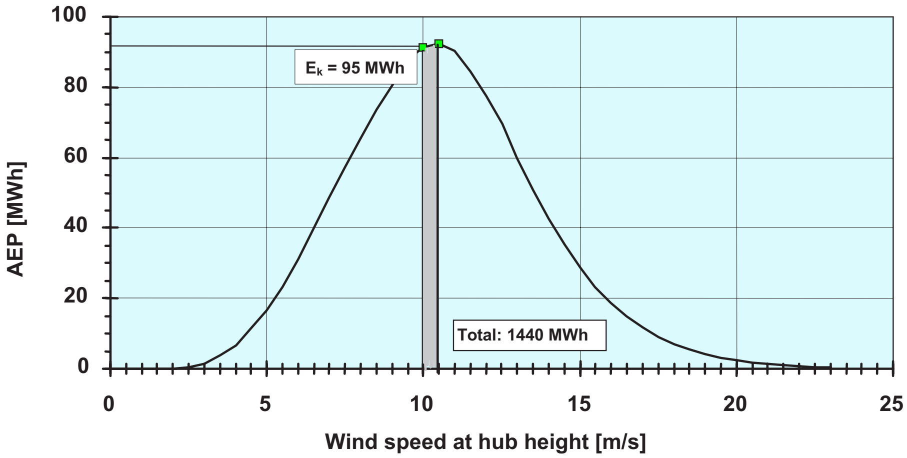


Figure 2.11. Example of estimated energy in bin *k* (E_k=95 MWh)

2.3.2.3. Capacity factor as a measure of energy production

The capacity factor CF_{Yr} (over one year) is a measure of the turbine's annual energy production performance. It is defined as the ratio of the actual (or estimated) energy produced to the energy production that would result from operation at full-rated power for every hour of the year:

$$CF_{Yr} = \frac{Energy\ Production\ /\ Year}{(Power\ Rating \times 8760\ hours/Year)} \tag{2.6}$$

The range of the capacity factor values is by definition from 0 to 100%. Capacity factor values in the range of 24 to 30% have been achieved by the better performing wind-farm installations worldwide, with 28% being a value for a rather good facility.

For example, if a 100 MW wind system generated and delivered 245 million kWh during a given year, the corresponding capacity factor would be 28%:

$$CF_{Yr} = \frac{245 \cdot 10^6\ kWh}{(100\ MW \times 8760\ hours)} = 0.28$$

As a further example, equation (2.6) can be used to calculate the annual energy production of a hypothetical 500 kW WT operating at a capacity factor of 0.28. The result is 1.226 million kWh/yr. When reviewing wind systems *CF* values, the period of interest should be ascertained. While it is usually one year, capacity factors also can be defined for one month.

If that month is one of very high wind speeds, then the corresponding *CF* value can be misleading if interpreted as an annual average value. On the other hand, it must be mentioned that conventional sources are also intermittent in a different way, since they are subject to various types of outages, e.g. due to maintenance, malfunctions, etc. Capacity factors for conventional power systems are significantly higher than wind turbines/farms ones, with representative values in the range of 60 to 70%, depending on the type of plant, its age and other factors.

2.3.3. Wind system reliability

2.3.3.1. Impact of design and manufacturing advances

The first-generation WTs installed in California in the early eighties experienced many failures (some quite spectacular), which were the result, in part, of inadequate understanding of the wind gust forces effect on the flexural or fatigue failure modes of structural components. With vastly improved knowledge about the actual gust structure of the wind, the development and widespread use of improved modelling and design tools, improved manufacturing techniques, and millions of hours of operating experience, the reliability of current WT designs has improved dramatically.

The reliability improvements encompass not only the major structural components, but also the supporting subsystems of the WT. These include, for example, the WT computer controller, the yaw system and the pitch control system. In addition, there have been improvements in the quality assurance and inspection programs of manufacturers. On the other hand, designers have given significant attention to the repairability and maintainability of the WT subsystems.

Moreover, the interval between major overhauls has been extended, for example from five to ten years or more. There are several measures of these improvements and of the current reliability. These include the mean-time-between-failures (MTBF) for major components and subsystems, the mean-time-to-repair (MTTR) and the cost to correct a failure. An often-encountered system-wide measure of reliability is the availability.

2.3.3.2. Availability

The availability (A) value for a wind-farm for a given period may be built up from the daily values of availability for each WT. However, in general, for a specified period (e.g., a day, week, month or year), availability is defined as the ratio of hours that the wind system was able to generate power to the number of hours in this time period:

$$A = \frac{\text{Wind Turbine Capable of Operation Hours}}{\text{Total Hours in Period}} \tag{2.7}$$

Another, more difficult-to-determine and possibly more ambiguous definition is the ratio of actual hours of operation to the number of hours that the wind speeds were in the operational range. No matter how defined, a perfect availability value would be 100%, meaning that the system would have no outages or malfunctions that prevent it from generating power. Modern wind-farms now routinely achieve availability values of 98% or more, up from 60% or (much) less in the early eighties.

2.3.3.3. Cost benefits

The cost of wind energy has been falling dramatically over the past 15 years, as the technology has developed and turbines have become cheaper and more productive. There are two main issues that affect the cost of electricity generated from the wind, and therefore its final price:

- Technical factors, such as the wind speed and nature of the turbines (availability, the way they are arranged, etc.).
- The financial perspective of those that commission and fund the projects, e.g. the rate of return that is required on the capital, and the length of time over which the capital is repaid.

Thus, wind energy costs in the Netherlands fell by a factor of three between 1985 and 1995, and in Germany by a third between 1991 and 1994. Energy prices have fallen even faster (they have halved in the last 9-10 years), also due to lower WT prices, the higher efficiency and availability of the machines used, and lower operation and maintenance costs. Current energy prices corresponding to a mid-range wind farm cost of €850/kW are 9.6 c€/kWh at 5 m/s, declining to 3.4 c€/kWh at 10 m/s (all wind speeds refer to hub height).

The cost of generating electricity is made up from:

- capital cost – for building the power plant and connecting it to the grid;
- running costs - for operating, fuelling, and maintaining the plant;
- financing, that is the cost of repaying investors and banks.

For WTs there are no fuel costs, as the wind is free. Once the project has been paid for, the only ongoing expenses are for the operation and maintenance (O&M) of the plant. The capital cost is between 75% and 90% of the total.

The cost of a turbine is now around €600-900/kW of power. Project preparation and installation costs add another €200-250/kW, depending on the number and size of machines in the wind farm, and the location. This brings the total cost of wind energy to about €1,000/kW of installed capacity. It may be noted that the most economic size has changed over the years and still moves upwards. The larger the machines, the fewer are required for a given capacity. This brings savings in site costs and in O&M costs. For example, site costs can be reduced by around 25% moving from machines of the 300 kW size range to 1 MW size machines.

Ongoing O&M costs include service, consumables, repair, insurance, administration, land rent, etc. These costs vary between countries and wind farms, but Danish and German experiences indicate that the annual O&M costs for new wind turbines with installed power between 0.5 and 1.5 MW are approximately 0.6 to 1.0 c€/kWh, of which half consists of insurance cost (O&M costs are around €25/kW/year for 200 kW machines, falling to around €15/kW/year for 500 kW machines). For machines of over 10 years of operation these cost may go up to a level of 1.5 to 2 c€/kWh.

The way in which machine sizes and productivity have increased in recent years is shown in fig. 2.12 (the data concern the case of Denmark). The average size of WTs installed in Denmark increased from 71 to 523 kW between 1985 and 1996. The productivity of new machines increased from 673 kWh/m^2 in 1985 to 1037 kWh/m^2 in 1996. The link between turbine sizes and energy prices was also analysed, indicating a 44% reduction from the early 95 kW machines to the 600 kW size (fig. 2.12 - right).

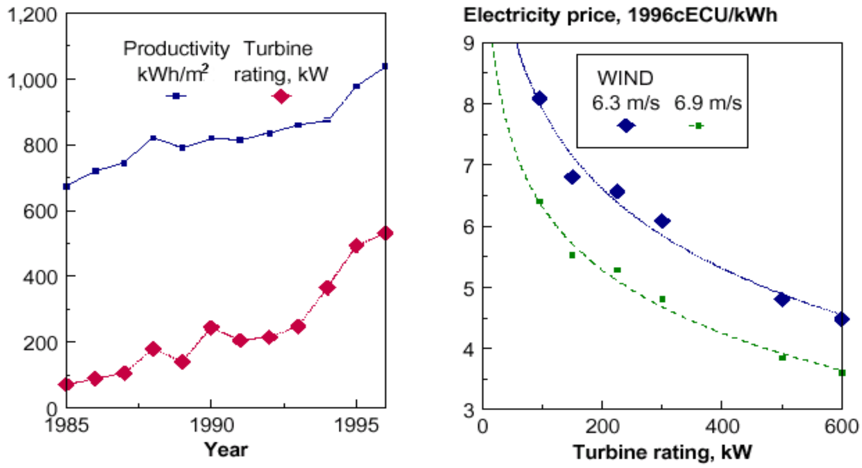


Figure 2.12. Danish wind turbine sizes, productivity and energy prices (Source: "Wind Energy in Europe - The Facts", 1997)

2.3.4. Power supply characteristics

The most significant technical characteristic of the electric power produced by wind systems is its variation with time. This reflects the time-variability of the wind resource. In this section, the range of time scales and their implications for wind system performance are examined.

2.3.4.1. Correlation with the load

As mentioned above, all utility loads have a significant predictable component. For example, the hourly demand during a summer or a winter day is fairly well known, as is also the month-to-month demand profile. The diurnal and monthly load profiles can be compared with the historical or expected electrical output from a wind-farm. Thus, to the extent that there exists a correlation between the time profiles of the wind-generated electricity and the load demand, the wind system may be given a capacity value in addition to the energy value.

The more correlated these profiles are, the more the wind-generated electricity can reliably supply part of the load. Depending on the capacity and cost structure of the conventional sources and the degree of wind penetration, the wind-generated electricity can be more useful and valuable than otherwise.

2.3.4.2. Output of a single wind turbine and a wind-farm

There is a significant difference in the short-term (seconds to minutes) temporal characteristics of the electric power from a single WT compared to those from a wind-farm. Over a significant range of operating wind speeds, the electrical power output of a single WT corresponds closely to the temporal characteristics of the wind flow field incident on it. The inertia of the rotor averages out wind temporal fluctuations on the order of a second or less.

Depending on the characteristics of the WT control system, wind fluctuation components with periods greater than this can be reproduced in the power output of an individual turbine. The WT control system can contribute to smoothing of the electric power output. This typically occurs when the wind speeds are high enough that, in the face of changing input wind speeds, the control system modulates the efficiency of the WT aerodynamic blades, so as to maintain the electrical output at a constant value equal to the WT power rating.

On the other hand, the electrical power output of a wind-farm is typically considerably smoothed relative to that of a single WT. The degree of smoothing depends on the geographical extent of the farm, the average wind speed, the control characteristics of the wind turbines and, finally, on the details of the terrain and how they influence the distribution of wind speeds across the wind-farm. The fundamental reason for the smoothing is that the wind gust structure, both in space and time, typically becomes increasingly uncorrelated over distances greater than several rotor diameters.

Relative to the fluctuations of a single WT, a complete lack of correlation would imply that the fluctuations in the wind-farm electrical power output are reduced by the square root of the number of uncorrelated machines in the wind-farm contributing to the power output. Thus, the same principle of areal smoothing of the aggregated output of the wind-farms may apply. As with the WTs in an individual wind-farm, such smoothing could occur as a result of the lack of correlation of the fluctuations in the wind fields incident upon the distributed wind-farms.

2.3.4.3. Power quality

Since wind-farms are typically connected to the utility grid, utility system planners and operations managers are interested in the technical characteristics of the electric power provided. Taken together, these characteristics are often referred to as power quality. The most important of them, as was already discussed, is the variability with time. Other power quality parameters include the power factor, harmonic distortion, voltage fluctuations, and frequency deviations. Their relative importance depends on the local electricity network, and the choice of WT.

Early WTs using induction generators were installed with inadequate hardware for reactive power compensation. As a result, utilities experienced increased line losses and difficulty controlling system voltage. Wind operators were forced to improve the quality of power supplied to the system when utilities started charging for excessive VAr [reactive power] support. Utilities now require small producers using induction generators to provide near unity power factor at the point of interconnection. Power electronics technology used with modern, variable-speed WTs provide a full range of power factor control under all operating conditions, even with the WT shut down.

Harmonics are undesirable distortions of the utility AC sinusoidal voltage and current waveforms, which are of concern due to potential damage to both utility distribution and customer load equipment. Some first-generation wind plants employed older AC conversion systems (6-pulse thyristor bridge configurations without external harmonic correction or filtering), resulting in the production of lower order harmonics. Advanced converter systems available today produce output with very little harmonic distortion. With the addition of harmonic correction devices and the use of advanced power electronics in variable-speed WTs, harmonics are no longer a significant concern.

When WTs are running, their output power varies second by second, depending on the strength and turbulence of the wind. The effect of the tower as the blades rotate past it also introduces a periodic disturbance in the power output, which is greater at high wind speeds. These power fluctuations cause voltage variations on the local electricity network, called "flicker". Limits on the flicker any connected equipment can cause are defined by relevant standards and are set to avoid disturbance to other consumers. Flicker is only likely to be a problem for small groups or single turbines, especially large machines connected at lower voltages.

Stall-regulated WTs produce fewer disturbances than pitch-regulated ones. Variable-speed turbines have very little effect. WTs with induction generators (most common) may also cause disturbances when starting, but this is not a problem any more, as "soft-start" units are fitted to most designs. However, the voltage step that will occur when a WT shuts down from full output, due to high winds, must also be considered. It is usually accepted that, under normal conditions, it is very unlikely that more than one or two turbines will shut down simultaneously.

Wind plants connected to weak, isolated grids can cause difficulty in maintaining normal system frequency, which varies when gusting winds cause the power output of wind plants to change rapidly. While this is typically not a problem in wind-farm areas, in order to accommodate more wind energy a system would need:

- the use of modern, variable-speed wind turbines with power electronic control and interface to the grid (the power electronic system can be controlled to limit WT output during gusty or strong wind periods), and/or
- automatic generation control with additional spinning reserve.

3.1. INTRODUCTION

3.1.1. Background

Solar photovoltaic modules, called “photovoltaics” or “PV”, is a high-technology approach to converting sunlight directly into electrical energy. The term "photo" is a stem from the Greek "phos", which means "light." "Volt" is named for Alessandro Volta (1745-1827), a pioneer in the study of electricity. "Photo-voltaic", then, literally means "light-electric". Conceptually, in its simplest form, a photovoltaic device is a solar-powered battery whose only consumable is the light that fuels it. There are no moving parts, operation is environmentally benign, and if the device is correctly encapsulated against the environment, there is nothing to wear out.

Because sunlight is universally available, photovoltaic devices have many additional benefits that make them usable and acceptable to all inhabitants of our planet. PV systems are modular, so their electrical power output can be engineered for virtually any application, from low-powered consumer uses - wristwatches, calculators and small battery chargers - to energy-significant requirements, such as generating power at electric utility central stations.

Moreover, incremental power additions are easily accommodated in photovoltaic systems, unlike more conventional approaches such as fossil or nuclear fuel, which require multi-megawatt plants to be economically feasible. PV systems enjoy so many advantages that, as their comparatively high initial cost is brought down another order of magnitude, it is very easy to imagine them becoming nearly ubiquitous late in the 21st century.

3.1.2. Solar energy

Solar radiation provides a huge amount of energy to the earth. The total amount of energy that is irradiated from the sun to the earth’s surface equals approximately 10,000 times the annual global energy consumption. On average, 1700 kWh per square meter is insolated every year. The light of the sun, which reaches the surface of the earth, consists mainly of two components: direct light and indirect or diffuse light, which is the light that has been scattered by dust and water particles in the atmosphere.

Photovoltaic cells not only use the direct component of the light, but also produce electricity when the sky is overcast. So, it is a misconception that PV systems only operate in direct sunshine and are therefore not suitable for use in temperate climates. This is not correct: photovoltaics make use of diffuse solar radiation as well as direct sunlight. To determine the PV electricity generation potential for a particular site, it is important to assess the average total solar energy received over the year, rather than to refer to instantaneous irradiance.

Using photovoltaic cells, this radiation can be used to generate electricity. When sunlight strikes a photovoltaic cell, direct current (DC) is generated. By putting an electric load across the cell, this current can be collected. Not all of the light can be converted into electricity however. Photovoltaic cells use mainly visible light. A lot of the sun's energy is in IR- or warmth- and UV radiation, which explain why theoretical conversion efficiencies are as low as 20-30%. Practical deficiencies as impurities may decrease the performance of a photovoltaic cell even further.

The amount of useful electricity generated by a PV module is directly related to the intensity of light energy, which falls onto the conversion area. So, the greater the available solar resource, the greater the electricity generation potential is. The tropics, for instance, offer a better resource for generating electricity than the one that is available at high latitudes. It also follows that a PV system will not generate electricity at night, and it is important that modules are not shaded. If electricity is required outside daylight hours, or if extended periods of bad weather are anticipated, some form of storage system is essential.

In order to capture as much solar energy as possible, the photovoltaic cell must be oriented towards the sun. If the photovoltaic cells have a fixed position, their orientation with respect to the south, and tilt angle, with respect to the horizontal plane, should be optimised. The optimum tilt angle lies within a range of approximately 15 degrees of the site latitude. For grid connected PV systems in Western Europe, for instance, the optimum tilt angle is about 35 degrees. For regions nearer to the equator this tilt angle will be smaller, for regions nearer to the poles it will be larger.

A deviation of the tilt angle of 30 degrees from the optimum angle, will lead to less than 10% loss of the maximum yield. PV modules are actually more efficient at lower temperatures, so to ensure that they do not overheat, it is essential to be mounted in such a way as to allow air to move freely around them. This is a particularly important consideration in locations that are prone to extremely hot midday temperatures. The ideal PV generating conditions are cold, bright, sunny days.

3.2. SOLAR CELLS

Solar cells are devices which convert solar energy directly into electricity, either directly via the photovoltaic effect, or indirectly by first converting the solar energy to heat or chemical energy. The most common forms of solar cells are based on the photovoltaic (PV) effect in which light falling on a two layer semi-conductor device produces a photovoltage or potential difference between the layers. This voltage is capable of driving a current through an external circuit and thereby producing useful work.

3.2.1. History of solar cells development

Although practical solar cells have only been available since the mid 1950s, scientific investigation of the photovoltaic effect started in 1839, when the French scientist Henri Becquerel discovered that an electric current could be produced by shining a light onto certain chemical solutions. The effect was first observed in a solid material (in this case the metal selenium) in 1877.

This material was used for many years for light meters, which only required very small amounts of power. A deeper understanding of the scientific principles, provided by Einstein in 1905 and Schottky in 1930, was required before efficient solar cells could be made. Chapin, Pearson and Fuller developed in 1954 a silicon solar cell that converted 6% of sunlight falling onto it into electricity, and this kind of cell was used in specialised applications such as orbiting space satellites from 1958.

Today's commercially available silicon solar cells have efficiencies of about 18% of the sunlight falling on to them into electricity, at a fraction of the price of thirty years ago. There is now a variety of methods for the practical production of silicon solar cells (amorphous, single crystal, polycrystalline), as well as solar cells made from other materials that show commercial potential, such as copper indium diselenide ($CuInSe_2$), cadmium telluride (CdTe), etc.

3.2.2. Method of production of solar cells

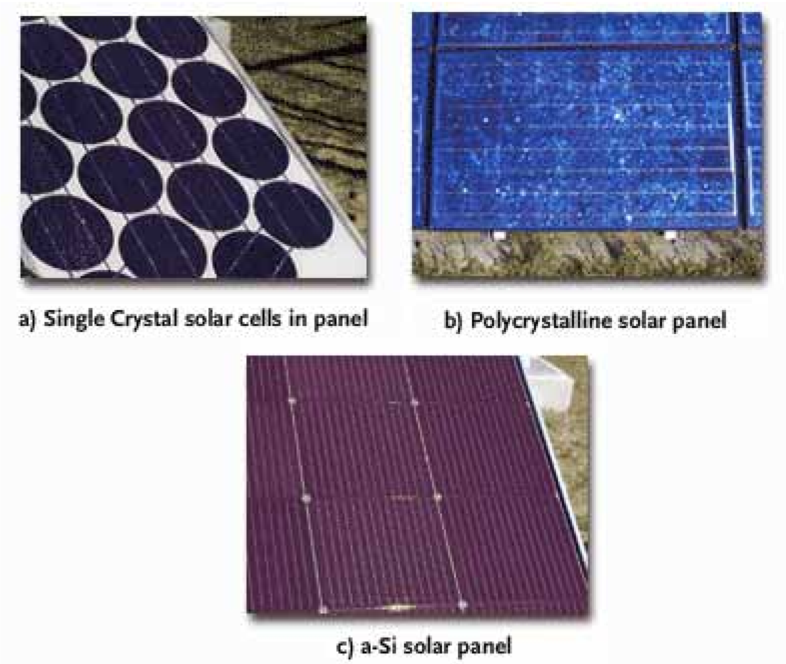


Figure 3.1. Solar panels

[Source: http://renewable.greenhouse.gov.au/technologies/pv/pv.html]

Silicon solar cells are made using single crystal wafers, polycrystalline wafers or thin films. Single crystal wafers are sliced (approximately 1/3 to 1/2 of a millimetre thick) from a large single crystal ingot that has been grown at around 1400°C, which is a very expensive process. The silicon must be of a very high purity and have a near perfect crystal structure (see figure 3.1(a)). Polycrystalline wafers are made by a casting process, in which molten silicon is poured into a mould and allowed to set. Then it is sliced into wafers (figure 3.1(b)).

As polycrystalline wafers are made by casting they are significantly cheaper to produce, but not as efficient as mono-crystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process. Almost half the silicon is lost as saw dust in the two processes mentioned above. Amorphous silicon, one of the thin film technologies, is made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4), as is shown in figure 3.1(c).

The thin film type of solar cell can be applied as a film to low cost substrates such as glass or plastic. Other thin film technologies include thin multi-crystalline silicon, copper indium diselenide/ cadmium sulphide cells, cadmium telluride/cadmium sulphide cells and gallium arsenide cells. There are many advantages of thin film cells including easier deposition and assembly, the ability to be deposited on inexpensive substrates or building materials, the ease of mass production, and the high suitability to large applications.

In solar cell production the silicon has dopant atoms introduced to create a p-type and an n-type region and thereby producing a p-n junction. This doping can be done by high temperature diffusion, where the wafers are placed in a furnace with the dopant introduced as a vapour. There are many other methods of doping silicon. In the manufacture of some thin film devices the introduction of dopants can occur during the deposition of the films or layers.

A silicon atom has 4 relatively weakly bound (valence) electrons, which bond to adjacent atoms. Replacing a silicon atom with an atom that has either 3 or 5 valence electrons will therefore produce either a space with no electron (a hole) or one spare electron that can move more freely than the others, this is the basis of doping. In p-type doping, the creation of excess holes is achieved by the incorporation into the silicon of atoms with 3 valence electrons, most often boron, and in n-type doping, the creation of extra electrons is achieved by incorporating an atom with 5 valence electrons, most often phosphorus (see figure 3.2).

Once a p-n junction is created, electrical contacts are made to the front and the back of the cell by evaporating or screen-printing metal on to the wafer. The rear of the wafer can be completely covered by metal, but the front only has a grid pattern or thin lines of metal, otherwise the metal would block out the sun from the silicon and there would not be any output from the incident photons of light.

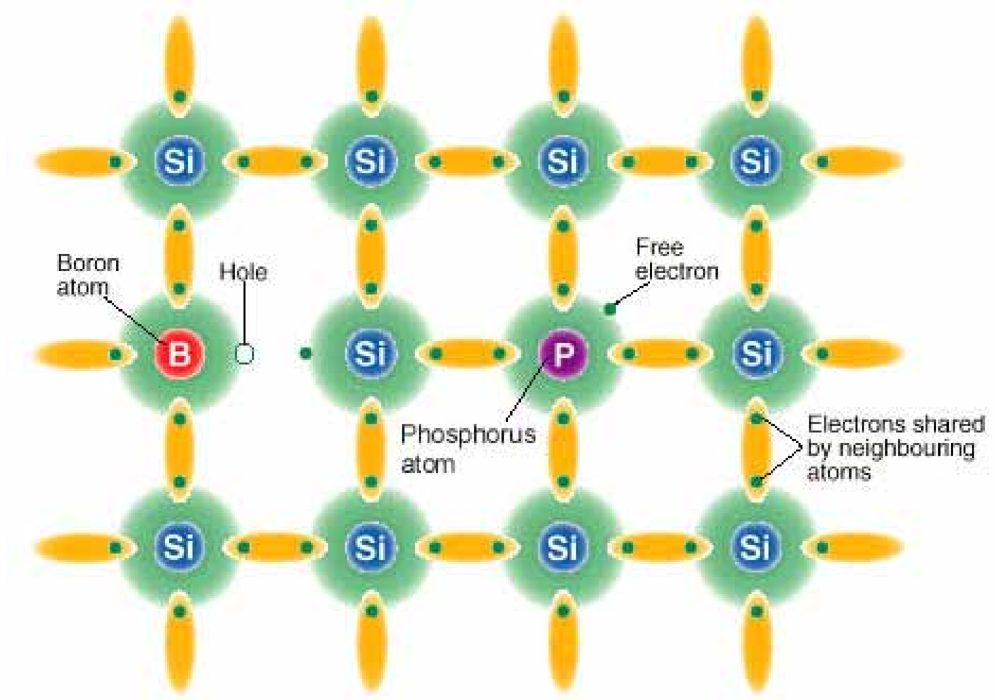


Figure 3.2. Silicon crystal lattice with dopant atoms

3.2.3. Operation of solar cells

To understand the operation of a PV cell, both the nature of the material and the nature of sunlight need to be considered. Solar cells consist of two types of material, often p-type silicon and n-type silicon. Light of certain wavelengths is able to ionise the atoms in the silicon and the internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (electrons) within the photovoltaic device.

The holes are swept into the positive or p-layer and the electrons are swept into the negative or n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier. Therefore, if a circuit is made as is shown in figure 3.3, power can be produced from the cells under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

The amount of power available from a PV device is determined by:

- the type and area of the material;
- the intensity of the sunlight (insolation); and
- the wavelength of the sunlight.

The ratio of electrical energy produced by a solar cell to the incident solar irradiance is known as the PV cell efficiency.

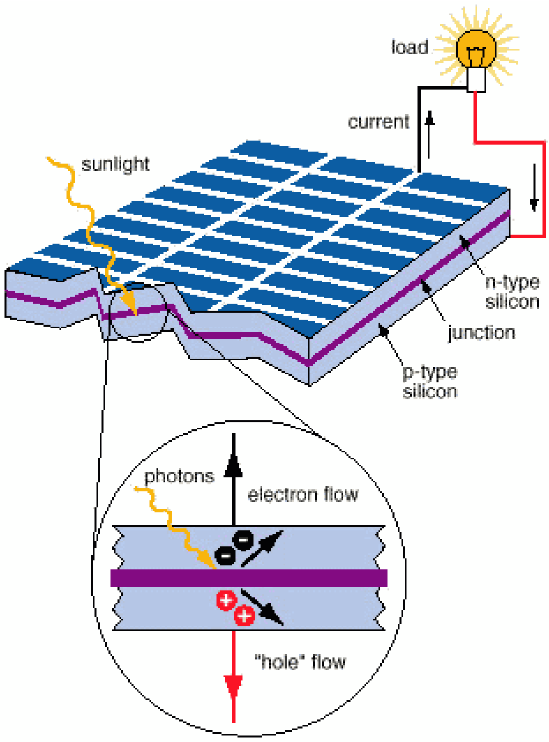


Figure 3.3. The photovoltaic effect in a solar cell

Single crystal silicon solar cells, for example cannot currently convert more than 25% of the solar energy into electricity, because the radiation in the infrared region of the electromagnetic spectrum does not have enough energy to separate the positive and negative charges in the material. Polycrystalline silicon solar cells have an efficiency of less than 20% at this time, and amorphous silicon cells are presently about 10% efficient, due to higher internal energy losses than single crystal silicon.

Numerous lab tests have been conducted to quantify solar cell performance. Certain conditions, namely the Standard Testing Conditions (STC), have been established as industry standards for testing, which are the following:

- Temperature = 25 °C
- Insolation = 1000 W/m^2
- Air mass = AM1.5

Air mass refers to the thickness of the atmosphere that the sunlight passes through and is an important indicator of the characteristics of the available light, since solar cells utilize solar radiation at specific wavelengths. If the sun is directly overhead, the air mass equals 1.

The amount of current produced is a function of the voltage, and solar cell *I-V* curves are graphs that show their relationship. These curves are used to determine how cells perform under certain conditions and to compare different cells. Figure 3.4 is a typical *I-V* curve for a crystal silicon cell under standard conditions. Notice that to the left of the curve's knee current changes very little with large voltage changes, but to the right of the knee current changes significantly with small voltage changes. The numbers given below are common values for this type of cell:

- I_{sc} = short circuit current = 3.36A
- V_{oc} = open circuit voltage = 0.6V
- P_{max} = maximum power point = 1.5W
- I_{max} = current at P_{max} = 3A
- V_{max} = voltage at P_{max} = 0.5V

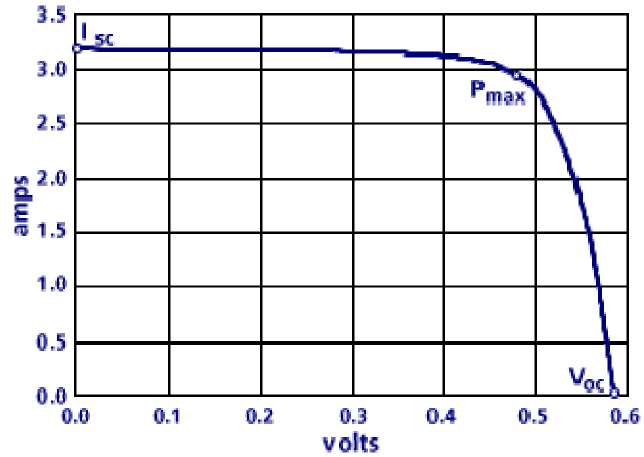


Figure 3.4. The *I-V* curve for a typical crystal silicon cell under STC

The power output of the cell is almost directly proportional to the intensity of the sunlight (for example, if the intensity of the sunlight is halved the power will also be halved). An important feature of PV cells is that the voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity. However, the current in a device is almost directly proportional to light intensity and size. This is illustrated in figure 3.5.

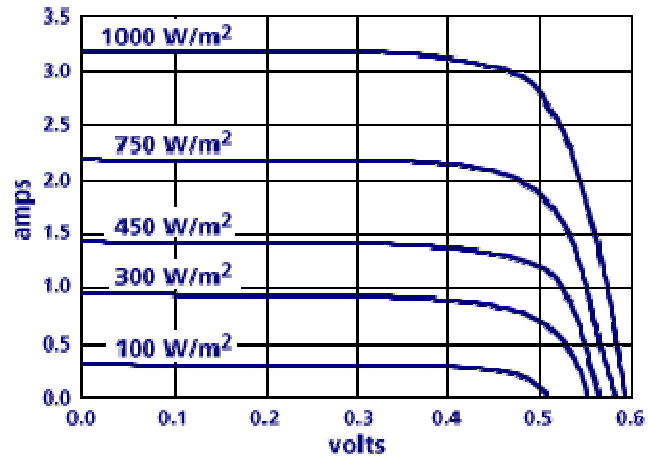


Figure 3.5. Current and voltage output of a solar cell at different light intensities

The power output of a solar cell can be increased quite effectively by using a tracking mechanism to keep the PV device directly facing the sun, or by concentrating the sunlight using lenses or mirrors. More information on PV concentrators can be found later in this chapter. However, there are limits to this process, due to the complexity of the mechanisms, and the need to cool the cells. Furthermore, the current output is relatively stable at higher temperatures, but the voltage is reduced (roughly 0.0023

Volts per increased degree C), leading to a drop in power as the cell temperature is increased. The graph 3.6 below shows a cell's *I-V* characteristics at three different temperatures (the other conditions being the same).

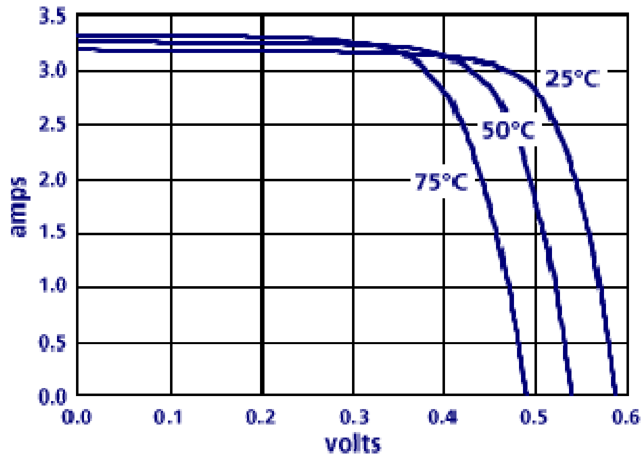


Figure 3.6. The temperature variation of *I-V* curves for a typical crystal silicon cell

3.3. PV MODULES (ARRAY)

The term “array” usually refers to the components discussed in this section, more specifically all of the modules in a photovoltaic system, their wiring and diodes, and the array stand.

3.3.1. PV array components

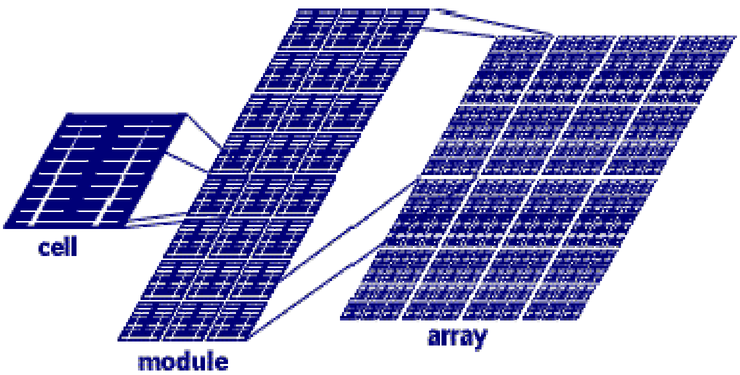


Figure 3.7. PV array components

Cells are grouped into modules and modules are grouped to form an array, as the one presented in figure 3.7. Depending on the application, the array may consist of one cell, one module, or many modules.

3.3.1.1. The cell

A typical single crystal silicon solar cell has a deep blue colour and weighs under 10 grams. It is roughly 10 cm in length and width. Different manufacturers produce cells with different dimensions. An individual cell produces roughly 1.5 Watts at 0.5 Volts under optimum conditions. By itself, this is not very useful for most electrical needs. In order to generate useful power, cells are wired together in series and in parallel and are sometimes cut into smaller pieces.

Cell cutting is done mainly for two reasons. The first is to increase the voltage. If only a small current is needed at a high voltage, then cutting cells in half and wiring them in series can create a small panel. Each piece will produce the same voltage as the whole cell, but with less current (for example, if a cell is cut in half, each half will produce approximately 0.5 Volts and 1.5 Amps). The other reason to cut cells is to increase packing density.

Notched cells create wasted space at their corners and this can be overcome by cutting the cells into rectangles. This is sometimes considered for applications where performance is critical and space is limited. The drawbacks of cutting cells are that the process often wastes sections of the cell and that it is highly likely that a percentage of cells will be damaged during cutting. The manufacturer can provide data on the exact dimensions and tolerances of specific cells. When calculating total cell area, it is important to note that some cells have notched corners.

3.3.1.2. String

When cells are wired together, it is often said that they are strung together to form a string. Cells are strung together by soldering the tabs from the top of one to the bottom of the next. This is generally done in the factory by tabbing machines. It is important that the cells are not damaged in the process, that the connections are strong, and that the correct spacing between cells is maintained. If the cells are touching, electrical shorting problems can arise as well as shading problems and a higher chance of cell cracking. Too large of a gap between cells wastes valuable space.

3.3.1.3. Module

Solar cells are typically strung in series to form a group called a module. A module is often defined as the smallest self-contained unit in an array. This means that it is a group of cells that have been strung together and then encapsulated as a unit. The number of cells in a module is usually determined by the voltage needs of the system. Since a common system involves 12 Volt batteries, most manufacturers produce modules that are sized by battery voltages. A standard module for charging one battery has 33 to 36 cells (it must supply over 12 V to charge the battery). Note that the word panel can refer to either a single module, or a group of modules.

3.3.1.4. Encapsulation

Solar cells need to be protected and supported. Cells are almost always encapsulated in some way to protect them and to electrically insulate them. Figure

3.8 below shows a cross section of a typical module that could be found in home, remote, or utility PV applications.

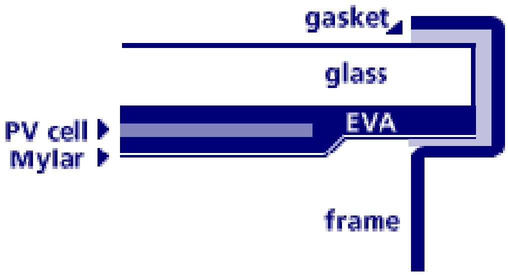


Figure 3.8. A cross section of a typical photovoltaic module

Most modules are encapsulated in a polymer such as ethylene vinyl acetate (EVA), which in turn is sandwiched between glass on the top and Mylar or Tedlar on the bottom. The edges are sealed with a gasket and supported by a frame. There have also been developments made in flexible lamination. There are many different factors that are considered when choosing materials for encapsulation, their importance depending on the application.

The list below covers most of the important characteristics of encapsulation:

- *Electrical resistivity*

The material should be an electric insulator. It is important to isolate the voltage of the array and to protect the array from any external voltages.

- *Light transmission*

Ideally, the encapsulation should not obstruct light from reaching the cells.

- *Heat conduction*

Solar cells are more efficient at cooler temperatures. If possible, it is beneficial to have an encapsulation material with a high thermal conductivity so heat can move away from the cells.

- *Thermal expansion*

In some locations module temperature is well below freezing in the winter and well above 40°C in the summer. It is important that the encapsulation does not expand or contract significantly because of the temperature changes.

- *Weight*

For some applications, weight is one of the factors in choosing encapsulation material.

- *Durability*

Many modules are placed outside year round and are subject to wind, rain, sun, hail, and snow. They are expected to operate for twenty plus years. The encapsulation material needs to be durable to make it through these conditions without significant amounts of deterioration.

3.3.1.5. Diodes

Solar arrays sometimes have blocking and bypass diodes. These are small devices that restrict the direction of current flow. They are discussed in the array operation section.

3.3.1.6. Stands/tracking

Some devices, such as solar watches or calculators, incorporate the solar cell into the object itself. There have been some recent developments in solar cell material that can be used directly for the roofing materials of buildings. Most PV applications, however, need some kind of stand to support and position them. Stands range from simple structures to hold a panel to a roof (perhaps tilted permanently at an angle), to complex dual axes tracking devices. Stand complexity is normally determined by the needs of a system and the funding available. Further information on stands and tracking systems can be found in the array operation section.

3.3.2. PV array operation

Generally, the environment affects a PV module or array in the same way as a single cell. Voltage decreases as temperature increases and current increases as insolation increases.

3.3.2.1. Series

When solar cells (or modules) are connected in series, an estimate of the output of the string can be made by the methods described below. This assumes that the operating conditions for the cells are the same and that the cells have similar *I-V* characteristics.

- *Current*

The current in a string of cells in series is the same at every point in the string. The current flowing through each point is the same as the current produced by one cell. If a cell with low current characteristics is connected in a string with other cells that have higher current characteristics, the string will be limited to the low cell's current.

$$I_{string} = (I_{max} \text{ of one cell}) \quad (3.1)$$

- *Voltage*

The voltage across a string of cells is equal to the sum of the voltages across each cell. Assuming similar cells, the voltage can be calculated by:

$$V_{string} = (\text{No of cells}) \times (V_{max} \text{ of one cell}) \quad (3.2)$$

- *Power*

The power produced by a string of cells is equal to the string current of equation (3.1) multiplied by the string voltage of equation (3.2):

$P_{string} = I_{string} \times V_{string} \Rightarrow P_{string} = (I_{max} \text{ of one cell}) \times (\text{No of cells}) \times (V_{max} \text{ of one cell})$ (3.3)

Note that individual cells can operate at different voltages, but each cell will operate at the same current as the others in the string. Figure 3.9 below shows how the *I-V* characteristics of the individual cells combine to form the *I-V* curve of the string in series. Figure 3.10 presents a string of four cells in series and their voltage and current characteristics.

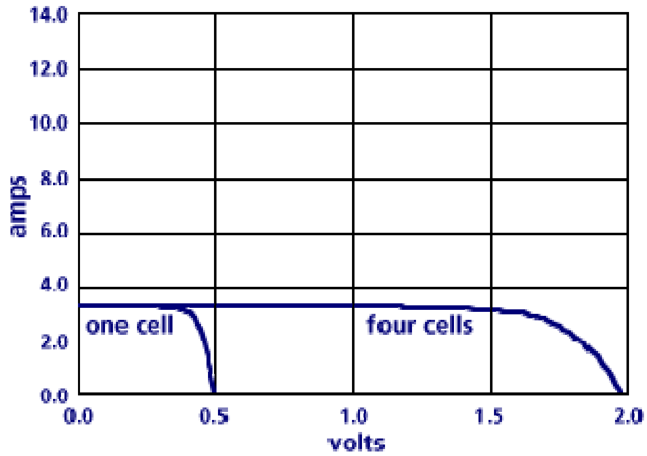


Figure 3.9. Typical *I-V* curves for one cell and four cells connected in series.

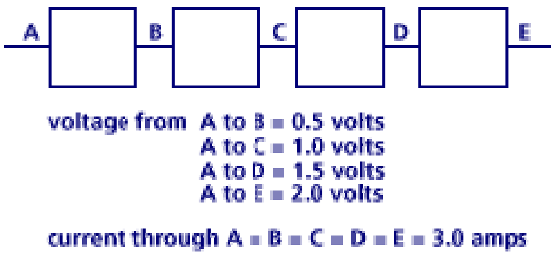


Figure 3.10. Four solar cells connected in series

3.3.2.2. Parallel

If cells (or modules) are wired in parallel, an estimate of their current, voltage and power, can be made by the methods described below (assuming again that the operating conditions are the same and the cells have similar *I-V* characteristics).

- *Current*

The current produced by a group of cells in parallel is equal to the sum of the individual currents of each cell. Assuming similar cells, the current can be calculated by:

$I_{parallel} = (\text{No of cells}) \times (I_{max} \text{ of one cell})$ (3.4)

- *Voltage*

The voltage across two nodes of a group of cells in parallel is equal to the voltage of each cell:

$V_{parallel}$ = (V_{max} of one cell) (3.5)

- *Power*

The power produced by cells in parallel is equal to the parallel current [equation (3.4)] multiplied by the parallel voltage [equation (3.5)]:

$P_{parallel} = I_{parallel} \times V_{parallel} \Rightarrow P_{parallel}$ = (No of cells) x (I_{max} of one cell) x (V_{max} of one cell) (3.6)

Note that, when a group of cells are connected in parallel, individual cells may produce different currents, but every cell will operate at the same voltage. Figure 3.11 below shows how the *I-V* characteristics of the individual cells combine to form the *I-V* curve of the group in parallel. Figure 3.12 below shows groups of cells in parallel and their voltage and current characteristics.

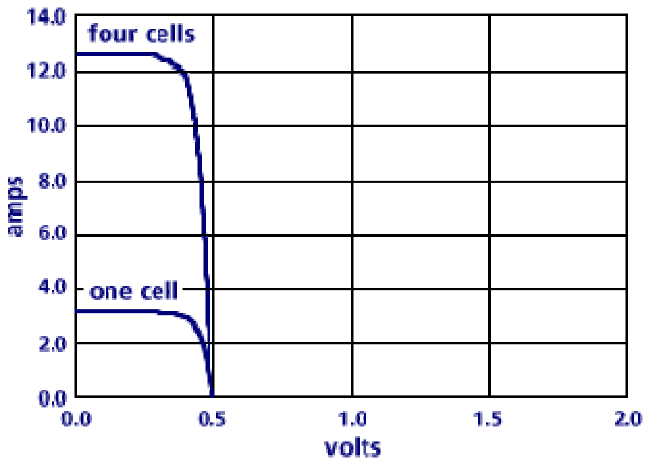


Figure 3.11. Typical *I-V* curves for a single cell and for four cells connected in parallel

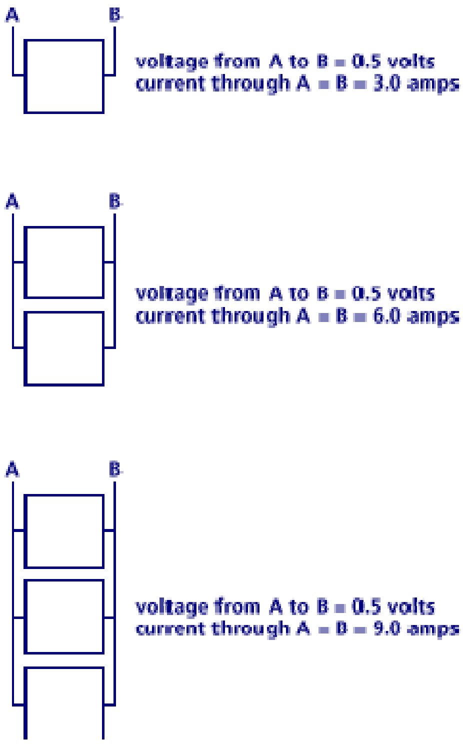


Figure 3.12. One, two, and three cells connected in parallel

3.3.2.3. Diodes

- Bypass Diodes

Bypass diodes are used to protect strings of cells in series. Generally, a module from a manufacturer will come with a bypass diode built in. The diode is wired in parallel with the entire module.

During normal operation, the diode is not doing anything except dissipating a very small amount of power. If part of the module is shaded or damaged, the bypass diode diverts the current through itself and around the module. Without the diode, the damaged or shaded module dissipates the current as heat and eventually fails.

- Blocking Diodes

Blocking diodes are used to prevent current flowing back into panels. A blocking diode is usually wired in series between the array and the batteries. If a large number of strings of modules are connected in series, blocking diodes may be wired in series with each string instead.

Some power conditioning equipment used in photovoltaic systems eliminate the need to add a blocking diode.

3.3.2.4. Tracking

A panel that is perpendicular to the rays of the sun will receive more power than the one that is not oriented toward the sun. The sun's path in the sky changes both with the time of the day and the day of the year. This means that for a panel to produce the most energy, it needs to be able to rotate to follow the path of the sun. Fixed panels are mounted at a set angle facing the equator and do not move. While not able to produce as much power as tracking panels, fixed panels have the benefit of being less expensive and easier to maintain. The majority of panels are fixed.

In some cases, fixed panels are manually adjusted. This may be done a few times a year to account for the seasonal changes of the sun's path, or in some cases, a few times a day. By manually adjusting the panels, a significant portion of the light that would be gathered through a tracking system can be obtained. Trackers can nearly double the output of an array (see figure 3.13). Careful analysis is required to determine whether the increased cost and mechanical complexity of using a tracker is cost effective in particular circumstances.

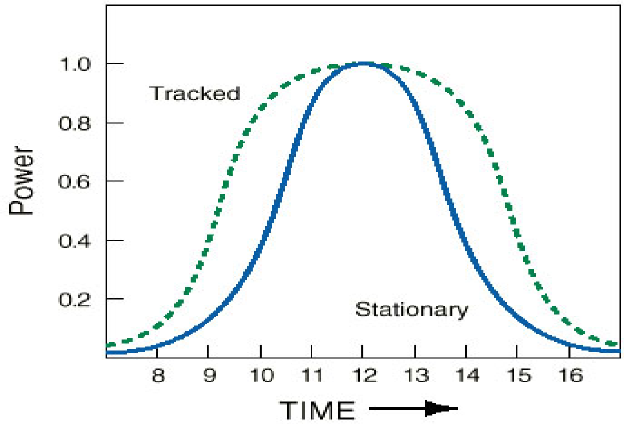


Figure 3.13. Graph showing power output for tracked and non-tracked array

Single axis tracking moves panels along one axis to follow the sun (figure 3.14 – left). It almost always tracks the changing elevation of the sun in the sky as opposed to tracking the movement from east to west. Dual axis tracking (figure 3.14 – right) moves panels along two axes to track the sun. Some arrays, such as the ones using concentrating cells, require dual axis tracking because the cells are only using direct radiation and the efficiency falls dramatically if the cell is not perpendicular to the rays of the sun.

Figure 3.14. Single axis tracking (left) and concentrator cells with dual axis tracking (right)

[Source: http://aurora.crest.org/pv/array/components/index.htm]

3.4. PV SYSTEMS AND APPLICATIONS

3.4.1. PV markets

Many people today are concerned for the future of the planet. Conventional energy technologies are widely recognized as a major cause of environmental destruction - both in terms of depletion of natural resources and pollution. PV and other renewable energy technologies are gaining acceptance as a way of maintaining and improving living standards without harming the environment. More and more energy utilities are responding to the wishes of consumers by including PV in their supply mix.

Incorporation into rooftops and facades of buildings (figure 3.15) is anticipated to be a main application for PV in many industrialized countries. Japan, Germany, the Netherlands and Switzerland in particular are already progressing along the path of distributed PV systems. The main attraction is that various costs - such as purchase of land and building components and transmission and distribution costs - can be avoided either wholly or partially. The total available rooftop generating potential in OECD countries is estimated to be some 1100 GW_p, sufficient to meet between 14 and 19% of the estimated 6,800 TWh total annual OECD electricity consumption.

Medium to large-scale generating plant will, nevertheless, be an important application for PV. The USA and Italy are the world leaders in development of large-scale PV systems. Several other countries are also looking to develop "redundant" land - for instance alongside motorways and railways - by incorporating PV into sound barriers (see figure 3.16). PV concentrators are also being developed for large-scale plants. These make use of large area reflectors to concentrate sunlight onto small area cells. This reduces the amount of PV material needed, which can result in lower costs.

Figure 3.15. All electric, zero-energy house in Zandvoort, the Netherlands
Source: [http://www.euronet.nl/users/oke/PVPS/pv/sa_syst.htm]

Figure 3.16. Noise barrier along A27 in Utrecht, the Netherlands (the PV modules in the top half of the barrier combine the production of electricity with noise protection)
Source: [http://www.euronet.nl/users/oke/PVPS/pv/sa_syst.htm]

Current (1998) estimates of the solar photovoltaic cells and modules worldwide production are about 135 MW, up steadily and dramatically from only 40 MW in 1990. Worldwide sales have been increasing at an average rate of about 15% every year during the last decade, although that growth rate has varied by region and application. It is believed that there is a realistic possibility for the market to continue to grow at a 15 to 25% rate into the next decade. At this rate, the world production would be in the 1,000 MW range by 2010, and photovoltaics could be a $5 to $8 billion industry.

3.4.2. Stand-alone systems

For many developing countries, where the electricity grid is largely confined to the main urban areas, and where a substantial proportion of the rural population does not have access to most basic energy services, PV is widely regarded today as the best - and least expensive - means of providing many of the services that are lacking. Based on minimum energy requirements to provide basic energy services to every individual in the developing world, the corresponding potential for PV is estimated to be 16 GW_p (approximately 15 W_p per capita).

PV modules can be used for (see also table 3.1 for examples of these applications):

- Pumping systems: to supply water to villages, for land irrigation or livestock watering
- Refrigeration systems: particularly to preserve vaccines, blood and other consumables vital to healthcare programs.
- Lighting: for homes and/or community buildings, such as schools and health centres, to enable education and income generation activities to continue after dark.
- Battery charging stations: to recharge batteries, which are used to power appliances ranging from torches and radios to televisions and lights
- Solar home systems: to provide power for domestic lighting and other DC appliances such as TVs, radios, sewing machines, etc.

Table 3.1. Stand-alone applications in developing countries

Agriculture	▪ water pumping ▪ electric fencing for livestock and range management
Community Level	▪ water pumping, desalination and purification systems ▪ lighting for schools and other community buildings
Domestic Sector	▪ lighting, enabling studying, reading, income-producing activities and general increase in living standards ▪ TV, radio, and other small appliances ▪ water pumping
Healthcare	▪ lighting for wards, operating theatre and staff quarters ▪ medical equipment ▪ refrigeration for vaccines ▪ communications (telephone, radio communications systems) ▪ water pumping ▪ security lighting
Small enterprises	▪ lighting systems, to extend business hours and increase productivity ▪ power for small equipment, such as sewing machines, freezers, grain grinders, battery charging ▪ lighting and radio in restaurants, stores and other facilities

3.4.2.1. Components and maintenance

Photovoltaic power systems are exceptionally modular, which not only provides for easy transportation and rapid installation, but also enables easy expansion if power requirements increase. PV systems for stand-alone applications (figure 3.17) may comprise some or all of the following basic components:

- A PV generator and support structure (a single module or an array of several modules).
- Power conditioning equipment (Optional - typically includes inverters and control and protection equipment).
- Power storage (Optional - usually provided by batteries).
- Cables.
- A load (e.g. lights, pumps, refrigerators, radio, television).

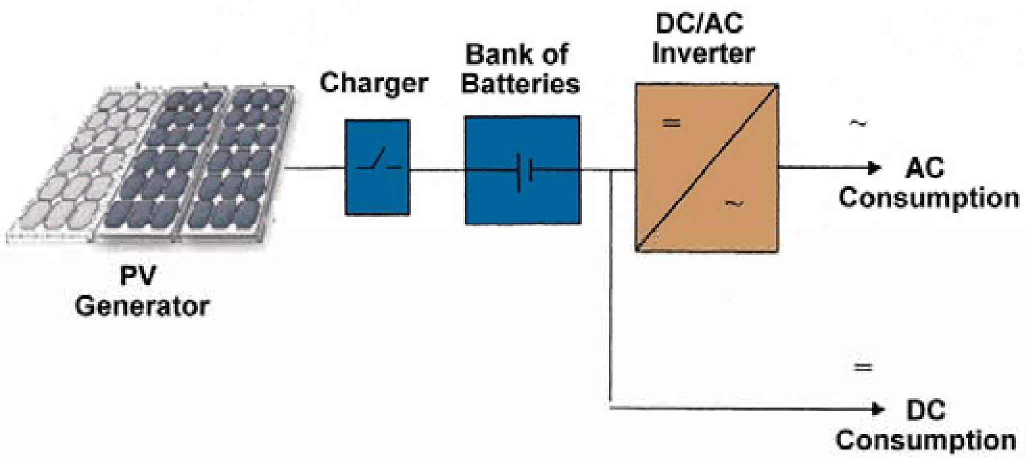


Figure 3.17. PV Stand-alone system scheme

The solar PV generating equipment has no moving parts, which on the whole keeps maintenance requirements to a minimum and leads to long service lifetimes. The modules themselves are typically expected to operate for about twenty years, and should not require much more than the occasional cleaning to remove deposits of dirt. The majority of the other components - referred to as the Balance of Systems (BOS) - are generally serviceable for ten or more years if simple preventative maintenance measures are followed.

Batteries, which are commonly required for most off-grid applications except water pumping, are currently the "weak-link" in the PV system and will typically need replacement every five years or so. It is essential that batteries, and indeed all system components, be of an acceptable quality. Where PV systems have failed in the past for technical reasons, it has generally been due to bad system design and/or poor selection of BOS components, rather than to failure of a PV module. As a result, considerable international research efforts are presently directed towards improving performance of BOS components.

3.4.2.2. Costs and economics

In terms of average unit energy costs calculated using traditional accounting techniques, PV generated electricity cannot yet compete with efficient conventional central generating plants. Accordingly, the vast majority of PV installations to date have been for relatively low-power applications in locations that do not have ready access to a mains electricity grid. In such cases, PV has been selected because it offers a secure and reliable power supply, and is often the cheapest power option.

Like any such commodity, the total purchase price of a PV system is based on all inherent costs of producing the individual components, transporting these to the site and installing them. There may also be associated costs of designing and engineering the system, and purchasing land - particularly for large-scale or one-off projects. However, there are many other factors to consider:

- Most PV systems manufacturers will offer some form of discount for bulk purchase agreements.
- Components imported from overseas will normally subject to some import levy.
- Where systems are purchased through a local distributor there will usually be a mark-up for handling and some form of local sales tax will generally be payable.

The total price is therefore very difficult to define, varying with application, size of system and location. However, the costs of the PV array are a significant factor and will typically constitute 30%-50% of the total capital cost with the BOS contributing a similar amount. As an example, a small domestic lighting system to power two or three fluorescent tubes would typically be in the order of 50 W_p, and would cost perhaps 500 Euro, whereas a solar photovoltaic vaccine refrigerator might require a 200 W_p array, bringing the total price of the system to around 5000 Euro.

Thus, PV systems are an attractive option in rural areas where no grid connection is available, though under simple payback terms, because of their high capital costs, PVs can often appear unattractive. However, using life-cycle costing, which accounts for all fuel and component replacement costs incurred over the life of the system, PV often compares favourable with the alternatives, which tend to have lower initial costs, but incur significantly greater operating costs.

Displacing conventional technologies with photovoltaic systems can bring various positive effects, which are difficult to quantify in direct financial terms, but which nonetheless offer significant economic and social benefits. For instance, in comparison to traditional kerosene lamps, PV can provide better lighting levels, enabling educational and income generating activities to continue after dark with reduced risk of fire and avoidance of noxious combustion fumes.

The World Health Organization has noted that PV offers a more reliable refrigeration service than other power supply options. This has resulted in increased efficacy of stored vaccines, which in turn has helped to reduce mortality rates. Such factors must be considered when PV is compared to the alternatives even though the cost benefits are not easy to assess.

3.4.2.3. PV-hybrid systems

Although PV systems will generally have some means of storing energy to accommodate a pre-defined period of insufficient sunshine, unfortunately there may still be exceptional periods of poor weather when an alternative source is required to guarantee power production. PV-hybrid systems combine a photovoltaic generator with another power source - typically a diesel generator, but occasionally another renewable supply such as a wind turbine. The PV generator would usually be sized to meet the base load demand, with the alternate supply being called into action only when essential. This arrangement offers all the benefits of PV in respect of low operation and maintenance costs, but additionally ensures a secure supply.

Hybrids can also be sensible approach in situations where occasional demand peaks are significantly higher than the base load demand. It makes little sense to size a system to be able to meet demand entirely with PV if, for example, the normal load is only 10% of the peak demand. By the same token, a diesel generator-set sized to meet the peak demand would be operating at inefficient part-load for most of the time. In such a situation a PV-diesel hybrid would be an ideal compromise.

3.4.3. Grid-connected systems

A different approach of photovoltaic technology is the application of grid-connected PV systems. In these systems solar photovoltaic electricity is fed into the grid. This can be done with two different types of systems:

- Private owners for their own consumption can use small utility interactive PV-systems. Energy surplus will be fed into the grid, while in times of shortage (e.g. at night) energy will be consumed from the grid.
- The other option is utility scale, central station PV array fields, managed by the utilities in the same way as other electric power plants. All DC-output of the array field, which are generally of megawatt range, is converted to AC and then fed into the central utility grid after which it is distributed to the customers.

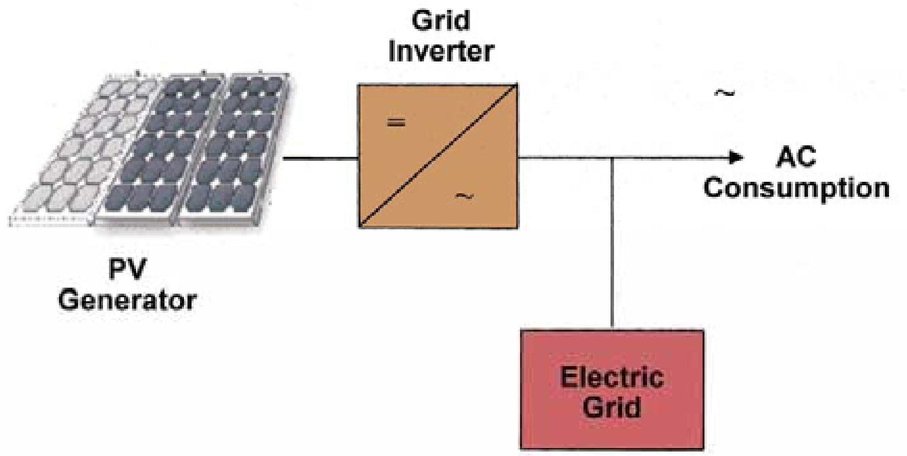


Figure 3.18. PV grid-connected system scheme

In a grid-connected system (figure 3.18) the grid acts like a battery with an unlimited storage capacity. Therefore the total efficiency of a grid-connected PV system will be better than the efficiency of a stand-alone system: as there is virtually no limit to the storage capacity, the generated electricity can always be stored, whereas in stand-alone applications the batteries of the PV system will be sometimes fully loaded, and therefore the generated electricity needs to be "thrown away".

In industrialized countries, where a connection to the main network is generally available, PV systems are definitely not an attractive economic option. For example, a 1.5 kW_p roof mounted PV system would typically have an installed cost of some €10,000. The cost of electricity produced by this system would depend on the overall system efficiency, the resource availability, the lifetime of the system and the assumed discount rate, but unit costs are typically in the order of €0.35-0.65/kWh. Nevertheless, this might not be an entirely accurate reflection because it is often not appropriate to assign a monetary value to the benefits that PV can bring. The most recognized "added value" of solar photovoltaic electricity is that it does not pollute the environment.

3.5. PHOTOVOLTAICS ISSUES OF CONCERN

3.5.1. Economics of photovoltaics

For photovoltaics to be widely used, the costs must be competitive with those of conventional forms of electricity. The average price for electricity is €0.017 – 0.15 per kWh. Today photovoltaics generate electricity at €0.5 – 0.6 per kWh; therefore, the costs must come down by about a factor of 5 to compete in the bulk electricity market. Figure 3.19 shows the relative proportion of cost of each element in a PV system, the cost of the cells making up a very substantial proportion of the final cost, mainly due to the high purity silicon required.

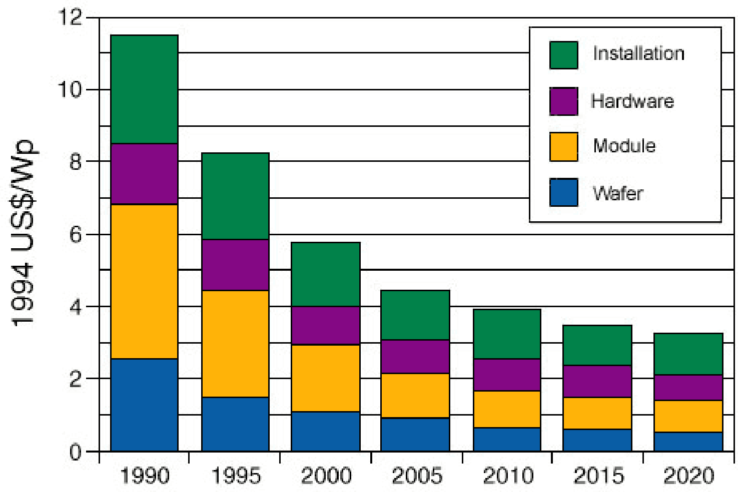


Figure 3.19. Graph showing component costs of PV system and price reduction over time

[Source: http://renewable.greenhouse.gov.au/technologies/pv/pv.html]

A number of factors influence photovoltaic energy costs. Foremost are the module efficiency, lifetime and cost per unit area. Figure 3.20 indicates the interrelationships of cost and module efficiency that lead to specific electricity costs, given a 30-year lifetime for the module and making a number of economic assumptions. From these curves it is clear that lower-efficiency modules have to cost less than higher-efficiency modules to produce the same cost of electricity. Hence there is a premium on higher efficiency.

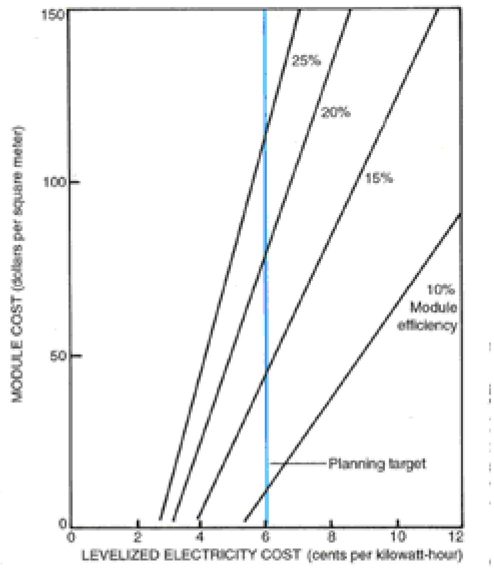


Figure 3.20. Interrelationships of cost and module efficiency that lead to specific electricity costs

[Source: http://www.nrel.gov/research/pv/docs/pvpaper.html]

Similar curves exist for concentrator systems, but higher efficiencies are required to offset the higher balance-of-system costs associated with the necessary lenses or mirrors and sun trackers. In both cases, efficiency can be traded off against area-related costs (such as land, wire and support structure) to achieve the same cost of electricity. The guaranteed durability of PVs enhances their cost effectiveness, particularly in applications where maintenance is a prime consideration.

The annual worldwide commercial production of photovoltaics amounts to about 60 MW, divided approximately equally amount the US, Japan and the European Community. Most of the markets are of the high-value variety that is, markets where today's photovoltaic systems are competitive with traditional ways of providing electrical power. These applications are largely remote from the electrical grid, serving such needs as water pumping, remote communication, refrigeration, signal lights, emergency lighting, pipeline corrosion protection and village power.

The competition typically is with diesel generators and with extension of electrical transmission lines. The cost of grid extension is such that if a power requirement lies more than about half a kilometre from the electrical line, photovoltaics will be cost-effective compared with the line extension. As the cost of PV systems declines, the number of cost-effective applications increases. The ultimate application, bulk electrical power generation, is expected to occur within the next 10 to 20 years, when photovoltaics decline in price below about €0.1 per kWh. Various utility niche markets are expected to grow before these large-power markets do.

Market growth will be tied to the continuing decline in photovoltaic costs relative to conventional supplies. The industry will need to build larger, more cost-effective production plants that take advantage of available economies of scale. Investment in these new, large plants will require identification of sustainable markets. Many high-value applications taken together, including international rural electrification projects, could provide the necessary market pull.

3.5.2. Environmental considerations

PV systems pose only few environmental problems. The generating component produces electricity silently and does not emit any harmful gases during operation. The basic photovoltaic material for most common modules (silicon) is entirely benign, and is available in abundance.

There are, nevertheless, some potential hazards allied to the production of some of the more exotic thin film technologies. The two most promising options, cadmium telluride and copper indium diselenide, both incorporate small quantities of cadmium sulphide, which poses potential cadmium risks during module manufacture. Fortunately, there are well-established procedures governing the handling of such compounds, which are adhered to throughout the production process.

One criticism of early PV modules was that they consumed more energy during their production than they generated during their lifetime. With modern production methods and improved operational efficiencies this allegation is no longer true. The exact energy payback is obviously dependent on the available solar resource and on the degree to which the system is operational. High levels of solar irradiation and a high utilization factor will offer more rapid energy paybacks than if there is less sun and less usage, but typically energy payback will be realized within two years.

4.1. INTRODUCTION

Solar energy has a high exergetic value since it originates from processes occurring at the sun's surface at a black-body equivalent temperature of approximately 5800 K. To make solar flux usable for technical processes and commercial applications, different concentrating technologies have been developed or are currently under development for various commercial applications. Solar thermal concentrating systems will undoubtedly provide within the next few decades a significant contribution to efficient and economical renewable and clean energy supply.

Concentrating solar technologies are devices that concentrate solar energy by focusing solar radiation onto a focal point or line. These technologies may be utilised to drive chemical reactions or to produce power. Solar chemical energy system utilise Concentrating Solar Technologies to drive thermochemical, photochemical or electrochemical processes. These technologies applications are at research stage, promising high potential future benefits.

The more mature Concentrating Solar Power (CSP) systems that utilise such technologies are already at commercialisation stage; multi-megawatt plants have been delivering the world's cheapest solar electricity for the last fifteen years. The final steps of generating electricity using CSP systems (see figure 4.1) are similar to conventional electricity generation, as the ultimate energy conversion process depends on the use of steam or gas to rotate turbines or move a piston in a Stirling engine. In a CSP system, however, steam or hot gas is produced by the concentration of direct solar radiation.

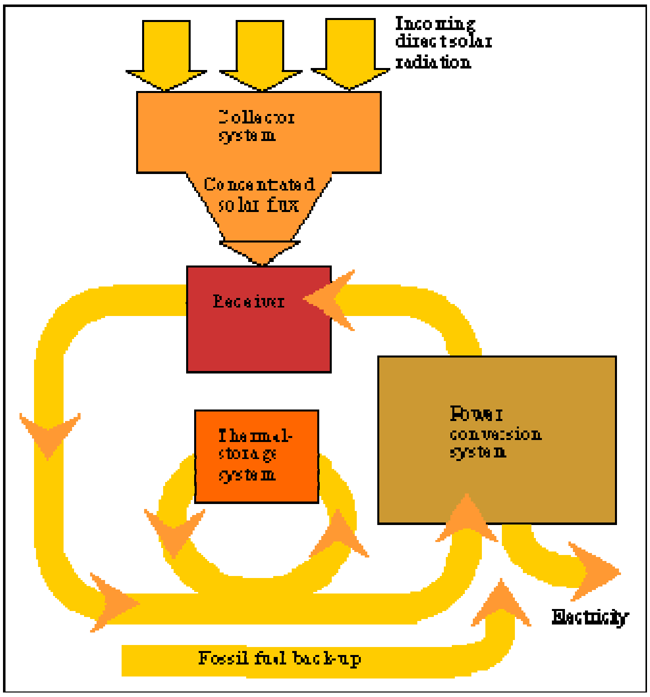


Figure 4.1. Basic concept of the Concentrating Solar Power technology

Solar thermal power technologies all involve a number of key concepts:
- Collection of direct solar radiation using a collector system
- Concentration of the radiation on a receiver
- Conversion by the receiver to thermal energy
- Transport of the thermal energy to the power conversion system
- Conversion of the thermal energy to electricity

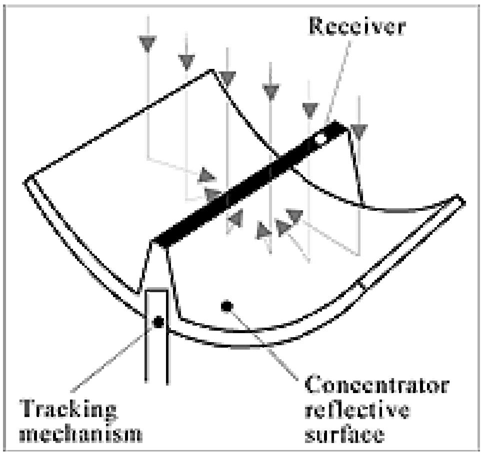
Many systems are possible and can be combined with other renewable and non-renewable technologies in hybrid systems. However it has been considered, namely by the SolarPaces programme from the International Energy Agency (IEA), that the three promising solar thermal power architectures, characterised by the technique used for solar concentration, are:
- parabolic troughs,
- power towers, and
- dish systems.

4.2. OVERVIEW OF POWER SYSTEMS TECHNOLOGIES

4.2.1. Parabolic trough systems

4.2.1.1. Current status of trough technology

The reflective surface of a parabolic trough concentrates sunlight onto a receiver tube located along the trough's focal line, heating the fluid flowing in the tube that is then transported through pipes to a steam turbine generator. The troughs are normally designed to track the sun along one axis, predominantly north-south. This technology may be used to provide process heat or to drive chemical reactions, but it is best known for its application providing electrical power. The concentration ratio of parabolic troughs ranges from 10 to 100, while temperature reaches up to 400°C.



Parabolic troughs assembled in collector fields are currently responsible for all commercially produced solar thermal power, with a total installed capacity of more than 350 MW in California representing over 90% of the world installed solar capacity (figure 4.2). These Solar Electric Generating Systems (SEGS) use thermal oil as a heat transfer fluid, which is pumped through a series of conventional heat exchangers that generate superheated steam at 390°C to operate a turbine. The electricity generated is then delivered to the local electric utility grid.

These plants have been operated on a 75% solar and 25% natural gas basis. To date, there are more than 110 plant-years of experience from the 9 operating plants, which range from 14 to 80 MW. No new plants have been built since 1991 because declining fossil fuel prices and reduced tax benefits in the US resulted in unattractive near term economic prediction for future plants.

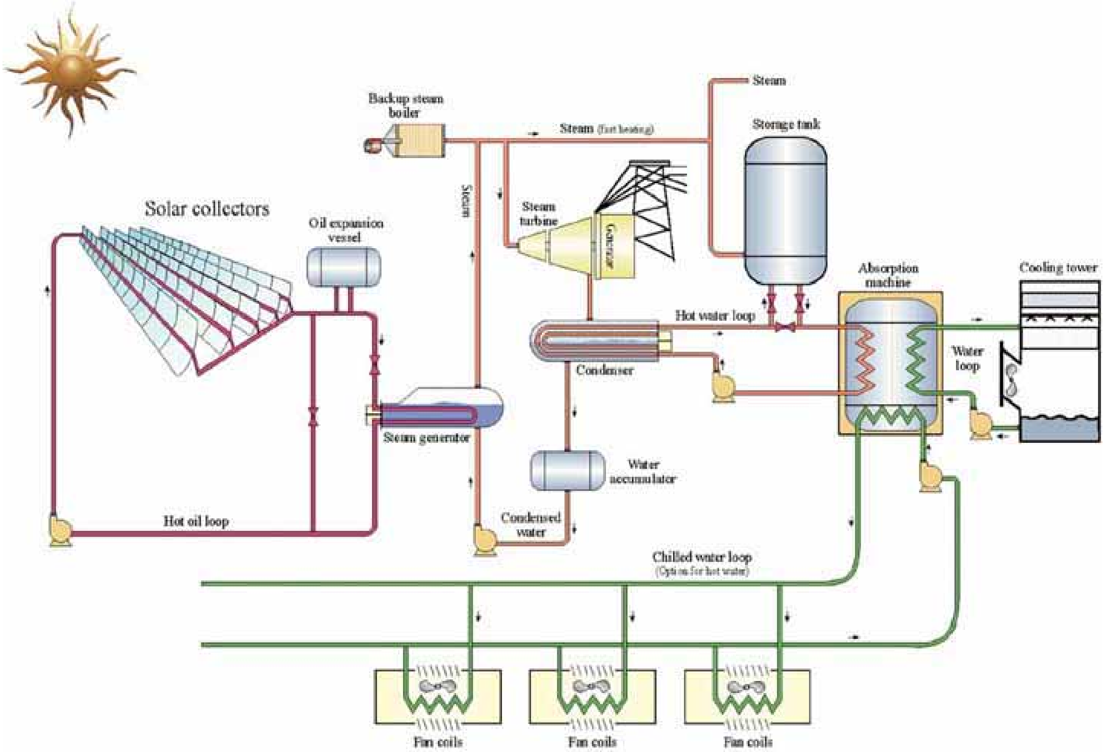


Figure 4.2. Simplified scheme of solar/Rankine SEGS plant

The performance of these power plants has continued to improve over their operational lifetime. The annual solar field availability, defined as the capability to operate, started at an adequate level in the 96 - 97% range but it slowly climbed to 99.5% as maintenance practises sharpened and spare parts problems were solved. The Kramer Junction site has achieved a 30% reduction in operation and maintenance (O&M) costs.

On a net basis, the SEGS VI annual solar to electric efficiency was 10.8% in 1997. However, in July 1997, the peak instantaneous solar to electricity value reached about 21%. The thermal efficiency of the solar field peaked at 60%. An annual capacity factor of 24% has been demonstrated (fraction of the year the technology can deliver solar energy at rated power). These achievements are for plants that have been in operation for 10 years. Reasonable projections for advanced troughs put the annual efficiency at the 15 - 16% level and the capacity factor in the 25-70% range.

4.2.1.2. Opportunities for cost reduction

Cost projections for parabolic trough plants are based on the SEGS experience and the current competitive market place. Recent feasibility studies project SEGS-type plant costs at about \$2700/kW and Integrated Solar Combined Cycle System (ISCCS) plants (figure 4.3) at about \$850/kW. The solar field costs are currently projected at \$275/m^2 installed. The cost breakdown for solar field components or sub-systems is shown in figure 4.4.

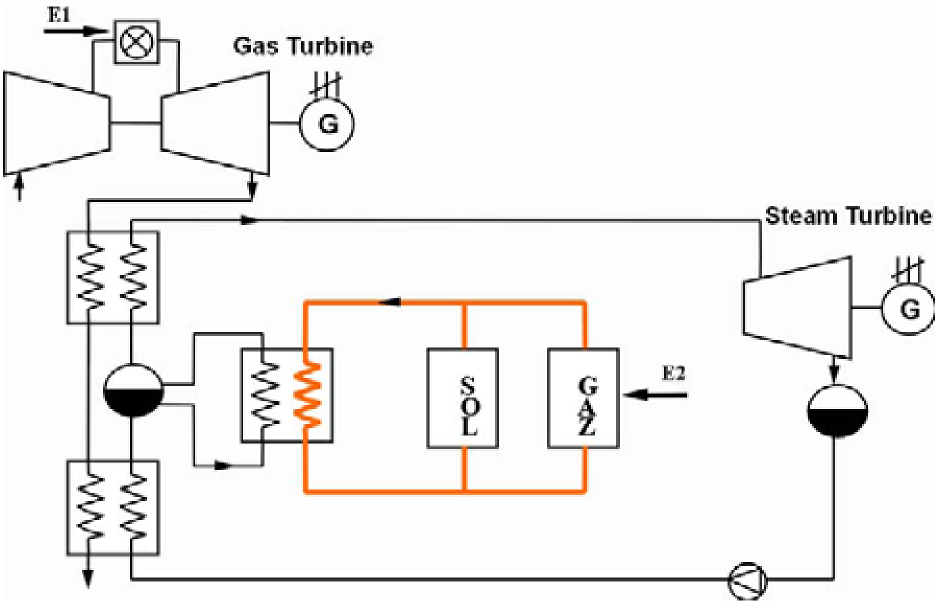


Figure 4.3. Schematic of an ISCCS

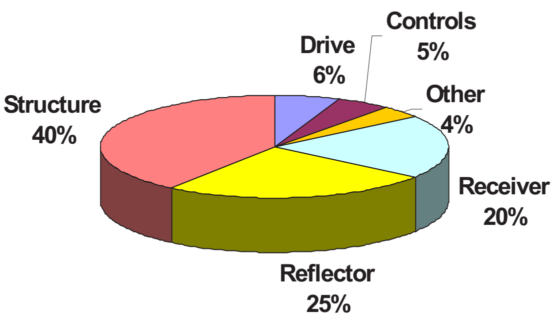


Figure 4.4. Collector cost breakdown

However a number of opportunities have been identified that will likely lead to substantial cost reduction in the levelised cost of electricity (LEC) (see fig. 4.5 below) and performance improvement over the current trough technology:

- Power plant size: Increasing power plant size is one of the easiest ways to reduce the cost of solar electricity from parabolic trough power plants. Studies have shown that doubling the size reduces capital cost by approximately 12-14%, playing essentially on economy of scale and O&M.

- ISCCS: The ISCCS is a proposed configuration that would utilise the steam bottoming cycle in a combined cycle plant to convert the solar thermal energy into electricity. Even if some design operation remains to be completed, initial studies show that the ISCCS configuration could reduce the cost of solar power by as much as 22% over the blended cost of power from a conventional SEGS plant (25% fossil) of similar size.

- Advanced trough collector: As illustrated in figure 4.3, the structure constitutes about 40% of the solar field costs, whereas the reflectors and the receivers each cost 20-25% of the total. Lower cost design can be explored for the steel structure, while evolutionary improvements in the receivers can be expected.
- Direct steam generation: In this concept, steam is generated directly in the parabolic trough collectors. This saves cost by eliminating the need for the Heat Transfer Fluid system and reduces the efficiency loss involved with using a heat exchanger to generate steam. A pilot demonstration of such technology is in progress at the Plataforma Solar de Almeria in Spain.
- Solar power park development: One opportunity for significantly reducing the cost of CSP plants is to develop multiple plants at the same location in a solar power park environment. Building five plants in a phased project approach at the same time could in fact reduce costs by 25-30% for a single project.
- Low cost debt: Finally, a number of institutions have indicated that low-cost debt may be available for renewable power projects. An availability of 2% debt in place of 9.5% debt could reduce the levelised cost of electricity by more than 30%.

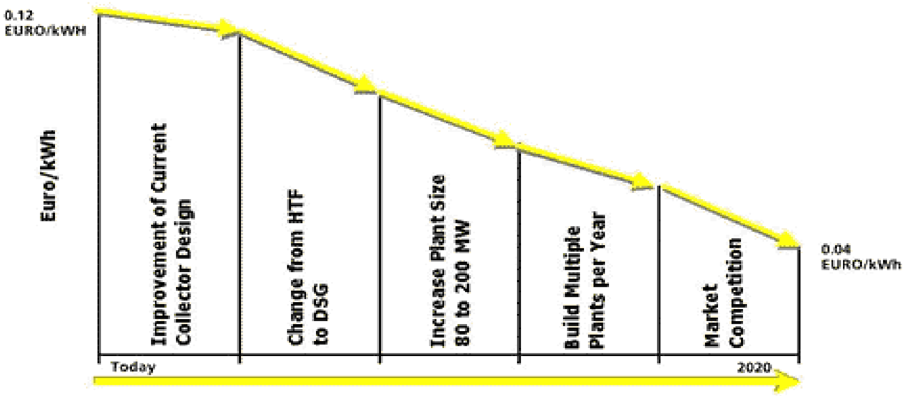


Figure 4.5. Cost reduction potentials of parabolic trough technology

4.2.1.3. Current international opportunities

The international market is driven by internal host country energy programmes and encouraged by the positive attitudes of the Global Environmental Facility (GEF) and the World Bank towards the implementation and development of CSP systems (figure 4.6). These opportunities exist in developing countries and, in recent years, discussions have been active with energy planners, utilities and government agencies in India, Mexico, Egypt, Jordan, Morocco, Greece, Brazil, Iran, China and Spain.

Although it is impossible to predict how many of these initiatives will develop over the next few years, opportunities clearly exist. Most countries have focussed on parabolic trough technology as having already reached the commercial stage, with the recognition that power towers and dish engine systems may become a more cost-effective solution at some point in the future.

Table 4.1. Parabolic trough projects status

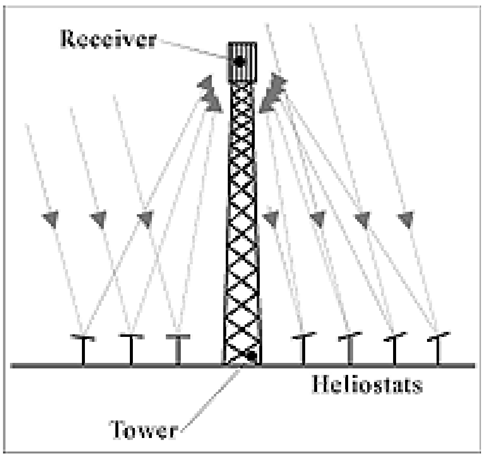
Country	Plant configuration	Status
India	135 MW_e ISCCS with 35 MW_e solar capacity	49 millions US $ GEF grant and 100 millions US $ KfW loan
Egypt	140 MW_e ISCCS with 35 MW_e solar capacity	40 to 50 millions US $ GEF grant approved
Morocco	150 MW_e ISCCS with 30-50 MW_e solar capacity	40 to 50 millions US $ GEF grant allocated
Mexico	310 MW_e ISCCS with 40 MW_e solar capacity	40 to 50 millions US $ GEF grant allocated
Greece (Crete)	50 MW_e SEGS - Project THESEUS	IPP development, EU Thermie programme grant
Spain	50 MW_e SEGS	Waiting outcome for solar tariff
USA (Nevada)	30 MW_e SEGS	Waiting outcome of solar portfolio standard

Figure 4.6. Photographs from a parabolic trough power plant
[Left: Kramer Junction - Right: Gould Electronics]

4.2.2. Power tower systems

4.2.2.1. Current status of power tower systems technology

In power tower systems, heliostats track the sun by two axes mechanism following the azimuth and elevation angle with purpose to reflect and concentrate direct sunlight onto a central tower-mounted receiver where the energy is transferred to a heat transfer fluid. This is then passed optionally to storage and finally to power conversion systems which convert the thermal energy into electricity and supply it to the grid.



Power towers are defined by the options chosen for a heat transfer fluid, for a storage medium and for the power conversion cycle. The heat transfer fluid may be water/steam, molten nitrate salt, liquid metal or air.

Thermal storage may be provided by phase changing material or ceramic bricks, while as regards power cycles, steam Rankine power conversion systems are used with a possible alternative of open cycle Brayton power conversion systems.

Power tower systems usually achieve concentration ratios of 300 to 1500, can operate at temperatures up to 1 500°C and are quite large, generally 10MW or more. Power tower systems currently under development use either nitrate salt or air as the heat transfer medium. The schematic diagram of the primary flow paths in a molten solar power plant is illustrated in figure 4.7.

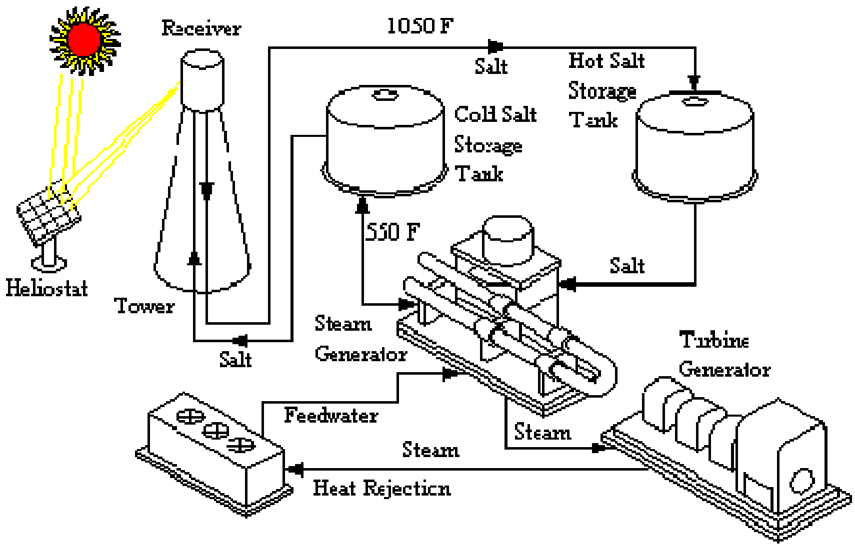


Figure 4.7. Schematic of power tower system electricity generation using molten salt storage

In a molten-salt solar power tower system, liquid salt at 290°C (550°F) is pumped from a "cold" storage tank through the receiver where it is heated to 565°C (1 050°F) and then on to a "hot" tank for storage. When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine/generator system. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver.

Determining the optimum storage size to meet power dispatch requirements is an important part of the system design process. Storage tanks can be designed with sufficient capacity to power a turbine at full output for up to 13 hours. The heliostat field that surrounds the tower is laid out to optimise the annual performance of the plant. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum required to provide steam to the turbine.

Consequently, the thermal storage system can be charged at the same time that the plant is producing power at full capacity. The ratio of the thermal power provided by the collector system to the peak thermal power required by the turbine generator is called the solar multiple. With a solar multiple of about 2.7, a molten-salt power tower system located in the Californian Mojave desert can be designed for an annual capacity factor of about 65%. Without storage, solar technologies are limited to annual capacity factors near 25%.

All annual energy estimates are based on simulations made with the SOLERGY computer code. The input to this code (mirror reflectance, receiver efficiency, start up times, parasitic power, plant availability, etc.) are based on measured data taken from the 10 MW Solar One plant and the small (~1MW) molten salt receiver system test conducted in the late 1980's. No overall energy data are available from an operating molten salt power tower. Collection of such data is one of the main goals of the Solar Two demonstration project.

An annual solar to electric efficiency of 8.5% is expected with the Solar Two power plant (figure 4.8). To save capital costs, the plant was sized to have a 20% annual capacity factor and three hours of thermal storage. The first commercial plant is expected to reach a solar to electric efficiency and annual capacity factor of respectively 15% and 43%. Reasonable projections for advanced solar power tower systems presents figures of 20% and 77% for solar to electric efficiency and annual capacity factor respectively.

Figure 4.8. Photographs from the Solar Two solar Power Tower 10 MW_e plant

4.2.2.2. Opportunities for cost reduction

The costs presented for the Power Tower systems are usually based on the actuals incurred for the Solar Two projects as reported by Southern California Edison. Capital and O&M cost estimates for 2000 and beyond are consistent with estimates contained in the IEA studies. Total capital requirements for the first commercial scale plant is about 4 400 \$/kW with a projection at 2030 of about 2 500\$/kW. The solar field costs are currently projected from 475 $\$/m^2$ to 200 $\$/m^2$ installed. The cost breakdown for solar field components or sub-systems is indicated in figure 4.9.

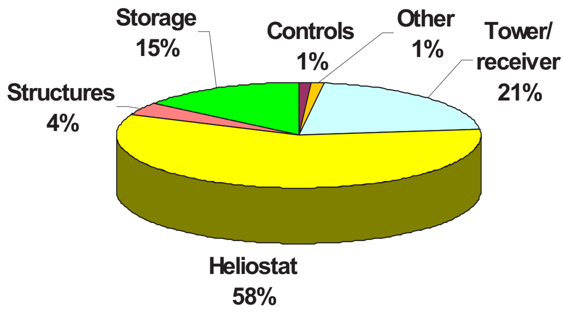


Figure 4.9. Collector cost breakdown

Assuming success at Solar Two, power tower technology will be on the verge of technology readiness for commercial applications. The target is to achieve electricity generation cost of less than 0.2 $/kWh for first commercial plants. However, progress related to scale-up and R&D for specific sub-systems is still needed to reduce costs and to increase reliability to the point where the technology becomes an attractive financial investment. Promising work is ongoing in the following areas:

- System scale-up: Ideally, to be economically competitive with conventional fossil technology, a power tower should be at least 10 times larger than Solar Two. Fossil hybridisation designs, only requesting an intermediate size of a few 10 MW, are also being explored as another possible way of aiding market entry. The benefits of the reduced size plant induce scale-up risk and reduced capital investment.
- Heliostats: Relatively few heliostats have been manufactured to date and their cost is high (>250 $/m^2). As the demand for solar power increases, heliostats mass production methods will be developed that will significantly reduced their cost, since prices are a strong function of annual production rate. For a high annual production (50 000/year), a reduction by a factor 3 to 4 can be achieved.
- Receiver: Smaller, simpler receivers are needed to improve efficiency and reduce maintenance. Advanced receiver development is currently underway for both Heat Transfer Fluids, either molten-salt (new steel alloys for the receiver tubes) or air (new volumetric air receiver concept).
- Molten salt: Molten nitrate, though an excellent thermal storage medium, can be a troublesome fluid to deal with because of its relatively high freezing point (220°C). To keep the salt molten, a fairly complex heat trace system must be employed. Design improvements and standardisation would reduce risk and ultimately reduce O&M costs.

Ultimately, as power technology matures and larger, more advanced plants are deployed, power costs should be similar to clean coal-fired generation. This is also evident in the data provided in table 4.2, as regards current and projective performance and cost indicators for the solar power tower technology.

Table 4.2. Performance and cost indicators for solar power tower technology

	Units	Solar Two	First	2005	2010	2020

		technology	commercial power plant	technology	technology	technology
Plant size	MW	10	30	100	200	200
Solar field size	m^2	81 000	275 000	883 000	2 477 000	2 477 000
Receiver	MW	43	145	470	1 400	1 400
Steam turbine	MW	10	30	100	200	200
Thermal storage	hrs	3	7	6	13	13
Annual capacity factor	%	20	43	44	65	75
Global efficiency	%	8.5	15	16	17	20
Total cost	€/kW	-	4 350	3 270	2 700	2 700

4.2.2.3. Current projects

European demonstration activities related to the technical and economic feasibility of hybrid solar tower power plants (ISCCS plants) are as relevant as trough power plant activities. Two EU funded central receiver projects (SOLGAS and Colón Solar) have established a market penetration strategy based on the integration of 20 MW of solar thermal saturated steam into a conventional power plant converted to a combined cycle plant by addition of a gas turbine, but have been unfortunately terminated after the detailed engineering phase due to budgetary reasons in 1998.

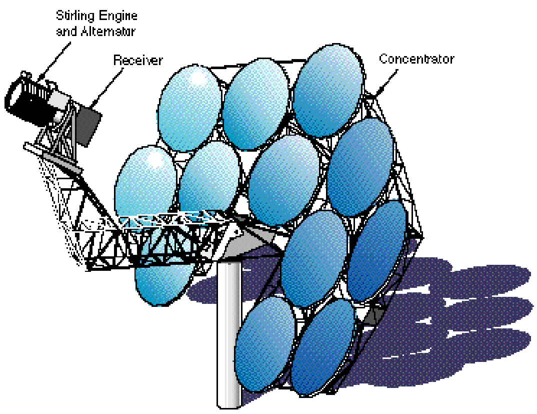
A 10 MW_e tower power plant based on the German PHOEBUS volumetric air receiver/heat storage technology and thousand Spanish glass-metal heliostat units is being promoted by the Spanish company ABENGOA, based on the Colón Solar design enlarged up to 90 m^2/unit (Planta Solar PS10 at Sanlúcar near Sevilla in southern Spain). This project received a 35 % subsidy of the solar investment from the EC Fifth Framework ENERGIE Programme in its 1999 call for proposals and will take credit of the Spanish Royal Decree. It is scheduled to start annual production of 20 GWh net of electricity in the year 2002 and is expected to validate installed plant capital costs for solar tower plants in the order of 2,700 Euro/kW_e.

A second 10 MW_e tower power plant project is being developed by a Spanish/U.S. industrial group formed by Ghersa, Boeing and Bechtel for a possible site at Córdoba in Spain, which is based on the U.S. molten salt receiver and energy storage technology. Key aspects of the plant are the large size of the molten salt thermal storage, which is large enough to allow for 24-hour operation of the solar-only plant, and the use of a new type of a Spanish low-cost heliostat with reduced dimension.

4.2.3. Dish/engine power plants

4.2.3.1. Current status of dish systems technology

A dish concentrates direct solar energy onto a receiver at its focal point. The receiver absorbs the energy and converts it into thermal energy. This can be used directly as heat or can support chemical processes, but its most common application is power generation. The thermal energy can either be transported to a central generator for conversion or it can be converted directly into electricity at a local generator coupled to the receiver.



Dishes track the sun on two axes and thus are the most efficient collector systems because they are always pointing at the sun. Concentration ratios usually range from 600 to 2 000 and they can achieve temperature in excess of 1 500°C. The ideal concentrator shape is a paraboloid of revolution. Some solar concentrators approximate this shape with multiple, spherically shaped mirrors supported with a truss structure.

An innovation in solar concentrator design is the use of stretched membranes in which a thin reflective membrane is stretched across a rim or a hop. A second membrane is used to close off the space behind. A partial vacuum is drawn in this space, bringing the reflective membrane into an approximately spherical shape. Intercept fractions, defined as the fraction of the reflected solar flux that passes through the receiver aperture, are usually over 95%. At a nominal maximum direct normal solar insolation of 1 kW/m^2, a 25 kW dish/Striling system concentrator has a diameter of about 10 meters.

While Rankine cycle engines, Brayton cycle engines and sodium heat engines have all been considered for systems using dish-mounted engines, greatest attention has been paid to Stirling engine systems. However, competition between Stirling and Brayton engines remains open. Dish/engine systems are characterised by high efficiency, modularity, autonomous operation and an inherent hybrid capability (the ability to operate on either solar energy or fossil fuel or both).

Of all solar technologies, dish/engine systems have demonstrated the highest solar to electricity conversion efficiency (29.4%) and therefore have the potential to become one of the least expensive sources of renewable energy. The modularity of dish/engine systems allows them to be deployed individually for remote applications or grouped together for small grid or end of line utility applications. Dish/engine systems can also be hybridised with a fossil fuel to provide dispatchable power.

This technology is in the engineering development stage and technical challenges remain concerning the solar components and the commercial availability of a solarisable engine. Dish/engine systems are not now commercially available except as engineering prototypes. The 25 kW dish Stirling system developed by Mc Donnell Douglas Aerospace (MDA) in the mid 1980's represents the base year (1997) technology. Assuming the success of current dish/engine joint ventures, these systems could become commercially available in the next 5 years.

As an example, a consortium of German companies, Schlaich, Bergermann and Partner working with Steinmüller (collector systems) and SOLO Kleinmotoren (Stirling engine) have developed a 9 to 10 kW unit. Six of such units are operating successfully in Spain. Three of them have been continually operated with great success since 1992, accumulating more than 30 000 hours of operating experience. As to performance, Southern California Edison Company operated a MDA system on a daily basis from 1986 through 1988.

During its last year of operation, it achieved an annual efficiency of 12% despite significant unavailability. Without outages, solar efficiencies in excess of 23% were achieved. A 23% annual efficiency is, therefore, a reasonable expectation for the near-term systems. Because dish/engine systems use heat engines, they have an inherent ability to operate on fossil fuels. The use of the same power conversion equipment means that only the addition of a fossil fuel combustor is required to enable a hybrid capability.

For dish/Brayton systems addition of a hybrid capability is straightforward, while in the case of dish/Stirling it represents a challenge. System efficiency, based on higher heating value is expected to be about 30% and 33% for a dish/Brayton and dish/Striling operating in the hybrid mode, respectively. An annual capacity factor of 12.5% was reached with the MDA technology. Considering a hybrid capability, an annual capacity factor of 50% is assumed, corresponding to a solar fraction of 50%.

4.2.3.2. Opportunities for cost reduction

The today's installed plant capital costs of a first stand-alone 9 to 10 kW_e dish/Stirling unit is 10,000 to 14,000 Euro/kW_e and of actual near-term units 7,100 Euro/kW_e (at 100 units/year production rate). The most attainable near-term goal of electricity costs is less than 15 Euro cents/kWh. In the medium- to long-term, dish/Stirling systems will have drastically decreasing installed system costs, which are projected with growing number of dish units produced in series.

The goal of the European Euro-Dish project is to drop from 7,100 Euro/kW_e (100 units/year) to 3,700 Euro/kW_e (1,000 units/year) to 2,400 Euro/kW_e (3,000 units/year) and to 1,600 Euro/kW_e (10,000 units/year), but not below due to extremely high modular technology. A typical dish/engine system cost breakdown is presented in figure 4.10.

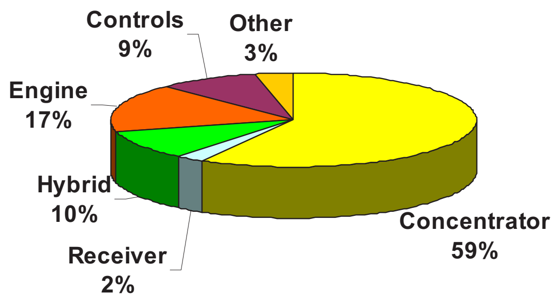


Figure 4.10. Dish/engine cost breakdown

Experienced dish costs trends show a drastic reduction of installed dish collector costs: 1,250 Euro/m² (40 m² Shenandoah, USA 1982), 300 Euro/m² (91 m² MDAC, USA 1985), 200 Euro/m² (44 m² LaJet, USA 1986) and 150 Euro/m² (44 m² German SBP stretched-membrane dish, 1992). Medium- to long-term installed dish collector costs are predicted in the range of 125 to 105 Euro/m² for high production rates.

Dish systems have the following main technological items for their roadmap to the market:

- Improvements of dish reflector and receiver, including better optical properties of the mirrors; lighter mirrors and structures; better controls; improved hybrid heat-pipe receivers; development of an automatic control system for remote operation and for long distance control.
- System improvements using Stirling and Brayton (gas turbine) engines adapted to solar processes with advanced heat-pipe and volumetric air receivers.
- Proof-of-reliable operation of advanced Stirling engine/receiver units over the long run.
- Improvements in system integration by reduction of parasitic loads, optimisation of start-up procedures, better control strategies and hybrid operation of Stirling or Brayton engines.

4.2.3.3. Current projects

In Europe a first ongoing industrial dish/Stirling demonstration programme is under successful operation for proof of continuous operation at the PSA, with six German dish/Stirling pre-commercial units with 9 to 10 kW_e ratings (three DISTAL-I systems since 1992 and three DISTAL-II systems since 1997). The DISTAL-I systems have accumulated over 30,000 operating hours in total up to now. There are promising advanced heat pipe receiver types and Stirling engines currently under development and testing for proof of system reliability.

New 9 to 10 kW_e dish/Stirling units are under way for testing on the PSA within the EuroDish R&D programme with EU co-funds since 1998, with the goal of cost reductions by advance of the structures for commercialised European dish/Stirling systems. A feasibility study and small demonstration project is promoted by a Spanish group in collaboration with the SES consortium using a 25 kW_e Dish /Stirling unit of McDonell Douglas (MDA) for erection in the south-east Spain.

In the south-west USA a first industrial series of five 25 kW_e U.S. dish/Stirling 2nd generation prototype systems for extended testing were initiated, but these large U.S. dish projects (figure 4.11) will possibly be shortened or stopped due to dropping public R&D funds in the short term. In southern Australia, a first 400 m^2 pilot experimental "big dish" project having a power capacity up to 150 kW_{th} is under scientific testing at the Australian National University since 1994.

This dish is an alternative to the small-unit philosophy described above; it is designed for power generation using a 50 kW_e steam engine generator or for co-generation applications. The Australian government is presently funding a 2.6 MW_{th} solar power plant project consisting of eighteen such units that will inject solar generated steam directly into the steam turbine of an existing coal-fired power station in Newcastle, New-South Wales. One Australian dish collector unit was sold to an Israeli solar test centre in the Negev desert for solar R&D test bed purposes.

Figure 4.11. Photographs from dish/Stirling systems
(Left: SERI's One Omnium G dish - Right: Arizona utility test center)

4.3. ENVIRONMENTAL IMPACTS

4.3.1. Effects on the environment

Regarding parabolic trough plants, environmental impacts can be caused by heat transfer fluid spillage or leakage. The fluid is generally an aromatic hydrocarbon that can be classified, depending on the countries or the states, as hazardous material. When spills occur, contaminated soil is removed to an on-site-bio-remediation facility that utilises indigenous bacteria in the soil to decompose the fluid until the concentration has been reduced to acceptable levels. In addition to liquid spills, there is some level of fluid vapour emissions from valve packing and pump seals during normal operation.

Although the scent of these vapours emissions is often evident, the emissions are well within permissible levels. No hazardous gaseous or liquid emissions are released during operation of the solar power tower plant. If a salt spill occurs, the salt will freeze before significant contamination of the soil occurs. Salt is picked up with a shovel and can be recycled if necessary. If these two technologies are hybridised with a conventional fossil-fuel plant, emissions will be released from the non-solar portion of the plant.

The environmental impacts of dish/engine systems are minimal. Stirling engines are known for being quiet, relative to internal combustion gasoline and diesel engines, and even the highly recuperated Brayton engines are reported to be relatively quiet. The biggest source of noise from a dish/Stirling system is the cooling fan for the radiator. There has not been enough deployment of such systems to realistically assess visual impact. The systems can be high profile, extending as much as 15 meters above the ground.

However, aesthetically speaking they should not be considered detrimental, since dish/engine systems resemble satellite dishes that are generally accepted by the public. Emissions from dish/engine systems are also quite low. Other than the potential for spilling small amounts of engine oil or coolant or gearbox grease, these systems produce no effluent when operating with solar energy. Even when operating with a fossil fuel, the steady flow combustion systems used in both Stirling and Brayton systems result in extremely low emissions levels.

4.3.2. Water and land requirements

Water availability can be a significant issue in the arid regions best suited for trough plants. The majority of water consumption at the SEGS plants (approximately 90%) is used by the cooling towers. Water consumption is nominally the same as it would be for any Rankine cycle power plant with wet cooling towers that produced the same level of electric generation. Dry cooling towers can be used to significantly reduced plant water consumption, by as much as 90%. However, this can result in up to a 10% reduction in power plant efficiency.

Regarding the power tower technology, figures mentioned are about the same as for the SEGS plant, in the range from 3 to 8 m^3/MWh produced. Dish/engine systems do not require water for engine cooling. In some locations, a minimal amount of water is required for mirror washing. The land requirement for each technology is gathered in table 4.3.

Table 4.3. Land requirement for each technology

	Units	Parabolic trough		Power Tower		Dish/engine
		SEGS	*Advanced*	*Solar Two*	*Advanced*	
Power size	MW	80	320	10	200	0.025
Land	m^2/MWh	7.5	8.5	27	11	3.5

4.4. THE MARKETS

4.4.1. General

With the advent of Independent Power Producers (IPPs) and deregulation of electricity sector, there is an intense competition within the power industry to gain market share. Profit margin on power projects is small and, consequently, IPPs are hesitant to take risks on advanced technology like CSP plants. As a result, it is very difficult to introduce a new technology into the marketplace.

Bringing a new technology into the marketplace requires attractive financial incentives. Resolving taxation issues can do as much for improving the economic competitiveness of CSP plants as will technological breakthroughs. Recent studies in the US have shown that taxation policy can affect the levelised electricity cost from the solar plant by as much as one-third. If a CSP plant is taxed in the same way as an equivalent fossil-fuel plant, the solar plant will, because of its capital-intensive nature, pay much more tax per kWh during its lifetime.

Nevertheless, CSP technologies are capable of meeting the requirements of two major electric power markets:

- large scale dispatchable markets comprised of grid connected peaking and base-load power;
- rapidly expanding distributed markets including both on-grid and remote/off-grid applications.

With appropriate commercialisation strategies, CSP can begin penetrating the market place, even during this time of intense competition.

On figure 4.12, the cost of CSP plants in California (SEGS, Central receiver, Dish/Stirling) is compared with power generated from fossil, nuclear and other renewable energy technologies.

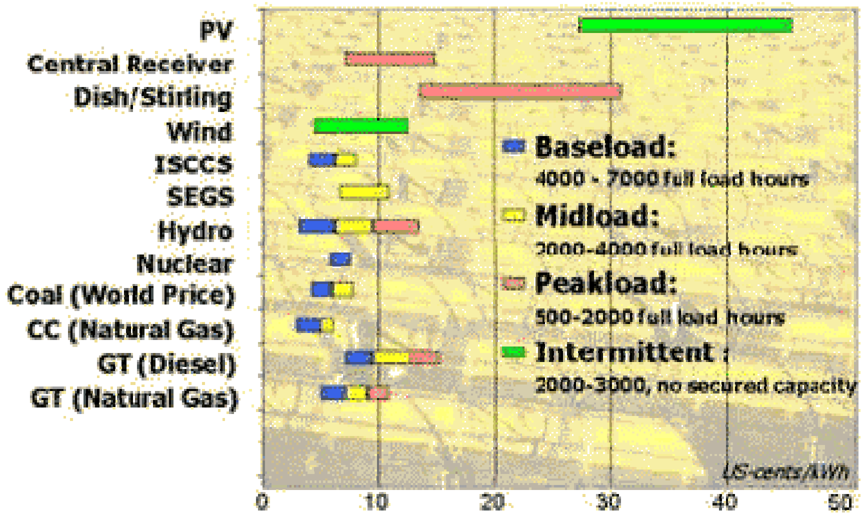


Figure 4.12. Power costs comparison between different technologies

Competitors for the trough and power tower technologies are the current conventional grid-connected fossil fuel-fired power plants, particularly the modern natural gas-fired combined cycle plants in mid- or base-load operation mode. As to dish/engine technology, competitors are conventional small-scale off-grid generation systems with unit ratings of the kW_e-range up to about 10 MW_e in peak- or mid-load operation at remote places, i.e. the gas oil- or heavy fuel oil-powered Diesel engine generators, particularly in developing Sunbelt countries and on islands with relatively high fuel costs.

4.4.2. Dispatchable power markets

Dispatchable power markets are dominated by fossil-fuel-fired electricity distributed over central utility grids. Power must be produced on demand in order to meet changing loads and command the highest value. Low life-cycle costs are the primary driver of investments decisions in this market and advanced gas-fired and coal-fired plants represent the conventional technology serving this market.

Using storage and hybridisation capabilities, dispatchable trough and power tower technologies can address this market. They currently offer the lowest cost, highest value solar electricity available and have the potential to be cost competitive with fossil energy in the long term. At present the Levelised Electricity Cost is higher than competing conventional technologies. Fortunately financial incentives are currently being offered in several countries that will help CSP to get over the cost hurdle.

4.4.3. Distributed power markets

The current emphasis in distributed power applications is to develop technologies that can operate reliably for loads ranging from several kWs to several MWs. The majority of these applications are currently for remote power where there is no utility grid. In these applications, diesel engine generators are the primary current competitors. Also a growing interest to utilities are grid connected applications in which the solar generator is sited at critical points on the transmission and distribution (T&D) system providing value, not simply from the energy produced but also in postponing T&D infrastructures upgrades to meet load growth and in maintaining power quality. Small gas turbine systems will also compete with CSP and other renewable energy technologies (such as PV and wind) for this market.

The CSP technology appropriate for distributed applications is the dish/engine system. Each dish/engine module (10 to 50 kW) is an independent power system designed for automatic start-up and unattended operation. Multiple dish/engine systems can be installed at a single site to provide as much power as needed and the system can be readily expanded with additional modules to accommodate future load growth. The system can be designed for solar-only applications, can be easily hybridised with fossil fuel to allow power production without sunlight or can be deployed with battery systems to store energy for later use. The high value of distributed power provides opportunities for commercial deployment early in the technology development.

4.5. CASE STUDY

In the second half of the 80s, nine solar power plants from 14 MW to 80 MW have been put into operation in the Mojave desert (south California), reaching as a whole 354 MW. These power plants are still in operation. The solar power plants of SEGS (Solar Electricity Generating System) type from the Luz Company use direct solar irradiation as a prime fuel. As they are operating with natural gas as an auxiliary fuel, they don't need any storage unit. They are used in California for peak consumption. Their productivity is about 400 kWh/m^2 of collector, which roughly means an annual production of 170 GWh for a 80 MW plant.

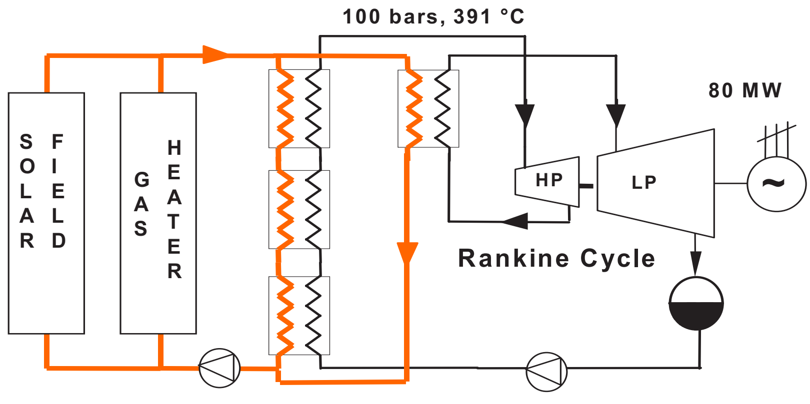


Figure 4.13. Schematic of the SEGS IX plant

The SEGS IX power plant located at Harper Lake (80 MW) is the more recent plant built by the Luz company. The schematic layout of plant is given in figure 4.13. This power plant is composed of different components the characteristics of which are presented in table 4.4:

- A solar field gathering 888 parabolic trough LS 3 collectors, oriented in a north-south axis.
- A natural gas heater that gives the possibility to heat the Heat Transfer Fluid in parallel with the solar field when the optimal operating temperature cannot be reached only with the solar part. It is typically the case in late afternoon or during cloudy days.
- A steam generator that feeds the turbine with overheated steam. The needed heat is taken from the Heat Transfer fluid through heat exchangers.
- A 80 MW turbo-alternator which supplies electricity to the grid. The expected lifetime is about 30 years with daily start and stops.
- Cooling towers are used.

The SEGS IX plant has been built to supply 250 GWh per year, which corresponds approximately to 3 000 hours of operation at nominal power. In order to benefit from the advantages of the US PURPA law (Public Utility Regulatory Policies Act) regarding Renewable Energies, 75 % of the production must come from the solar part of the plant. Without energy storage, this power plant operates in the peak load mode.

Table 4.4. Characteristics of the SEGS IX power plant

SITE		
Location		Harper Lake (California, 35°N)
Yearly direct normal irradiation	kWh/m^2	2 727
Land requirement	ha	169
SOLAR FIELD		
Number of LS3 collectors		888
Number of single mirrors		198 912
Solar field area (aperture)	m^2	483 960
Solar field outlet temperature	°C	391
Heat Transfer Fluid		Diphenyl/Diphenyl Oxyde
Volume of fluid	m^3	1 289
Volume of expansion vessel	m^3	567
Heat Transfer Fluid circulation pumps		
LS3 COLLECTORS		
Aperture area	m^2	545
Number of single mirrors		224
Width	m	5.76
Length	m	95.2
Tube diameter	m	0.07
Concentration factor		82
Mean focal distance	m	2.12
Distance between two rows	m	17.3
Optical efficiency		0.8
Mirrors reflectivity		0.94
Transmittance of the tube		0.965
Emittance of the tube at 350 °C		0.19
Absorptivity of the tube		0.96
Maximal collector efficiency		0.68

Thermal annual efficiency		0.49
FACTORY BLOCK		
Gross power of the turbo alternator	MW	89
Net electrical power	MW	80
Power of the natural gas heater	MW	251
Flow rate of the steam generator	tons/h	357
TURBINE ADMISSION CONDITIONS		
Pressure of condensation	mbar	80
Rankine cycle nominal efficiency - Solar mode		0.338
Rankine cycle nominal efficiency - Natural gas mode		0.324

5.1. GEOTHERMAL ENERGY CHARACTERISTICS

5.1.1. Geothermics basics

Geothermal power is the thermal (at first) and electrical (in a second step) power produced from the thermal energy contained in the Earth (geothermal energy). Use of geothermal energy is based thermodynamically on the temperature difference between a mass of subsurface rock and water and a mass of water or air at the Earth's surface. This temperature difference allows production of thermal energy that can be either used directly or converted to mechanical or electrical energy.

Temperatures in the Earth, in general, increase with increasing depth, to 200-1000°C at the base of the Earth's crust and to perhaps 3500-4500°C at the centre of the Earth. The heat that produces geothermal gradients comes from two sources: flow of heat from the deep crust and mantle; and thermal energy generated in the upper crust by radioactive decay of isotopes of uranium, thorium, and potassium. However, some granite rocks in the upper crust have abnormally high contents of uranium and thorium, thus producing anomalously great amounts of thermal energy and enhanced flow of heat toward the Earth's surface.

The thermal gradients are calculated under the assumption that heat moves toward the Earth's surface only by thermal conduction through solid rock. However, thermal energy is also transmitted toward the surface by movement of molten rock (magma) and by circulation of water through interconnected pores and fractures. These processes are superimposed on the regional conduction-dominated gradients and give rise to very high temperatures near the Earth’s surface. Areas characterized by such high temperatures are the primary targets for geothermal exploration and development.

Commercial exploration and development of geothermal energy to date have focused on natural geothermal reservoirs-volumes of rock at high temperatures (up to 350°C) and with both high porosity (pore space, usually filled with water) and high permeability (ability to transmit fluid). The thermal energy is tapped by drilling wells into the reservoirs. The thermal energy in the rock is transferred by conduction to the fluid, which subsequently flows to the well and then to the Earth's surface.

Natural geothermal reservoirs, however, make up only a small fraction of the upper 10 km of the Earth's crust. The remainder is rock of relatively low permeability whose thermal energy cannot be produced without fracturing the rock artificially by means of explosives or hydro-fracturing. Experiments involving artificial fracturing of hot rock have been performed, and extraction of energy by circulation of water through a network of these artificial fractures may someday prove economically feasible.

5.1.2. Geothermal resources

There are four types of geothermal resources, namely hydrothermal, geo-pressured, hot dry rock and magma. Of the four types, only hydrothermal resources are currently commercially exploited.

5.1.2.1. Hydrothermal

All the reservoirs developed to date for electrical energy are termed hydrothermal convection systems and are characterized by circulation of meteoric (surface) water to depth at shallow to moderate depths (100m to 4.5km). The driving force of the convection systems is gravity, effective because of the density difference between cold, downward moving, recharge water and heated, upward-moving, thermal water. A hydrothermal convection system can be driven either by an underlying young igneous intrusion or by merely deep circulation of water along faults and fractures.

Hydrothermal resources require three basic components, namely a heat source (e.g. crystallised magma), an aquifer containing accessible water, and an impermeable cap rock to seal the aquifer (see figure 5.1). The geothermal energy is usually tapped by drilling into the aquifer and extracting the hot water or steam. High temperature hydrothermal resources (with temperatures from 180^{o}C to over 350^{o}C) are usually heated by hot molten rock, while low temperature resources (with temperatures from 100^{o}C to 180^{o}C) can be produced by either process.

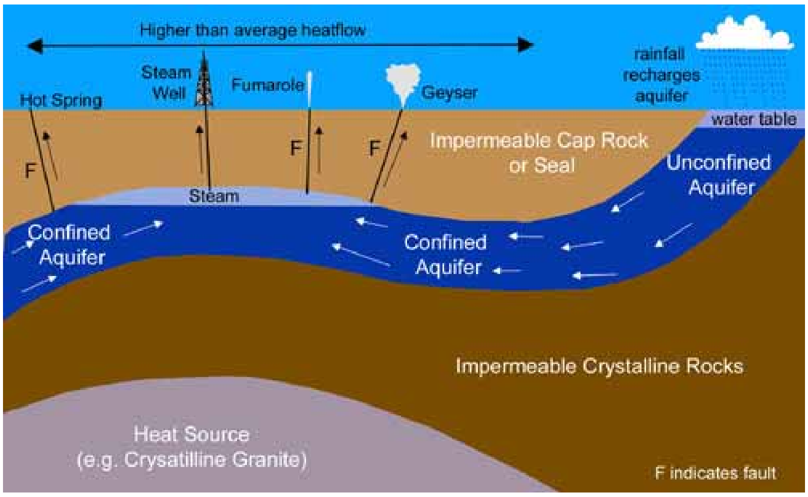


Figure 5.1. Simplified cross section of the essential characteristics of a geothermal site (Source: Boyle, 1998)

Depending on the physical state of the pore fluid, there are two kinds of hydrothermal convection systems:

a. liquid-dominated, in which all the pores and fractures are filled with liquid water that exists at temperatures well above boiling at atmospheric pressure, owing to the pressure of overlying water; and
b. vapour-dominated, in which the larger pores and fractures are filled with steam.

Liquid-dominated reservoirs produce either water or a mixture of water and steam, whereas vapour-dominated reservoirs produce only steam, superheated in most cases. Natural geothermal reservoirs also occur as regional aquifers, such as the

Dogger Limestone of the Paris Basin in France and the sandstones of the Pannonian series of central Hungary.

5.1.2.2. Geo-pressured

In some rapidly subsiding young sedimentary basins, such as the northern Gulf of Mexico Basin, porous reservoir sandstones are compartmentalized by growth faults into individual reservoirs at a depth of about 3km-6km that can have fluid pressures exceeding that of a column of water and approaching that of the overlying rock. The pore water is prevented from escaping by the impermeable shale that surrounds the compartmented sandstone.

The temperature of the water is in the range of 90^{o}C-200^{o}C. The energy in these geo-pressured reservoirs consists not only of thermal energy, but also of an equal amount of energy from methane dissolved in the waters (chemical energy), plus a small amount of mechanical/hydraulic energy due to the high fluid pressures.

5.1.2.3. Hot dry rock

Hot dry rock (HDR) is a heated geological formation formed in the same way as hydrothermal resources, but containing no water as the aquifers or fractures required to conduct water to the surface are not present (figure 5.2). Water is pumped down one well to induce hydraulic fracturing to create a reservoir. Water is then circulated under pressure through these fractures, absorbing heat before returning to the surface via one or more production wells. The concept was initially pioneered in the UK and the USA. This resource is virtually limitless and is more accessible than hydrothermal resources.

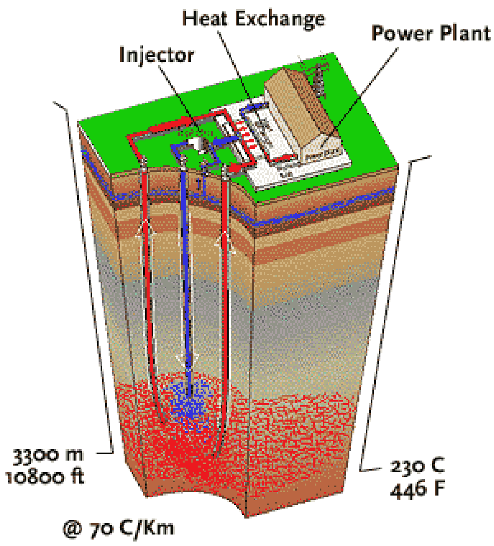


Figure 5.2. Hot dry rock technology
(Image: courtesy of the Hot Rock Energy program, Australian National University)

5.1.2.4. Magma

Magma, the largest geothermal resource, is molten rock found at depths of 3km-10km and deeper, and therefore not easily accessible. It has a temperature that ranges from 700 - 1,200°C. The resource has not been well explored to date.

5.1.3. Geothermal potential

Geothermal energy, in the broadest sense, is the natural heat of the earth. The recoverable thermal energy theoretically suitable for direct applications has been estimated at 2.9 x 10^{24} Joules, which is about 10,000 times the present annual world consumption of primary energy. However, most of the earth's heat is far too deeply buried to be tapped, even under the most optimistic assumptions of technological development. Geothermal energy has at present a considerable economic potential only in areas where thermal water or steam is concentrated at depths less than 3 km in restricted volumes analogous to oil in commercial oil reservoirs.

The drilling technology is similar for geothermal fluid as for oil. However, as the energy content of a barrel of oil is much greater than an equivalent amount of hot water, the economic requirements for permeability of the formations and the productivity of the geothermal wells are much higher than for oil wells. Geothermal production wells are commonly 2 km deep, but rarely much over 3 km at present. Exploitable geothermal systems occur in a number of geological environments.

High-temperature fields used for conventional power production (with temperature above 150°C) are largely confined to areas with young volcanism, seismic and magmatic activity. Low-temperature resources can, on the other hand, be found in most countries. They are formed by the deep circulation of meteoric water along the faults and fractures, and by water residing in high-porosity rocks, such as sandstone and limestone, at sufficient depths for the water to be heated by the earth's geothermal gradient. The heat resources in hot but dry (low porosity) rock formations are found in most countries, but are yet not economically viable for utilization.

5.1.4. Geothermal energy utilisation

Although geothermal energy is present everywhere beneath the Earth's surface, its use is possible only when certain conditions are met:

(1) The energy must be accessible to drilling, usually at depths of less than 3 km but possibly at depths of 6-7 km, in particularly favourable environments (such as in the northern Gulf of Mexico Basin).

(2) Pending demonstration of the technology and economics for fracturing and producing energy from rock of low permeability, the reservoir porosity and permeability must be sufficiently high to allow production of large quantities of thermal water.

(3) Since a major cost in geothermal development is drilling and since costs per meter increase with increasing depth, the shallower the concentration of geothermal energy the better.

(4) Geothermal fluids can be transported economically by pipeline on the Earth's surface only a few tens of kilometres, and thus any generating or direct-use facility must be located at or near the geothermal anomaly.

The table below lists the basic technologies normally utilised according to resource temperature.

Table 5.1. Basic technologies utilised for geothermal exploitation

Reservoir Temperature	***Reservoir Fluid***	***Common use***	***Technology commonly chosen***
High Temperature (>220°C)	Water or Steam	Power Generation	• Flash Steam • Combined (Flash & Binary) Cycle
		Direct Use	• Direct Fluid Use • Heat Exchangers • Heat Pumps
Intermediate Temperature (100-220°C)	Water	Power Generation	• Binary Cycle
		Direct Use	• Direct Fluid Use • Heat Exchangers • Heat Pumps
Low Temperature (50-150°C)	Water	Direct Use	• Direct Fluid Use • Heat Exchangers • Heat Pumps

5.1.4.1. Power generation

The use of geothermal energy for electric power generation has become widespread because of several factors. Countries where geothermal resources are prevalent have desired to develop their own resources in contrast to importing fuel for power generation. In countries where many resource alternatives are available for power generation, including geothermal, geothermal has been a preferred resource because it cannot be transported for sale, and the use of geothermal energy enables fossil fuels to be used for higher and better purposes than power generation.

Also, geothermal steam has become an attractive power generation alternative because of environmental benefits and because the unit sizes are small (normally less than 100 MW). Moreover, geothermal plants can be built much more rapidly than plants using fossil fuel and nuclear resources, which, for economic purposes, have to be very large in size. Electrical utility systems are also more reliable if their power sources are not concentrated in a small number of large units. The process used for generating power varies in accordance with the characteristics of the geothermal resource.

Almost all resources discovered to date are of the hydrothermal type (pressurized hot water), which can be produced from a well by two methods. If the temperature of a hydrothermal resource is below 204°C, a geothermal well can be produced with a pump, which maintains sufficient pressure on the geothermal brine to keep it as pressurized hot water. For hydrothermal resources over 204°C, the most suitable method of production is to flow the wells naturally, yielding a flashing mixture of brine and steam from the wells.

5.1.4.2. Direct use

Equally important worldwide is the direct use of geothermal energy, often at reservoir temperatures less than 100°C. Geothermal energy is used directly in a number of ways: to heat buildings (individual houses, apartment complexes, and even whole communities), to cool buildings (using lithium bromide absorption units), to heat greenhouses and soil, and to provide hot or warm water for domestic use, for product processing (for example, the production of paper), for the culture of shellfish and fish, for swimming pools, and for therapeutic (healing) purposes.

Geothermal resources currently provide directly used heat capacity of over 12,000 MW in over 30 countries worldwide. In Europe, major localities where geothermal energy is directly used include Iceland (30% of net energy consumption, primarily as domestic heating), the Paris Basin of France (where 60-70°C water is used in district heating systems for the communities of Melun, Creil, and Villeneuve la Garenne), and the Pannonian Basin of Hungary.

5.2. ELECTRICITY PRODUCTION METHODS

5.2.1. Fundamentals

There are basically three types of geothermal plants used to generate electricity. The type of plant is determined primarily by the nature of the geothermal resource at the site. The process of generating electricity from a low temperature geothermal heat source (or from steam in a conventional power plant) involves a process known as Rankine Cycle. The cycle, as illustrated in figure 5.3, includes a boiler, the turbine, generator, condenser, feed water pump, cooling tower and cooling water pump.

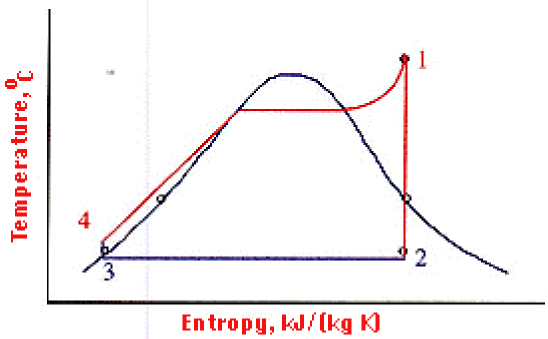


Figure 5.3. The T-s diagram of the Rankine cycle

Saturated or superheated steam enters the turbine at state 1, where it expands isentropically to the exit pressure at state 2. The steam is then condensed at constant pressure and temperature to a saturated liquid, state 3. The heat removed from the steam in the condenser is typically transferred to the cooling water. Then the saturated liquid flows through the pump which increases the pressure to the boiler pressure (state 4), where the water is first heated to the saturation temperature, boiled and typically superheated to state 1. Then the whole cycle is repeated.

Summarizing, a power plant is simply a cycle that facilitates the conversion of energy from one form to another. Although the energy content of the final product (electricity) is normally expressed in units of watts-hours or kilowatt-hours (kWh), calculations of plant performance are often done in units of BTU's (1 kWh is the energy equivalent of 3413 BTU). One of the most important determinations about a power plant is how much energy input (fuel) is required to produce a given electrical output. To make this calculation, it is necessary to know the efficiency of the power plant.

5.2.2. Dry steam process

This was the first type of geothermal power plant (in Italy in 1904). These plants use the steam as it comes from the hydrothermal production wells in the ground (without the necessity of any separation and brine injection equipment), and direct it into the turbine/generator unit to produce power. The steam turns the turbine to generate electricity and is then condensed and returned to the geothermal reservoir via an injection well.

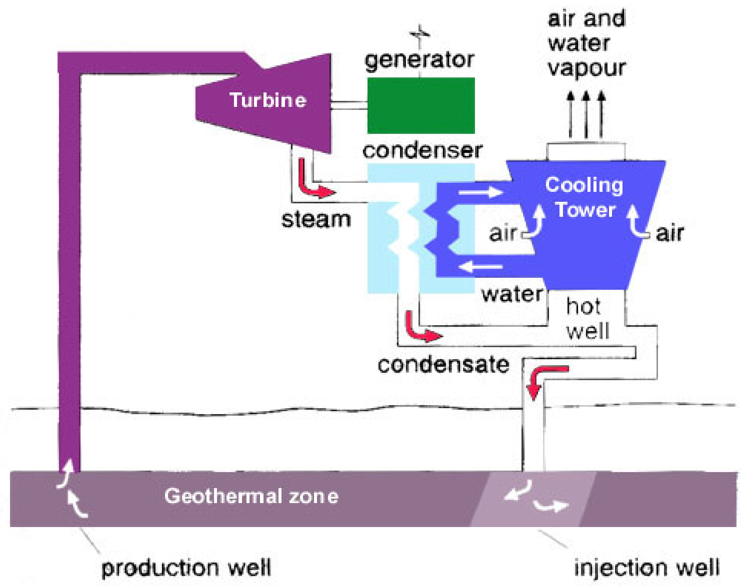


Figure 5.4. Schematic diagram of a dry steam power plant process

This type of plant is illustrated in figure 5.4. Recent direct steam plants in the U.S., at the Geysers in northern California, which is the world's largest single source of geothermal power, have been installed in capacities of 55 and 110 MW. Unfortunately, steam resources are the most rare of the all-geothermal resources and exist in only a few places in the world. Obviously steam plants would not be applied to low-temperature resources.

5.2.3. Steam flash process

The most common process is the steam flash one, which incorporates steam separators to take the steam from a flashing geothermal well and passes the steam through a turbine that drives an electric generator. More specifically, a flash steam power plant (figure 5.5) draws hot water from a hydrothermal production well to a flash tank where a drop in pressure "flashes" the water to steam. The steam turns a turbine/ generator that generates electricity, then is condensed and, with any hot water not flashed to steam, returned to the geothermal reservoir via an injection well.

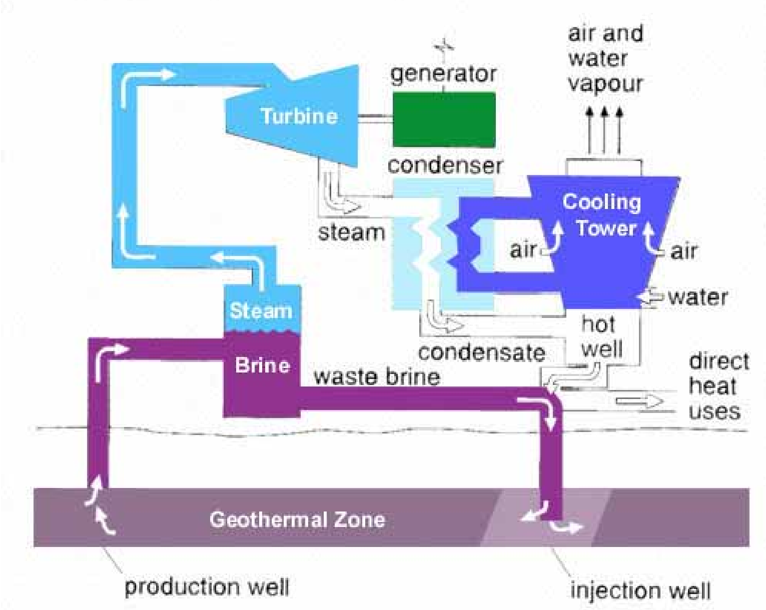


Figure 5.5. Schematic diagram of a flash steam power plant process

Depending on the temperature of the resource, it may be possible to use two stages of flash tanks. In this case, the water separated at the first stage tank is directed to a second stage flash tank where more (but lower pressure) steam is separated. Remaining water from the second stage tank is then directed to disposal. The so-called double flash plant delivers steam at two different pressures to the turbine. Again, this type of plant cannot be applied to low-temperature resources.

For the greatest efficiency in this process, a double-entry turbine is utilized which enables the most amount of steam available in the production from the geothermal well to be converted to electric power. If the resource has a high level of suspended and dissolved solids, it may be necessary to incorporate scaling control equipment in the steam flash vessel at the front of the plant and solids-settling equipment at the tail end of the plant. This will keep the process equipment from becoming plugged and allows a clean residual brine to be maintained for re-injection into the reservoir.

If there are significant amounts of non-condensable gases, it may be necessary to install equipment to eject these gases out of the condenser to keep the back pressure on the system from rising and thereby cutting down on the efficiency of the process. Typically, flash condensing geothermal power plants vary in size from 5 MW_e to over 100 MW_e.

Depending on the steam characteristics, gas content, pressures, and power plant design, between 6 and 9 tonne of steam each hour is required to produce each MW of electrical power. Small power plants (less than 10 MW) are often called wellhead units as they only require the steam of one well and are located adjacent to the well on the drilling pad in order to reduce pipeline costs. Often such wellhead units do not have a condenser, and are called backpressure units. They are very cheap and simple to install, but are inefficient (typically 10-20 tonne per hour of steam for every MW of electricity) and can have higher environmental impacts.

5.2.4. Binary process

A more efficient utilization of the resource can be obtained by using the binary process on resources with a temperature less than 180°C. This process is normally used when wells are pumped, and is schematically shown in fig. 5.6. The pressurized geothermal brine yields its heat energy to a second fluid in heat exchangers (called boilers or vaporizers) and is re-injected via an injection well into the reservoir. In some plants, two heat exchangers in series, the first a pre-heater and the second a vaporizer (evaporator), are used.

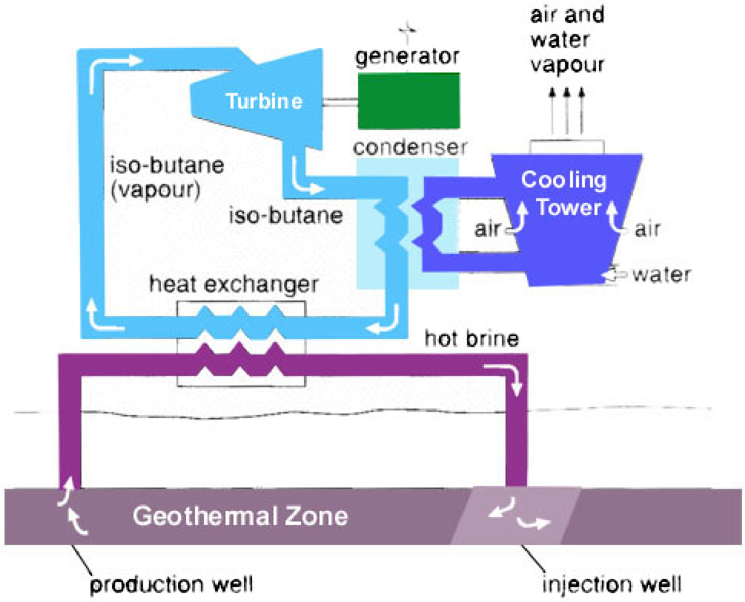


Figure 5.6. Schematic diagram of a binary cycle power plant process

The second fluid (commonly referred to as the power fluid) has a lower boiling temperature than the geothermal brine and therefore becomes a vapour on the exit of the heat exchangers. It is separately pumped as a liquid before going through the heat exchangers. The vaporized, high-pressure fluid then passes through a turbine that drives an electric generator. The vapour exhaust from the turbine is then condensed in conventional condensers and is pumped back through the heat exchangers. There is a distinct environmental advantage to this process since both the geothermal brine and power fluid systems are closed from the atmosphere.

Past working fluids in low temperature binary plants were CFC (Freon type) refrigerants. Current machines use hydrocarbons (isobutane, pentane, etc.) of HFC type refrigerants with the specific fluid chosen to match the geothermal resource temperature. The binary cycle is the type of plant that should be used for low temperature geothermal applications. Currently, off-the-shelf binary equipment is available in modules of 200 to 1,000 kW.

5.2.5. Combined or hybrid plants

Combined cycle power plants are usually a combination of conventional steam turbine technology and binary cycle technology. By combining both technologies, higher overall utilisation efficiencies can be gained, as the conventional steam turbine is more efficient at generation of power from high temperature steam, and the binary cycle from the lower temperature separated water. In addition, by replacing the condenser-cooling tower cooling system in a conventional plant by a binary plant, the heat available from condensing the spent steam after it has left the steam turbine can be utilised to produce more power.

Thus, the following hybrid or combined plants can be designed:

- Direct-steam/Binary plants;
- Single-flash/Binary plants;
- Integrated single- and double-flash plants;
- Hybrid fossil-geothermal systems.

A number of such plants have been built in the USA, Philippines and New Zealand with plant sizes ranging between 10 and over 100 MW_e. Efficiencies of such plants in terms of the power generated for the total fluid flow (both steam and water) produced by the wells are significantly higher than conventional plants, mainly due to the extra power generated by utilising the heat in the brine.

5.2.6. Power-plant performance

The modern approach for measuring the performance of energy systems is to use the 2nd Law of Thermodynamics as the basis for the assessment. The concept of available work or energy has been widely used for this purpose. Geothermal power plants are an excellent illustration of the application of the Second Law (or utilization) efficiency η_u. Since geothermal plants do not operate on a cycle, but instead as a series of processes, the cycle thermal efficiency η_{th} for conventional plants does not apply.

The only case where the cycle thermal efficiency η_{th} can be meaningfully applied to geothermal power plants is the case of binary plants. However, even then the thermal efficiency must be used solely to assess the closed cycle involving the secondary working fluid and not the overall operation involving the flow of the geo-fluid from the production wells, through the plant, and ultimately to the fluid disposal system. The utilization efficiency η_u measures how well a plant converts the exergy (or available work) of the resource into useful output.

For a geothermal plant, the utilization efficiency is found as follows:

$$\eta_u = \frac{\dot{W}}{\dot{m}e} \tag{5.1}$$

where $\dot{W}$ is the net electric power produced, $\dot{m}$ the required total geo-fluid mass flow rate, and e the specific energy of the fluid under reservoir conditions, given by:

$$e = h(P_1,T_1) - h(P_0,T_0) - T_0\,[s(P_1,T_1) - s(P_0,T_0)] \tag{5.2}$$

The specific enthalpy h, and entropy s are evaluated at reservoir conditions, P_1 and T_1, and at the so-called "dead state", P_0 and T_0. The latter correspond to the local ambient conditions at the plant site. In practise, the design wet-bulb temperature may be used for T_0 (in absolute degrees) when a wet cooling system is used, while the design dry-bulb temperature may be used when an air-cooled condenser is used.

Direct-steam plants operate at quite impressive efficiencies based on exergy, typically between 50-70%, while binary cycle plants present a greater range of efficiencies (15 to 50%). All that have been discussed up to now are referred to the "gross" plant efficiency, but in all plants there are electrical loads (e.g. for fans, pumps, and controls) necessary to operate the facility, which are often referred to as "parasitic loads". The "net" plant efficiency incorporates the consumption of these devices to arrive at the performance of the plant in terms of net power output actually available to the owner for use or sale.

5.2.7. Geothermal small and mini-grid power generation

Power plants as small as 100 kW, but commonly 1-5 MW, may provide distributed generation on larger grids or they may be a major generation source for smaller power grids. There is a perception that geothermal power plants are base load stations that operate 24 hours a day and 365 days a year, but this is not necessarily the case. Indeed geothermal power plants can be designed to follow load demand if necessary such as may be required in mini-grid applications.

Small power plants are usually built using a modular approach that reduces site construction costs and can be placed adjacent to the wells so that the overall project has a minimal environmental impact. These plants have played an important role in the development and acceptance of geothermal energy. Opportunities for small geothermal projects exist in many areas of the developing world. Electricity generated from small, local geothermal plants (with less than 5 MW of capacity) could meet many of these needs.

Small power plants would serve these markets almost exclusively in countries where strong government or regional policies promote this application. However, government intervention is frequently needed for such projects because they face special financial and operational challenges associated with their small size. Rural people have pressing energy needs. The key to the success of a small-scale geothermal power plant is not to build a plant of oversized capacity compared to the demand, and to always look for a possibility of integrating a hot water direct use system to improve the plant economy.

The "Kirishima International" hotel in Japan is unique in the use of geothermal energy besides the hot spa bathing, which is the basic function of this resort hotel. It has a small-scale geothermal unit (100 kW) that was built in 1983 and is still in use. It also uses the steam from the wells for space heating and cooling.

Figure 5.7. The small (300 kW) modular binary power plant in Fang, Thailand

CASE STUDY: Mini-grid (< 5MW$_e$)	
Location:	In Fang, Thailand (figure 5.7)
Description:	Since December 1989, thermal fluids have been produced by the Electricity Generating Authority of Thailand (EGAT) from three shallow wells (150 m depth) at the Fang geothermal prospect, at a rate of about 60 tonne/hr (120°C inlet temperature). This energy is used to generate electricity in a 0.3 MW$_e$ ORMAT plant (85-90% availability factor). The preliminary economics study indicated that the electricity generating cost is about 6.3-8.6 c/kWh (1995) based on the assumption of a 5% interest rate and a 90% capacity factor. EGAT also implemented an air conditioning cold storage and crop dryer using exhausted hot water (80°C) from the power plant to demonstrate the downstream utilisation for local people. Now the Food Processing Section of the Royal Recommended Project is constructing a new larger crop dryer using geothermal heat source to preserve products. Meanwhile, the Mae Fang National Park constructed a public bathing pond and a sauna room to serve visitors. The utilisation of geothermal energy at the Fang area is successful, even on a very small scale, and this project is known as the first 'multi purpose project' in Thailand that can be applied to other geothermal resources.

System:	The 300 kW ORMAT plant is a binary module. The 120°C fluid passes through a heat exchanger that heats a secondary working fluid with a boiling point lower than 100°C. This is typically an organic fluid such as Isopentane, which is vaporised and is used to drive the turbine. The organic fluid is then condensed in a shell and tube type condenser. The fluid in a binary plant is recycled back to the heat exchanger and forms a closed loop. The cooled reservoir fluid (80°C) is then used downstream for the air conditioning cold storage and crop dryer.

5.2.8. Geothermal grid-based power generation

High temperature geothermal reservoirs containing water and/or steam can provide steam to directly drive steam turbines and electrical generation plant. More recently developed binary cycle power plant technologies enable more of the heat from the resource to be utilised for power generation. A combination of conventional flash and binary cycle technology (combined cycle) is becoming increasingly popular. Power plants with generation units up to 100 MW in size are connected to national power grids and usually operated in a base load mode, operating at full capacity 365 days of the year. This type of generation is widespread in Indonesia and the Philippines.

Figure 5.8. The power plant of Kamojang geothermal field, Java, Indonesia

CASE STUDY: Grid Connected Power Generation	
Location:	Kamojang Geothermal Field, Java, Indonesia (figure 5.8)
Description:	The Kamojang geothermal field is located in west Java, Indonesia. The Dutch discovered this field in 1920 during the colonization period. Initial exploration was initiated in 1973 by the cooperative work between the Government of Indonesia and the Government of New Zealand. The field was the first operational Indonesian geothermal field and has been commercially operating and producing reliable electricity since 1983. The Kamojang field is currently producing 140 MW_e. The Kamojang geothermal field is located within protected forest, productive forest and nature reserve forest. Environmental studies show that the geothermal activities have not had any significant impact on the natural ecosystem.
System:	Three Mitsubishi condensing turbine units of 1x30 MW_e and 2x55 MW_e have been used. These are supplied with steam from 26 wells at an

	average optimum wellhead pressure of about 15 bars to feed 6.5 bar inlet pressure of the turbines. The 30 MW turbine has been producing electricity since 1983 and the 2x55 MW units since 1987. The generated electricity is connected to 150 kV transmission delivered to the Bandung grid system. The turbines show high reliability with an average capacity, availability and load factors of 85%, 90% and 97.5% respectively, even though each turbine requires an overhaul job every year to remove silica deposit within turbine blades. Reservoir simulation studies indicate that the present proven resource is capable of supplying 140 MW_e until the year 2021 corresponding to a 38-year life for Unit I (30 MW) and a 34-year life for Units II & III (55 MW each).

5.3. GEOTHERMAL POWER PROJECT DEVELOPMENT PROCESS

As is the case with all projects of significant size, geothermal projects are developed through a series of logical stages, which may be summarised in the Geothermal Development Flow Chart, presented in figure 5.9. Decisions to proceed to the next stage are normally made progressively throughout the project.

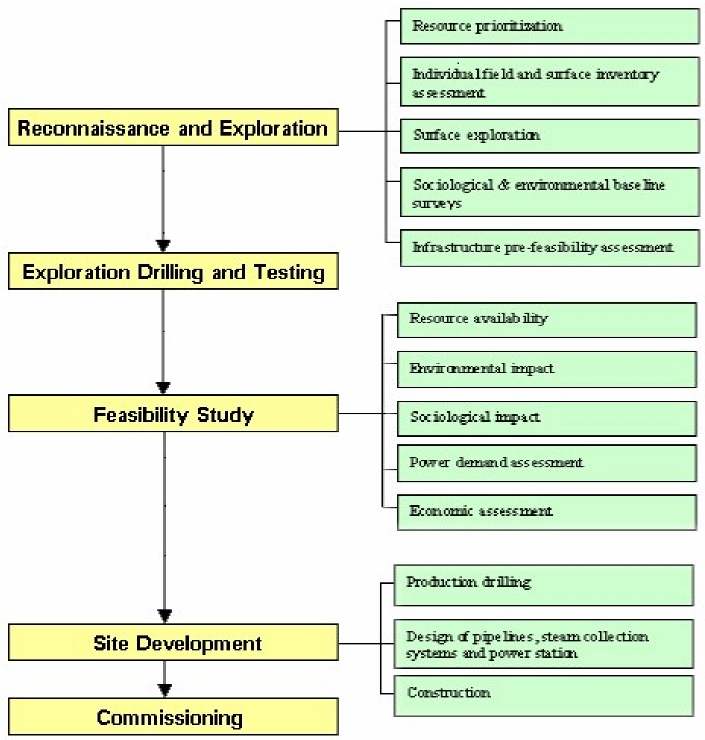


Figure 5.9. Geothermal development flow chart

5.3.1. Reconnaissance and exploration

5.3.1.1. Studies and techniques

Geothermal resources are usually located and defined by a progressively more intensive (and expensive) exploration programme that starts at a regional level and eventually results in a drilling program to positively delineate the resource.

Reconnaissance surveys will identify the most suitable prospect areas by recognition of favourable geological settings and locating any hot springs or other surface thermal discharge. Reconnaissance studies involve mapping any hot springs or other surface thermal features and the identification of favourable geological structures.

The chemical composition of the discharging fluids reveals information about the deeper reservoir, including temperature and fluid characteristics. Geological studies provide information about the probable distribution and extent of aquifers, as well as the likely heat source and heat flow regime. Areas identified as having high potential or that are favoured because of proximity to an energy use centre, will be explored by more comprehensive scientific survey methods.

In addition to more detailed geological and geochemical studies, a range of geophysical techniques may be used including gravity, magnetic and resistivity surveys. Resistivity surveys in particular can locate anomalies that are directly related to the presence of geothermal fluids. Interpretation of these integrated geo-scientific studies leads to prioritisation of targets for exploration drilling programmes. The application of sound scientific method and analysis during these early phases increases the probability of success with subsequent drilling and development.

If these surveys provide very good indications for the presence of a useful geothermal reservoir, the resource is tested by the drilling of exploration wells so that actual subsurface temperatures can be measured and reservoir productivity tested. The exploration programme should therefore be designed to suit the type of resource expected, the amount of energy expected to be produced from the project and the timeframe for the development.

5.3.1.2. Infrastructure

Many geothermal prospects are located in remote sites and frequently in active volcanic areas in developing nations. As such, the infrastructure requirements may be very extensive and, most probably, costly. This can include roading, bridges, port facilities and communications, while if development occurs then power reticulation costs may be very high.

5.3.2. Exploration drilling

The results of the various geo-scientific survey activities described above lead in the majority of geothermal development projects to an exploration-drilling phase. Geothermal wells, whether exploration or production, are drilled using rotary drilling technologies adopted largely from the oil industry, and to a lesser extent from water and mineral exploration. These have been modified to cater for the significantly higher temperatures and rock formation characteristics encountered.

Typically, geothermal wells are drilled to depths ranging from 200 to 1500 metres for low and medium temperature systems, and from around 700 to 3000 metres depth for high temperature systems. Wells are drilled in a series of stages, with each stage being of smaller diameter than the previous stage, and each being secured by steel casings, which are cemented in place prior to drilling the subsequent stage. The final production section/s of the well are secured by an un-cemented, perforated liner. The design of a typical geothermal well may be vertical (straight) or deviated.

The objectives of this phase are to prove the existence of an exploitable resource and to delineate the extent and the characteristics of the resource. An exploration-drilling programme may include shallow temperature gradient wells, 'slim-hole' exploration wells, and production sized exploration/production wells. The size and objective of the development will determine the number and type of wells to be included in this programme.

Temperature gradient wells are often drilled to depths ranging from 2 metres to 200 metres in depth (on rare occasions to 500 metres in depth) and from 50 mm to 150mm in diameter. Exploration wells can range from 200 metres to 3000 metres depth, with bottom-hole diameters of 100 mm to 220 mm. These wells must be drilled with a drilling rig fully equipped to operate in conditions of high temperature and resource pressures.

An exploration well drilling strategy will generally involve drilling from three to five wells depending on the size of the planned development. Typical costs for 'slim-hole' wells range from US$250 to $1000 per metre of depth – this means an amount of US$450,000 to $1,000,000 for a 1500 m deep well. For larger developments these wells will be drilled vertically or directionally deviated from individual drilling pads, while smaller projects may utilise one drilling pad and directionally deviated wells.

5.3.3. Feasibility study

Detailed resource assessments and feasibility studies integrate the information from surface surveys and well results to evaluate the sustainable production capacity of a reservoir using available development technology. Other studies should include estimates of:

- infrastructure costs,
- power demand,
- related engineering costs for site preparation, installation and commissioning,
- related environmental and sociological programmes and costs,
- required roading, buildings and services,
- reticulation and connection to grids.

The preliminary design of steam collection systems and pipelines, as well as the selection of power plant technologies, size, design and cost, should also consist part of this phase.

The cost of a geothermal power plant is heavily weighted to the early expenses. Well drilling and pipeline construction begin before power plant construction, and resource information from drilling is necessary for designing the power plant. The final field development is completed together with the power plant. The costs associated with building and operating a geothermal power plant vary widely and depend on several factors, such as:

- resource type (steam or hot water);
- resource temperature;
- reservoir productivity;
- power plant size (rating);
- power plant type (single-flash, binary, etc.);
- environmental regulations;
- cost of capital;
- cost of labour.

The first three factors influence the number of wells that must be drilled for a given plant capacity. Using typical costs and power potential for production wells, a single well can cost $100-400/kW. The next three items determine the capital cost of the energy conversion system, whereas the last two affect the cost of running the plant, i.e. debt service, and operation and maintenance (O&M). The influence of resource temperature and power rating on plant costs for small-size binary units are summarized in table 5.2.

Table 5.2. Capital and O&M costs for small binary cycle geothermal plants (1993$)
[Source: DiPippo, 1998]

Net Power (kW)	Resource Temperature (°C)			Total O&M Cost ($/year)
	100	120	140	
	Capital Cost ($/kW)			
100	2,535	2,210	2,015	19,100
200	2,340	2,040	1,860	24,650
500	2,145	1,870	1,705	30,405
1,000	1,950	1,700	1,550	44,000

Capital costs per kW vary inversely with temperature and rating, while annual O&M costs (covering a range from 1.5 cents to 4.5 cents per kWh produced) increase with rating but are independent of the fluid temperature (over the range presented in the table). These costs are favourable when compared to other renewable energy sources, and are absolutely favourable for remote locations where electricity is usually generated by diesel engines.

The operating and maintenance costs for geothermal power plants depend also on the contract price for the electricity. That is, the higher priced electricity makes it worthwhile to keep the power plant working as close to 100% of the time as possible, and higher maintenance costs are then justified. Most geothermal power plants have availability factors over 90% (i.e. they can produce electricity over 90% of the time), but getting availability factors up to 97 or 98% can be much more expensive.

The three most influential parameters as regards the cost of electricity produced are the plant size, the resource temperature and the production well depth. Evidently, this cost decreases with increasing values of the first two of the above parameters, while it increases (almost linearly) with the increment of the depth of the production well. The typical unit cost of power from geothermal plants, based upon a discount rate of 10%, is shown in table 5.3 below, where capacity factor of 90% has been assumed. These costs are based upon projects constructed in developing countries.

Table 5.3. Unit cost of power (in US c/kWh) from three main types of geothermal plants

	High Quality Resource	*Medium Quality Resource*	*Low Quality Resource*
Small plants (<5 MW)	5.0 - 7.0	5.5 - 8.5	6.0 - 10.5
Medium Plants (5-30 MW)	4.0 - 6.0	4.5 - 7.0	Not suitable
Large Plants (>30 MW)	2.5 - 5.0	4.0 - 6.0	Not suitable

With the unit cost of diesel generation at least 10c/kWh and up to 20c/kWh, geothermal generation is a very attractive option, especially in remote, off-grid areas and small islands, where diesel generation is often the only alternative for power generation. Direct use of the low temperature reject water fraction from geothermal power generation can often be attractive. It is advantageous for the power developer to be approached at an early stage to enable any such arrangement to be incorporated into the power plant/steam field designs.

5.3.4. Development

5.3.4.1. Production drilling

On conclusion of a successful exploration phase the commitment to development of an initial production phase of a project may occur immediately or after completion of some longer-term period of resource testing and feasibility studies. A production drilling strategy will be developed using the exploration well and resource data. Drilling targets, hole and casing profiles, and a drilling sequence will result. Well targets are spaced such that interference from one well to another is avoided and are typically such that the production zones of each well are separated by a distance of from 300 to 500 metres.

Obviously, production well sized drilling rigs fully equipped for geothermal are required. Production well design and the drilling process will be very similar to that developed during the exploration phase of the project, as is described above. However, in the case where very high reservoir permeabilities are encountered, large diameter wells may be appropriate. Drilling of such wells is common in vapour dominated reservoirs, such as the Darajat geothermal field in Indonesia.

The cost of drilling production wells is generally as described for the exploration/ production wells above, however, it is normal to see some 'learning curve' reduction in these costs as experience is gained in each field. A large diameter production well is usually around 20% more expensive to drill than a 'standard' sized well. Depending on the nature of the resource an appropriate number of re-injection wells also will be required.

5.3.4.2. Design of pipelines, steam collection systems and power station

From an integrated assessment of the resources studies, environmental and sociological impacts, the power potential and power demand, a suitably sized generation facility is designed. Information on typical capital costs and operating cost structures are discussed elsewhere. The design must take into account a wide range of factors including the temperature of the resource, chemistry and gas content of the fluid, and suitable size of the plant. Design variables are optimised to ensure that the design solutions chosen are the most cost effective and energy efficient.

5.3.4.3. Construction and commissioning

The implementation (construction) of a geothermal project can be achieved in a number of ways. Traditionally, geothermal projects were developed under a number of separate construction and procurement contracts, with the design and project management being undertaken by consulting engineers. Recently the trend has been away from the multi-contract implementation method to the single turnkey/EPC (Engineering-Procurement-Construction) type. The advantages of this contract is that it allows more room for vendor innovation, reduces cost overrun risks and most importantly, gives a single point responsibility and liability for plant performance.

Often, this type of implementation method is advantageous in being able to attract project funding. An example of an aid-assisted geothermal development constructed under the multi-contract implementation method is the Kamojang power station in west Java, Indonesia (see relevant case study), which was commissioned with a significant aid contribution from New Zealand. More recent geothermal developments in Indonesia, such as Salak and Wayang Windu, however have been constructed using the EPC implementation method.

5.4. ADVANTAGES AND PROBLEMS OF GEOTHERMAL POWER

5.4.1. Worldwide distribution of geothermal utilisation

Humans have used geothermal energy for many centuries in applications such as space and water heating, cooking, and medicinal bathing. The first geothermal power generation plant was constructed in 1904 in Larderello, Italy. This had a capacity of 250kW and used geothermal steam to generate electricity. The second geothermal power station built was in the 1950s at Wairakei, New Zealand, and was followed by The Geysers in California in the 1960s. Currently there are 12,000 MW of direct use and over 8,000 MW of generating capacity in geothermal resources worldwide.

To put geothermal generation into perspective, this generating capacity is about 0.4% of the World total installed generating capacity. The USA, Philippines, Italy, Mexico, Iceland, Indonesia, Japan and New Zealand are the largest users of geothermal (both direct and indirect). Table 5.4 shows the location of present electric power generation from geothermal energy in order of size per country. The 1999 capacity of 8246 MW of electricity was a 40% increase from the capacity installed in 1990.

Table 5.4. World wide installed geothermal power capacity by country

Country	1990 (MW_e installed)	1999 (MW_e installed)
USA	2775	2850
Philippines	891	1848
Italy	545	769
Mexico	700	753
Indonesia	145	590
Japan	215	530
New Zealand	283	345
Iceland	45	140
Costa Rica	0	120
El Salvador	95	105
Nicaragua	70	70
Kenya	45	45
China	19	32
Guatemala	0	29
Turkey	20	20
Total installed electrical generating capacity	**5867**	**8246**

Source: International Geothermal Association (1998), updated with data published in 1999.

Other countries with less than 20 MW generation are: Argentina, Australia Ethiopia, France (Guadeloupe), Greece, Portugal (Azores), Russia, Thailand. The majority of the earlier geothermal plants were funded and operated by National Power agencies around the world with the exception of California, where privately funded utility companies carried out the development of the Geysers geothermal field. With the recent international trend towards de-regulation in the power industry, private developers have become more directly involved in both resource assessment and development. This has been particularly so in Indonesia and the Philippines.

Flash steam plants totally dominate the marketplace, but over the past ten years many smaller scale binary cycle plants have been installed, while several combined (flash steam/binary) plants have also been installed. The majority of the World's geothermal power stations are base load stations meaning that they operate 24 hours a day 365 days. Allowing for a load factor of about 80% and an average steam cost of 5 cents per kWh geothermal power is worth about 3 billion US$ per year.

5.4.2. Competitiveness of geothermal energy

Geothermal energy has been produced commercially on the scale of hundreds of MW for over three decades since it has a number of positive features that make it competitive with conventional energy sources and some renewable sources. These features include:

- it is a local energy source that can reduce demand for imported fossil fuels;
- it has a large positive impact on the environment by displacing combustion of fossil fuels;
- it is efficient and competitive with conventional sources of energy;
- geothermal plants can operate continuously, without constraints imposed by weather conditions, unlike other renewable sources;
- it has an inherent storage capability and is best suited to base-load demand;
- it is a reliable and safe energy source which does not require storage or transportation of fuels.

Moreover, the more recent generation of geothermal power plants emits on average only 136gr of carbon dioxide per kWh of electricity generated compared to the 453gr/kWh of CO_2 for a power plant fuelled by natural gas or 1,042 gr/kWh of CO_2 for a coal fired power plant. The bar chart below (fig. 5.10) shows a comparison of sulfur dioxide (SO_2 - a primary cause of acid rain) and carbon dioxide (a greenhouse and global climate-change gas) emissions between coal- and oil-fired power plants, and a geothermal power plant with and without waste gas injection back into the ground.

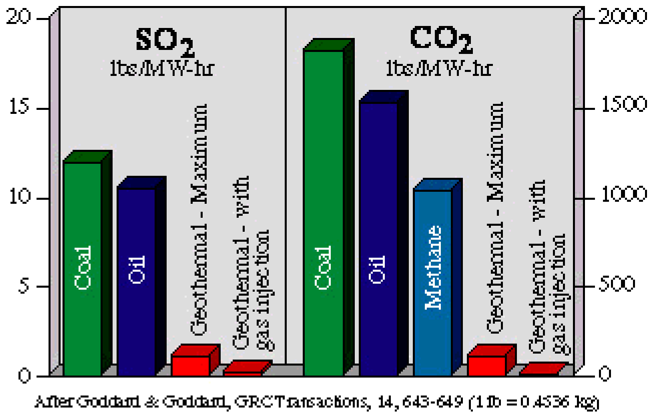


Figure 5.10. Emissions comparisons for various fuels powered power plants

At present, the renewable energy sources with the greatest potential and the lowest emissions in Europe, in the short to medium term, are hydropower and geothermal energy. In this respect, it should be noted that the capacity factors for hydro and geothermal in Europe is now more than 70%, whereas 20-35% are typical values for solar and wind. The availability factor of geothermal energy, expressed as the percentage of time the rated energy may be produced, depends mainly on the nature of the resource and secondarily on the availability of the equipment.

Experience shows that the availability is often over 90% for geothermo-electric power plants. The bar chart of figure 5.11 shows a comparison of the percentages of time, on average, that geothermal, coal, and nuclear power plants are available to generate electricity (i.e. the availability factor). Under these circumstances, the plant factor expressed as the percentage of time the plant actually produces energy is almost equal to the availability factor.

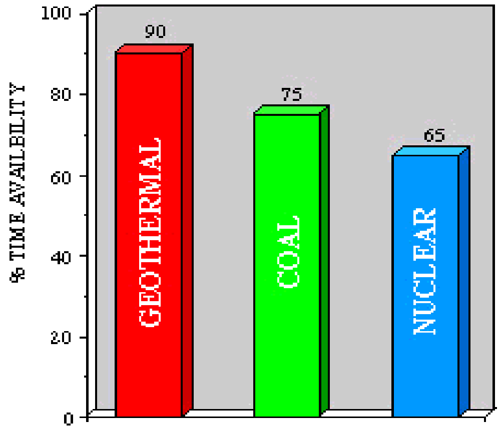


Figure 5.11. Availability factors for three types of power plants

Taking the above factors into consideration, only an increase in the use of biomass, hydro and geothermal energy can realistically influence the level of greenhouse gas emissions in Europe over the next 5 to 10 years for total energy use. These technologies can displace considerably more greenhouse gas emissions than any contribution from the foreseeable increase in utilisation levels from other renewables. Wind energy could make a significant contribution by 2005 and is growing rapidly.

Both high and low enthalpy geothermal power plants can be implemented in modular units. This approach reduces the initial capital outlay and spreads investment, while it also enables the availability of the resource to be evaluated before full-scale operation commences and allows revenue generation at the earliest possible opportunity, thereby improving the overall scheme financial performance and reducing exposure to geological or mining risk.

Costs, therefore the economic viability of geothermal energy schemes, are in reality strictly dependent on site-specific conditions and the type of application. It should be emphasised that the electricity generation cost is most sensitive to the specific cost of drilling wells and individual well productivity which varies considerably between different countries. The variability of technical and economic parameters involved in the implementation of geothermal projects (the specific field cost plus the plant cost) means that each geothermal project will invariably have a unique production cost and no broad generalisation is possible.

The overall competitiveness of geothermal energy is also determined by comparison with both conventional and other renewable energy sources. Usually the cost of energy is based upon standard economic and financial analyses. The funding of geothermal projects by the main international financing agencies are currently based on strict application of a least-cost analysis as part of their procedure for granting loans for energy projects.

It should be stressed that in Europe, at present, the low cost of fossil fuels, especially natural gas, makes only the best geothermal resources competitive from a strict financial comparison. Nevertheless, geothermal energy could become more competitive compared with conventional sources of energy if the comparison is not limited exclusively to strict financial criteria, but also takes account of other factors such as shadow costs and their economic consequences (known as "externalities").

The related *external costs* of conventional generation become *external benefits* in the case of geothermal resources (similar to other renewable sources), and are a parameter that substantially changes the level of the competitiveness in favour of geothermal energy. These external benefits can be quantified in monetary terms and should be an acknowledged factor for comparative purposes. If externalities are included among the investment parameters, the full social and economic benefits can be realised. However, this may require public incentives to ensure that successful investment in geothermal energy is possible.

The acquaintance to the investor of this "added value" should not be regarded as a subsidy but looked on as a realignment of the economic benefits that arise from the project. The external cost of traditional fuels has been estimated to be almost 10 times higher than the corresponding cost of renewables and almost 50% of the overall economic cost (against 1% for the renewable sources case). Quantification of externalities is a crucial aspect if geothermal energy is to be fairly evaluated, and also avoids penalising projects evaluated purely on the basis of a cash flow analysis.

5.4.3. Production and pollution problems

The major problems in producing geothermal power involve mineral deposition, changes in hydrological conditions, and corrosion of equipment. Pollution problems arise in handling geothermal effluents, both water and steam.

5.4.3.1. Mineral deposition

In some water-dominated fields there may be mineral deposition from boiling geothermal fluid. For example, silica deposition in wells caused problems in the field of Salton Sea, California. More commonly, calcium carbonate scale formation in wells or in the country rock may limit field developments, for example, in Turkey and the Philippines. Fields with hot waters high in total carbonate are now regarded with suspicion for simple development. In the disposal of hot wastewaters at the surface, silica deposition in flumes and waterways can be troublesome.

5.4.3.2. Hydrological changes

Extensive production from wells changes the local hydrological conditions. Decreasing aquifer pressures may cause boiling water in the rocks (leading to changes in well fluid characteristics), encroachment of cool water from the outskirts of the field, or changes in water chemistry through lowered temperatures and gas concentrations. After an extensive withdrawal of hot water from rocks of low strength, localized ground subsidence may occur (up to several meters) and the original natural thermal activity may diminish in intensity.

Some changes occur in all fields, and a good understanding of the geology and hydrology of a system is needed so that the well withdrawal rate can be matched to the well's long-term capacity to supply fluid.

5.4.3.3. Corrosion

Geothermal waters cause an accelerated corrosion of most metal alloys, but this is not a serious utilization problem except, very rarely, in areas where wells tap high-temperature acidic waters (for example, in active volcanic zones). The usual deep geothermal water is of near-neutral pH. The principal metal corrosion effects to be avoided are sulphide and chloride stress corrosion of certain stainless and high-strength steels and the rapid corrosion of copper-based alloys. Hydrogen sulphide, or its oxidation products, also causes a more rapid degradation than normal of building materials, such as concrete, plastics, and paints.

5.4.3.4. Pollution

A high noise level can arise from unsilenced discharging wells (up to 120 decibels adjusted), and well discharges may spray saline and silica-containing fluids on vegetation and buildings. Good engineering practice can reduce these effects to acceptable levels. Because of the lower efficiency of geothermal power stations, they emit more water vapour per unit capacity than fossil-fuel stations. Steam from wellhead silencers and power station cooling towers may cause an increasing tendency for local fog and winter ice formation.

Geothermal effluent waters liberated into waterways may cause a thermal pollution problem unless diluted by at least 100:1. Geothermal power stations may have four major effluent streams. Large volumes of hot saline effluent water are produced in liquid-dominated fields. Impure water vapour rises from the station cooling towers, which also produce a condensate stream containing varying concentrations of ammonia, sulphide, carbonate, and boron. Waste gases flow from the gas extraction pump vent.

Geothermal steam supplies differ widely in gas content (often 0.1-5%). The gas is predominantly carbon dioxide, hydrogen sulphide, methane, and ammonia. Venting of hydrogen sulphide gas may cause local objections if it is not adequately dispersed, and a major geothermal station near communities with a low tolerance to odor may require a sulphur recovery unit (such as the Stretford process unit).

Sulphide dispersal effects on trees and plants appear to be small. The low radon concentrations in steam (3-200 nanocuries/kg or 0.1-7.4 kilobecquerels/kg), when dispersed, are unlikely to be of health significance. The mercury in geothermal stream (often 1-10 microgram/kg) is finally released into the atmosphere, but the concentrations created are unlikely to be hazardous.

The compositions of geothermal waters vary widely. Those in recent volcanic areas are commonly dilute (<0.5%) saline solutions, but waters in sedimentary basins or active volcanic areas range upward to concentrated brines. In comparison with surface waters, most geothermal waters contain exceptional concentrations of boron, fluoride, ammonia, silica, hydrogen sulphide, and arsenic. In the common dilute geothermal waters, the concentrations of heavy metals such as iron, manganese, lead, zinc, cadmium, and thallium seldom exceed the levels permissible in drinking waters.

However, the concentrated brines may contain appreciable levels of heavy metals (parts per million or greater). Because of their composition, effluent geothermal waters or condensates may adversely affect potable or irrigation water supplies and aquatic life. Ammonia can increase weed growth in waterways and promote eutrophication, while the entry of boron to irrigation waters may affect sensitive plants such as citrus. Small quantities of metal sulphide precipitate from waters, containing arsenic, antimony, and mercury, can accumulate in stream sediments and cause fish to derive undesirably high (over 0.5 ppm) mercury concentrations.

5.4.3.5. Re-injection

The problem of surface disposal may be avoided by re-injection of wastewaters or condensates back into the countryside through disposal wells. Steam condensate re-injection has few problems and is practiced in Italy and the United States. The much larger volumes of separated waste hot water (about 55 tons or 50 metric tons per MW_e) from water-dominated fields present a more difficult re-injection situation.

Silica and carbonate deposition may cause blockages in rock fissures if appropriate temperature, chemical, and hydrological regimes are not met at the disposal depth. In some cases, chemical processing of brines may be necessary before re-injection. Selective re-injection of water into the thermal system may help to retain aquifer pressures and to extract further heat from the rock. A successful water re-injection system has operated for several years at Ahuachapan, El Salvador.

5.4.4. The future for geothermal energy

Forecasts regarding geothermal energy development are closely linked to evolutions in the price of oil. Even if the last few years have shown that the sector can progress in a context of low barrel prices, the impact of this factor remains a determinant one. Furthermore, oil fluctuations are very difficult to foresee. This is why experts have developed two different scenarios for the future. The first projection recuperates a relatively low oil price for the year 2005 and the year 2010. The second projection counts on an increase in barrel price that should favour development of renewable energies and so geothermal installations.

In the case of the second scenario, installed capacities could reach 32 250 MW_e for electricity production and 69 500 MW_{th} for direct use. In light of current figures, this forecast represents a four-fold increase for the two sectors. However, these figures must be considered as rough estimates and in no case as precise figures. This is because, beyond the impact of the price of fossil fuel resources, the level of proven geothermal reserves is also a preponderant factor. The knowledge of planet Earth is still, in both the literal and the figurative meanings of the word, “superficial”. New deposits as well as new technologies could appear and totally modify trends that may have been observed up until then.

In the short to medium term, it is likely that hydrothermal resources will remain the only geothermal resource that is commercially viable. This resource alone represents an immense source of energy. It is estimated that 80 GW of geothermal electricity could be generated in the short to medium term from known hydrothermal resources worldwide. In the longer term, technological developments will see the utilisation of the geothermal energy in hot dry rocks and geopressured reservoirs.

These resources represent a virtually limitless source of energy, and are the future of sustainable geothermal energy. For electricity production, there is a group of countries that appear to be the important actors of the geothermal sector of the future. The Philippines, Indonesia and Mexico are among the most dynamic of these countries. On the other hand, it should be noted that the United States probably wouldn’t regain the growth rate that it had during the '80s again. U.S. shall probably lose its leading position to the Philippines.

The European Union is also proposing to develop its capacities. Concerning electricity production, Italy, Portugal and France remain the only sector actors, but are all ambitious to increase their installed capacities. In this way, Italy forecasts reaching 946 MW_e in 2005, Portugal 45 MW_e and France 20 MW_e. These efforts will bring the amount of power put into service in the European Union up to 1,011 MW_e in 2005 and up to 1,200 MW_e by the year 2010. These figures exceed White Paper objectives that target 1,000 MW_e in 2010.

6.1. BIOMASS AS A RESOURCE

6.1.1. Terminology

The world's energy markets rely heavily on the fossil fuels such as coal, petroleum crude oil, and natural gas as sources of energy, fuels, and chemicals. Since millions of years are required to form fossil fuels in the earth, their reserves are finite and subject to depletion as they are consumed. The only other naturally occurring, energy-containing carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass.

“Biomass” is a scientific term for living matter, more specifically any organic matter that has been derived from plants as a result of the photosynthetic conversion process. The word biomass is also used to denote the products derived from living organisms - wood from trees, harvested grasses, plant parts, and residues such as twigs, stems and leaves, as well as aquatic plants and animal wastes. In this sense, fossil fuels, like coal and oil, are in fact fossilised biomass resources.

While the primary uses for biomass are food, paper, lumber, and chemicals, biomass and its by-products can also be used as sources for fuelling many energy needs. Biomass energy or "bioenergy" is stored chemical energy and includes any solid, liquid or gaseous fuel, or any electric power or useful chemical product derived from organic matter, whether directly from plants or indirectly from plant-derived industrial, commercial, or urban wastes, or agricultural and forestry residues. Thus, bioenergy can be derived from a wide range of raw materials and produced in a variety of ways.

The energy value of biomass from plant matter originally comes from solar energy through the process known as photosynthesis [equation (6.1)]. In nature, all biomass ultimately decomposes to its elementary molecules with the release of heat. During conversion processes such as combustion (burning), biomass releases its energy, often in the form of heat, and the carbon is re-oxidised to carbon dioxide to replace that which was absorbed while the plant was growing. Essentially, the use of biomass for energy is the reversal of photosynthesis.

$$CO_2 + 2H_2O \underset{\text{heat}}{\overset{\text{light}}{\longleftrightarrow}} ([CH_2O] + H_2O) + O_2 \qquad (6.1)$$

Unlike fossil fuels, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource. In practice, different terms for the different end uses - e.g. electric power or transportation - are used. The term "biopower" describes biomass power systems that use biomass feedstocks instead of the usual fossil fuels (natural gas or coal) to produce electricity, while the term "biofuel" is used mostly for liquid transportation fuels that substitute for petroleum products, such as gasoline or diesel.

It must be mentioned that, in certain cases (mainly in the U.S.), municipal solid waste (MSW) is not considered as biomass, although MSW is burned in all over the world to generate electric power and heat. This is due to the fact that, although most of the mass of municipal solid waste is derived from plant matter and could be used to fire special power systems, MSW also contains a variety of potentially toxic materials, such as creosote-treated wood, batteries that contain mercury, and other hazardous products.

As a result, MSW power systems must either remove these materials from their feedstocks before burning them, or treat the exhaust very carefully to avoid toxic emissions. "Biopower" plants use only uncontaminated feedstocks. Ordinary biomass contains no toxic chemicals and, when used in modern power systems, produces fewer emissions than conventional fossil fuel fired power plants. This is the reason why the term “wastes” is used in the following for contrast to the “pure” biomass.

6.1.2. Biomass energy cycle

Bioenergy is produced in a cycle. Sustainable use of natural energy flows mimics the Earth's ecological cycles and minimizes the emission of pollutants into the air, rivers and oceans. Most of the carbon to create it is taken from the atmosphere and later returned to the atmosphere. The nutrients to create it are taken from the soil and later returned to the soil. The residues from one part of the cycle form the inputs to the next stage of the cycle. This is schematically presented in figure 6.1.

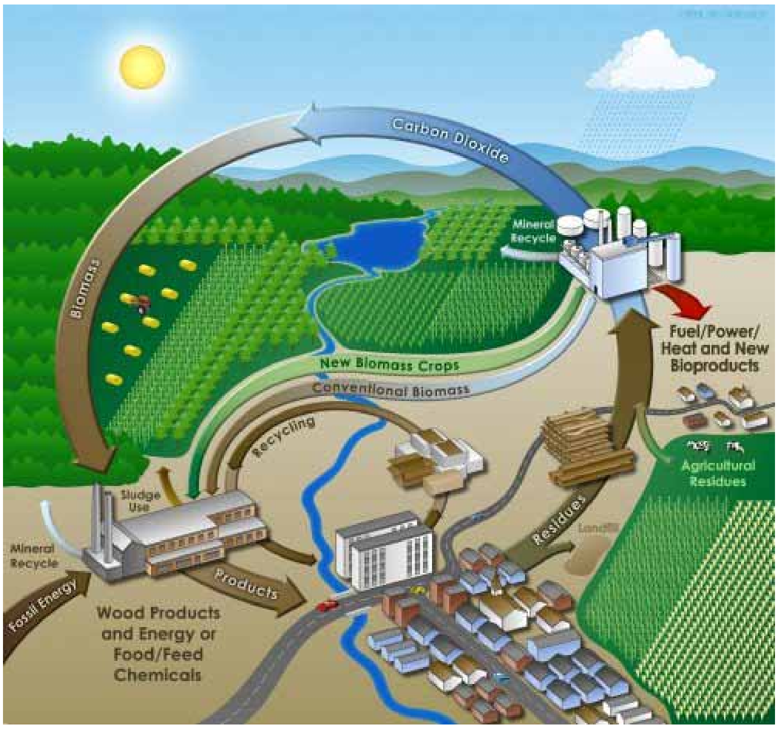


Figure 6.1. Schematic representation of the biomass energy cycle (source: BIN)

Carbon dioxide (CO_2) is withdrawn from the atmosphere by the process of plant growth (photosynthesis) and converted into vegetation biomass (trees, grasses, and other crops). Harvested biomass, together with forestry and crop residues, can be converted into building materials, paper, fuels, food, animal feed and other products such as plant-derived chemicals (waxes, cleaners, etc.). Some crops may be grown for ecological purposes such as filtering agricultural run-off, soil stabilization, and providing habitat for animals as well as bioenergy.

The solid biomass processing facility (represented by the factory building at the bottom left) may also generate process heat and electric power. As more efficient bioenergy technologies are developed, fossil fuel inputs will be reduced. Organic by-products and minerals from the processing facility may be returned to the land where the biomass grew, thereby recycling some of the nutrients such as potassium and phosphorus that were used for plant growth.

Selected residues from the town may be combined with forestry and crop residues, animal wastes, and biomass crops to provide the feedstocks for a different type of biomass processing (represented by the factory at the top right). This new biomass processing facility (or biorefinery) could make a range of products - fuels, chemicals, new bio-based materials, and electric power. Animal feed could be an important co-product of some processes.

Such biomass processing facilities would use efficient methods to minimize waste streams and would recycle nutrients and organic materials to the land, thereby helping to close the cycle. The town at the bottom of the figure represents all the biomass products (food, materials, and energy) used by the human population. The residues from the town (scrap paper and lumber, municipal refuse, sewage, etc.) are subject to materials and energy recovery, and some may be directly recycled into new products.

Throughout the cycle, CO_2 from biomass is released back into the atmosphere - from the processing plants and from the urban and rural communities - with little or no net addition of carbon to the atmosphere. If the growing of bioenergy crops is optimised to add humus to the soil, there may even be some net sequestration or long-term fixation of carbon dioxide into soil organic matter. The energy to drive the cycle and provide for the human population comes from the sun, and will continue for many generations at a stable cost, and without depletion of resources.

6.1.3. Biomass electricity (bio-power)

In many respects electricity from biomass is different from other renewable energies in that the primary energy resource encompasses a variety of feedstocks with wide ranging properties. To generate power from biomass two systems of a quite different character need to work together, namely a supply system that produces, collects and delivers the fuel, and a power station that generates (and sells) the electricity. The current and future technologies that can be used in these systems and the way in which the two influence each other are presented in the following paragraphs.

The use of biomass for power generation has increased over the last decade. In the United States, electricity generation from biomass grew by 7 percent each year between 1990 and 1994, reaching 59,000 Gigawatt-hours in 1994. Such growth could result in an industry with a capacity of approximately 30 Gigawatts, producing 150,000 to 200,000 Gigawatt-hours of electricity by 2020. In Europe, biomass energy currently accounts for about 2% of total consumption, and the European Commission predicts that figure will reach 15% in the European Union until 2010.

Unlike renewable-based systems that require costly advanced technology (such as solar photovoltaics), biomass can generate electricity with the same type of equipment and power plants that now burn fossil fuels. Many innovations in power generation with other fossil fuels may also be adaptable to the use of biomass fuels. However, various factors that are described later on have hindered the growth of this renewable energy resource.

Most biomass power plants operating today are characterized by low boiler and thermal-plant efficiencies; both the fuel's characteristics and the small size of most facilities contribute to this. In addition, such plants are costly to build. Today's best biomass-based power plants cost approximately $2,000 per kW of electricity to build, with a thermal efficiency of about 40%, while large coal-fired stations cost about $1,500 per kW, with a thermal efficiency of 45%. Therefore, the main challenge to using biomass for power generation is to develop more-efficient, lower-cost systems.

Advanced biomass-based systems for power generation require fuel upgrading, combustion and cycle improvement, and better flue-gas treatment. Future biomass-based power generation technologies have to provide superior environmental protection at lower cost by combining sophisticated biomass preparation, combustion, and conversion processes with post-combustion cleanup. Such systems include fluidised-bed combustion, biomass-integrated gasification, and biomass externally fired gas turbines.

6.2. BIOMASS FEEDSTOCKS

Biomass feedstocks used, or being considered for use for fuelling power plants usually fall into one of the following four general categories:

- wood (forestry wood, wood residues, and short-rotation coppice);
- agricultural residues, including bagasse (sugar cane waste), olive waste, rice husks (hulls), and straw;
- energy crops (such as miscanthus, reed canary grass, and switch grass);
- waste, including municipal solid waste, refuse-derived fuel, sludge, and manure.

Excluding wastes, the “pure” biomass feedstocks worldwide potential is illustrated in figure 6.2 below (according to the US DoE).

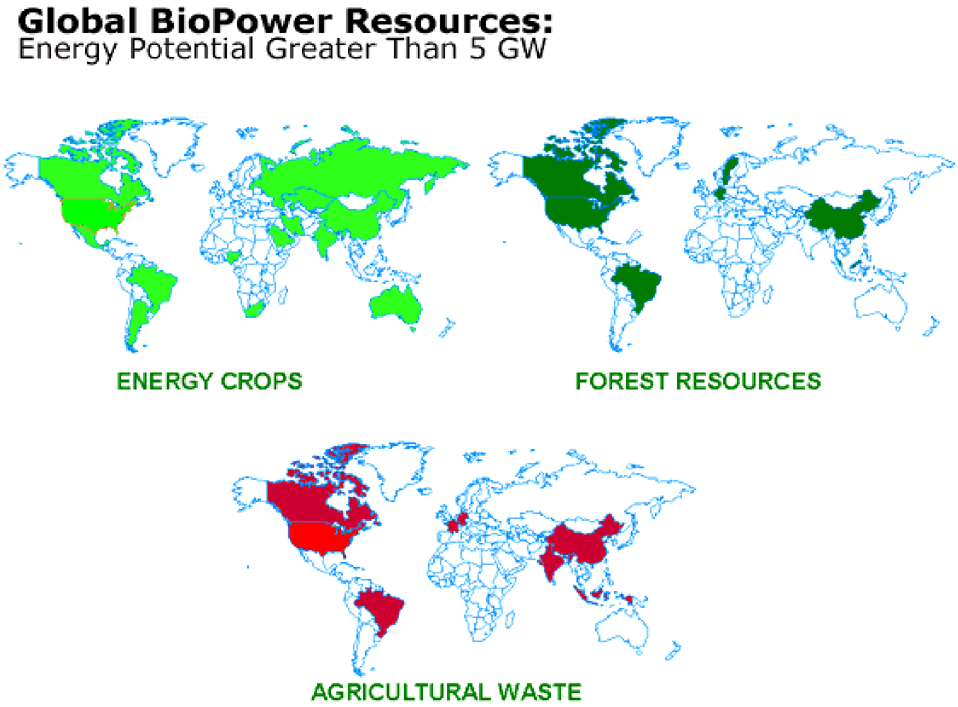


Figure 6.2. Map of geographic distribution of biomass feedstocks

Today, the most economical forms of biomass for generating electricity are residues. These are the organic by-products of food, fibre, and forest production. Common examples used for power are sawdust, rice husks, and bagasse (the residue remaining after juice has been extracted from sugar cane). Low-cost, clean wood waste materials are also common near population and manufacturing centres. Examples are pallet and crate discards and woody yard trimmings. Using biomass residues as a fuel can avoid fossil-fuel purchases while reducing the costs and environmental impacts of disposal.

In the future, larger quantities of biomass feedstocks may be needed to meet a growing demand for electricity. Various institutions worldwide are testing and developing fast growing trees and grasses which could be grown specifically for use as fuels. These "energy crops" will be planted primarily on unused agricultural lands. Developing economic energy crops could greatly increase biomass supplies for power generation. For example, if energy crops were planted on approximately 4% of the land within a radius of 80 km, they could supply a 100 MW biomass power plant with all of its fuel needs.

6.2.1. Wood residues

Wood is the most commonly used biomass fuel for heat and power. The most economic sources of wood fuels are usually wood residues from manufacturers (mill residues), discarded wood products or woody yard trimmings diverted from landfills, and non-hazardous wood debris from construction and demolition activities. Using these materials for electricity generation recovers their energy value while avoiding landfill disposal. Recent studies in U.S. indicate that quantities of available mill and urban wood residues exceed 39 million dry tons per year - enough to supply more than 7,500 MW of new bio-power, or a doubling of the existing capacity in the U.S.

6.2.1.1. Mill residues

Wood residues from pulp and paper manufacturing, lumber mills, and other industrial wood users are frequently used for producing biomass electricity. These residues are typically very clean and can be used as fuel by a wide range of biomass power systems. In many cases, mill residues are used to generate steam and electricity at the site of the manufacturing facility where they are produced.

6.2.1.2. Urban wood residues

Large quantities of urban wood waste are presently landfilled, with post-consumer wood products, broken wood pallets and crates, untreated clean construction and demolition debris as examples. These materials can be diverted from landfill disposal at materials recovery facilities that separate clean wood from other debris (e.g. heavy metals, usually due to paint left in the wood). The clean wood, with moisture content as low as 5%, can then be used productively as biomass fuel and landscaping products.

6.2.1.3. Tree trimmings

Woody yard trimmings are another abundant source of wood presently sent to landfills. Similar material is also generated from right-of-way trimming near roads, railways, and utility systems such as power lines. In some cases these tree limbs and branches are converted to mulch, used in compost, or ground and used for landfill cover; however, they are often wasted. Energy projects can be a steady user of these materials.

6.2.1.4. Forest residues

Forestry waste includes under-utilized logging residues, imperfect commercial trees, dead wood, and other non-commercial trees that need to be thinned from crowded, unhealthy, fire-prone forests. Forest thinning is not only necessary to help some forests regain their natural health, but it will also provide a large supply of wood residues that can be converted to biomass power or biofuels. Because of their sparseness and remote location, these residues are much more difficult and expensive to recover than urban wood residues.

6.2.2. Agricultural residues

Large quantities of crop residues are produced annually worldwide, and are vastly under-utilised. These include agricultural residues such as wheat straw, corn stover (leaves, stalks, and cobs), orchard trimmings, rice husks, and bagasse (sugar cane residue). Corn harvests alone could generate more than three times the amount of residue presently available from all forms of wood waste (excluding forest residues). Current farming practice is usually to plough these residues back into the soil, or they are burnt, left to decompose, or grazed by stock.

Most agricultural residues have yet to be widely used for power generation. However, they can offer a sizeable biomass resource if supply infrastructures are developed to economically deliver them to power plants that can use them as fuel. Indeed, a number of agricultural and biomass studies have concluded that it may be appropriate to remove and utilise a portion of crop residue for energy production, providing large volumes of low cost material. These residues could be processed into liquid fuels or combusted/gasified to produce electricity and heat.

6.2.2.1. Bagasse

When sugar cane is crushed to extract the juice, the remaining pulp is called bagasse. In the sugar manufacturing industry, it is common to use bagasse as a fuel for cogeneration - making steam for sugar production and electricity for use at the sugar mill and for sale to electric companies. The ash content typically varies from 4-11% (dry basis), but the melting temperature of the ash is high. U.S. is the leading producer of electricity from bagasse, with operating bagasse-fueled cogeneration facilities in Florida, Hawaii, and Louisiana. Bagasse is also an important energy source in a number of other nations, including Australia, Pakistan, India, Reunion Island, Thailand, and others in Africa, Southern Asia, and South America.

6.2.2.2. Rice husks

Rice is the second most abundant crop in the world, behind wheat, in terms of production and planted area. It is a food staple for more than half of the world's population. Rice husks or hulls are a residue material produced during the rice milling process (about 20% of rough rice is husk). Instead of discarding the husks, rice mills can utilize them for producing steam and electricity. In the U.S., several mills in Arkansas, Louisiana, and California are already doing this. In countries like China, India, Pakistan, Thailand, and Vietnam, where rice is produced in large quantities, rice husks could be an important fuel source in meeting rising electric demands and offsetting fossil fuel use and imports.

6.2.2.3. Straw

Straw has low ash-melting temperatures. It can become sticky at temperatures as low as 550-600^{o}C. Its sometimes high chlorine content, especially in near-coastal areas, may cause corrosion of heat exchangers in power plants. Examples can be found in some straw-fired plants in Denmark. Chlorine content can vary by a factor of five between coastal and far-inland areas.

6.2.3. Energy crops

Various organizations worldwide, such as national labs, agricultural and forestry groups, power companies, and other governmental agencies are working to make energy crops a viable fuel source in the near future. Energy crops are crops developed and grown specifically for fuel. These crops are carefully selected to be fast growing, drought and pest resistant, and readily harvested to allow competitive prices when used as fuel.

Energy crops include fast-growing trees, shrubs, and grasses. Examples under development include hybrid poplar, willow, switchgrass, and eucalyptus. Energy crops can be grown on agricultural lands not needed for food, feed, or fiber. These include lands taken out of service for price control reasons and other agricultural lands that are considered marginal for food production. Compared to traditional agricultural crops, energy crops are lower maintenance and require less fertilizer and pesticide treatment.

The period between harvests for woody energy crops varies from 3 to 10 years, depending on the tree species, and the period between plantings can be longer than 20 years. In addition to their fuel value, energy crops can also be planted for erosion control, soil remediation, and as nutrient filters that prevent nutrient run-off from land into waterways. In addition to environmental benefits, energy crops can provide income benefits for farmers.

The typical modern farm usually only produces one or two major commercial products such as corn, soybeans, milk or beef. The net income of the entire operation is often vulnerable to fluctuations in market demand, unexpected production costs, and the weather, among other factors. Since biomass fuelled power plants require a fairly steady supply of fuel throughout the year, raising energy crops can provide income stabilization for farmers who choose to diversify their production.

6.2.4. Wastes

2.4.1. Industrial waste

The food industry produces a large number of residues and by-products that can be used as biomass energy sources. These waste materials are generated from all sectors of the food industry with everything from meat production to confectionery producing waste that can be utilised as an energy source. Solid wastes include peelings and scraps from fruit and vegetables, food that does not meet quality control standards, pulp and fibre from sugar and starch extraction, filter sludges and coffee grounds. These wastes are usually disposed of in landfill dumps with the food company paying for their disposal.

Liquid waste streams are generated by washing meat, fruit and vegetables, blanching fruit and vegetables, pre-cooking meats, poultry and fish, cleaning and processing operations and wine making. These wastewaters contain sugars, starches and other dissolved and solid organic matter, but in a fairly dilute form. The potential exists for these industrial wastes to be anaerobically digested to produce biogas, or fermented to produce ethanol, and several commercial examples of waste-to-energy conversion already exist.

Furthermore, black liquor is a waste product generated by the paper and pulp making industry. Black liquor can be pyrolysed or gasified as a biomass energy source. A process has been developed, namely the fluidised bed fast pyrolysis process, which can convert black liquor into a "bio-oil". The bio-oil can be processed into transport fuel substitutes such as biodiesel.

6.2.4.2. Municipal solid waste (MSW)

Millions of tonnes of household waste are collected each year with the vast majority disposed of in landfill dumps. The composition of MSW varies according to the location and type of the collection service. An average composition of the Australian MSW was found to be 46% putrecibles (decaying organic matter), 24% paper, 26% plastic, glass and metal, and 4% "other". The biomass resource in this MSW comprises the putrecibles, paper and plastic, and averages 80% of the total MSW collected. Its lower heating value is typically around 8-12 GJ/tonne.

Municipal solid waste can be converted into energy by direct combustion, or by natural anaerobic digestion in the landfill. At the landfill sites, the gas produced by the natural decomposition of MSW (approximately 50% methane and 50% carbon dioxide) is collected from the stored material and scrubbed and cleaned before feeding into internal combustion engines or gas turbines to generate heat and power.

6.2.4.3. Animal waste

There is a wide range of animal wastes that can be used as sources of biomass energy. The most common sources are manures from pigs, chickens and cattle (in feed lots) because these animals are reared in confined areas generating a large amount of waste in a small area. In the past this waste has been recovered and sold as a fertilizer or simply spread onto agricultural land, but the introduction of tighter environmental controls on odour and water pollution means that some form of waste management is now required.

This provides further incentives for waste-to-energy conversion. A common method of converting these waste materials is via anaerobic digestion, described in a later section. The product from anaerobic digestion is a 'biogas' that can be used as a fuel for internal combustion engines to generate electricity, or burnt directly for cooking, or for space and water heating.

6.2.4.4. Sewage

Sewage is a source of biomass energy that is very similar to the other animal wastes previously mentioned, the only difference being that it has been treated in developed countries for many years. Energy can be extracted from sewage using anaerobic digestion to produce biogas. The remaining sewage sludge can then be incinerated or undergo pyrolysis to produce more biogas and 'bio-oil'.

6.3. POWER PRODUCTION TECHNOLOGY

6.3.1. Biomass conversion technologies

The technologies for the primary conversion of biomass for electricity production are direct combustion, gasification, and pyrolysis. Direct combustion involves the oxidation of biomass with excess air, giving hot flue gases that are used to produce steam in the heat exchange sections of boilers. The steam is then used to produce electricity, expanding through a steam turbine in a Rankine cycle (figure 6.3); usually, only electricity is produced in a condensing steam cycle, while electricity and steam are cogenerated in an extracting steam cycle.

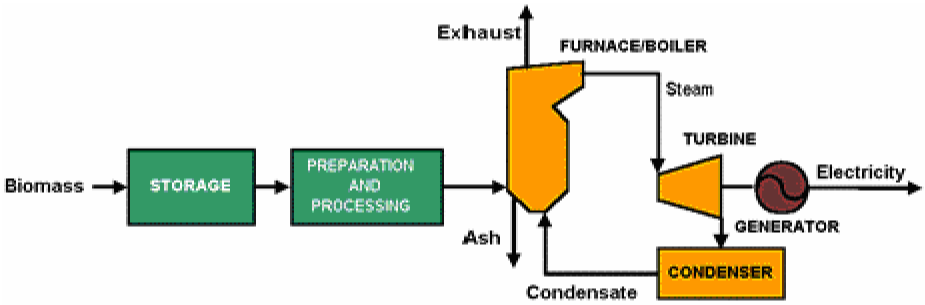


Figure 6.3. Direct combustion steam turbine system

In air-based gasification cycles, biomass is partially oxidized by sub-stoichiometric amounts of oxygen, normally with steam present, to provide energy for thermal conversion of the remaining biomass to gases and organic vapours. For power production, the cleaned gasification product gases (producer gas) will be fed directly to a boiler or to the combustion section of an industrial or aero-derivative turbine. In indirect gasification cycles an external heat source, instead of oxygen, is used to provide the energy for high-temperature steam gasification of the organic fraction of biomass to vapours and gases.

In pyrolysis processes, indirect heating is also used to convert biomass to a mixture of gases and organic vapours. Pyrolysis is defined as the thermal destruction of organic materials in the absence of oxygen. Therefore, technically speaking, indirect gasification is a pyrolysis process. For purposes of this discussion, if the primary pyrolysis product is gas the process is considered gasification, while if the primary products are condensable vapours the process is considered pyrolysis. Steam is not usually added to pyrolysis processes.

All the above are thermal conversion technologies. On the other hand, anaerobic digestion (AD) is a biological process by which organic wastes are converted to biogas, a mixture of methane (40-75% per volume) and carbon dioxide. The process is based on the breakdown of the organic macromolecules of biomass by naturally occurring bacterial populations. This bioconversion takes place in the absence of air (”anaerobic”) in digesters, i.e., sealed containers, offering ideal conditions for the bacteria to ferment (”digest”) the organic feedstock to biogas.

During anaerobic digestion, typically 30-60% of the input solids are converted to biogas. The co-products consist of an undigested residue (sludge) and various water-soluble substances. Anaerobic digestion of especially wet biomass and waste is a well-established and commercially proven technology. In principle, biogas, either raw or after some enrichment in CH_4, can be used to generate heat and/or electricity through gas, diesel or “dual fuel” engines, at capacities up to 10 MW_e. The average productivity is 0.2-0.3 m^3 biogas/kg of dry solids.

Nowadays, 80% of the industrialised world biogas production is from commercially exploited landfills. Production and utilisation of landfill gas based on MSW may also be an option for power production. However, it should be noted that, in most cases, power generated in digestion processes is a by-product of the process. Like waste incineration, the main purpose of digestion is the processing of waste, not power production. An overview of all the above biomass primary conversion technologies is provided in figure 6.4.

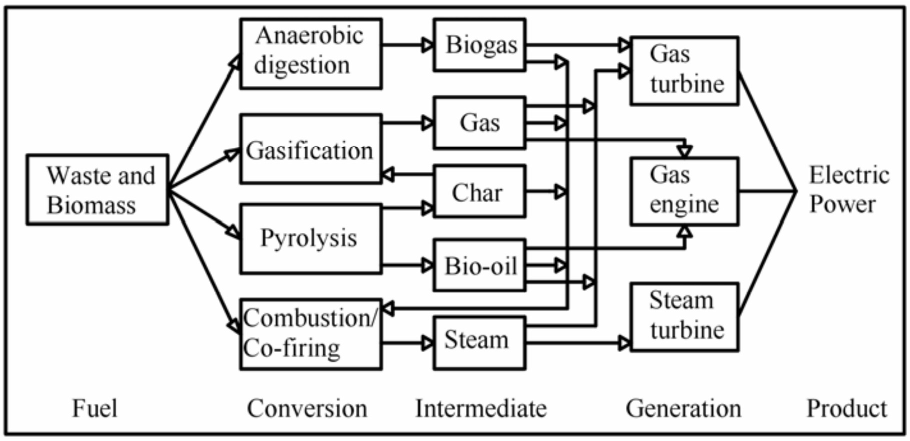


Figure 6.4. Overview of biomass conversion routes for power production

6.3.2. Direct combustion (direct fired plants)

Of the various primary conversion technologies for biomass or waste, combustion-based systems are well established and represent mature technology. Modern large-scale plants combine municipal solid waste incineration with an increasing net output of electric power, to generate up to 45 MW_e. New developments include integration with fossil fuel streams in existing power plants, resulting in higher overall efficiencies compared to stand-alone systems.

Combustion of wood for power production, sometimes in combination with other types of biomass or waste, is a well-proven technology. Numerous examples can be found, especially in the Scandinavian countries and the USA. Combustion of energy crops in dedicated power plants is in development and some demonstration projects are underway. Biomass combustion can be broken into a range of different technologies that can be grouped into either 'fixed bed' or 'fluidised bed' combustion.

6.3.2.1. Fixed bed combustion

Fixed bed combustion, also known as stoker firing, uses mechanical devices that feed and burn fuels in a bed at the bottom of the furnace. The combustion air passes through the grate on which the fuel sits. Air flow-rate is restricted so that the fuel is not stirred and remains in contact with other solids. Fixed bed combustors can be categorised by the method by which fuel is fed onto the grate.

Overfeed stokers (or travelling grate stokers) have fuel fed by gravity at one end of the grate surface and a fuel gate at the furnace entry adjusts the depth of the fuel surface. The grate travels slowly across the furnace as an open conveyer belt, with ash and slag being continuously discharged at the opposite end of the grate. This type of grate has been designed for coal firing. If biomass combustion is being undertaken, then there can be higher maintenance costs and boiler efficiency can decrease due to reduced combustion air temperatures.

Spreader stokers include an air–cooled travelling grate, but take advantage of suspension firing. The fuel distributors force fuel into the furnace above an ignited fuel bed. Either mechanical or pneumatic throwers can be used, depending on fuel type. Fine particles burn in suspension while larger particles fall and burn on the travelling grate. Because of the suspension firing principle, fuels need to be relatively dry (moisture content less than 50 percent) and appropriately sized.

An ash layer needs to be maintained on the grate to protect it from thermal degradation, which can result from intermittent operation. Biomass ash frequently is abrasive having high silica content which can result in high maintenance costs of the grate. A further disadvantage with this type of firing is that there can be a significant amount of fly ash and unburned carbon in the flue gas resulting in lower combustion and boiler efficiencies. Countering this is the responsive nature of such stokers to load change by adjusting travel speed and air intake.

A *sloping grate furnace* is the most commonly used for biomass combustion systems. It allows pre-drying of the fuel in the upper part of the furnace prior to it falling under gravity onto a reciprocating grate lower in the furnace where combustion takes place. Because the grate is water- or air-cooled, it does not need an ash layer to protect it, which makes it more suitable for low ash biomass fuels.

6.3.2.2. Fluidised bed combustion

Fluidised bed combustion is characterised by high air velocity through the fuel bed giving it fluid properties. The bed will normally include coarse sand that assists the mixing of the fuel and air, and increases the heat transfer to the fuel for drying and ignition. The separation of fuel and other bed particles occurs above the “minimum fluidisation velocity”, this being a function of particle size, density and pressure drop through the bed. As air velocity is increased, the bed can change from a bubbling bed to a turbulent bed, and to a circulating bed with increasing recycling rates.

Commercial developments are categorised as either bubbling fluidised bed (BFB) combustion or circulating fluidised bed (CFB) combustion and can be pressurised or not and use air or oxygen. In the BFB system, air velocity is typically 1-3m/s causing the sand bed to bubble separating the bed particles from one another. Primary air supply is via nozzles from the wind-box at the bottom of the bed, with secondary air flowing to the furnace above the bed. Bed temperature is maintained and controlled by altering the ratio of primary to secondary air, or by recirculating some of the flue gas.

In a CFB system, the air velocity is typically 4-9m/s above the wind-box. The sand can circulate in the furnace assisting heat transfer. Flue gas and entrained solids leave the furnace and pass through cyclones, which collect the particles and return these to the area immediately above the wind-box. As for the BFB boiler, there are primary and secondary air supplies (see figure 6.5). There is no distinct bed surface with combustion occurring throughout the furnace. CFB systems tend to be more expensive than other options, but reduce NO_x emissions significantly due to lower operating temperatures.

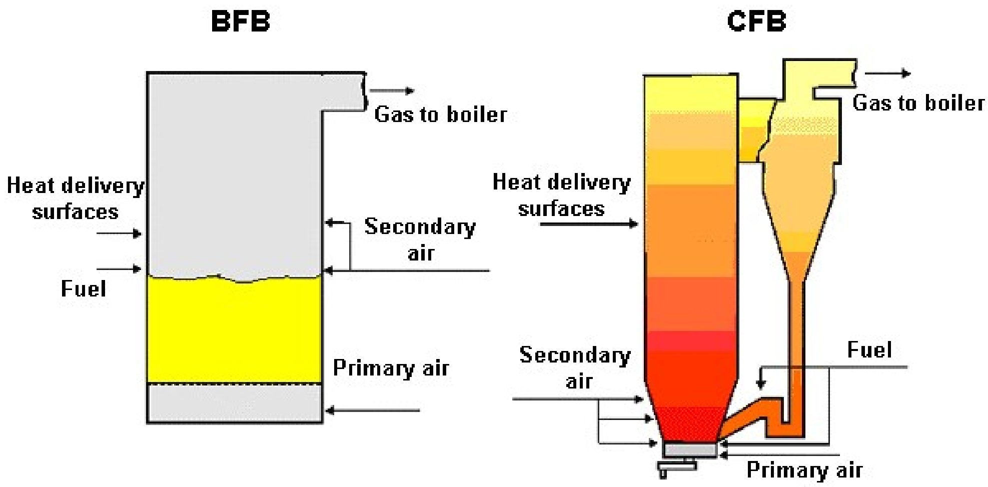


Figure 6.5. BFB and CFB boilers

Fluidised bed combustors are more technically intricate with associated higher costs of design, construction and operation. As a general rule, there is a threshold in the region of 8 MW_{th} above which they begin to gain economic advantage over fixed bed combustors. On the other hand, fluidised bed has the following advantages over fixed bed combustion:

- The high thermal inertia of the bed provides conditions for stable ignition, despite variability of fuel quality. Hence it is more tolerant of a wider range of fuel characteristics.

- Control of bed temperature allows a range of fuels with varying ash properties to be burnt while avoiding ash softening conditions in the bed.
- Relatively low combustion temperatures mean that NO_x emissions are low.
- If limestone is added to the bed material then in-situ capture of SO_2 is possible, though this is not necessary for biomass fuels since they are low in sulphur.

BFB units are commercially offered up to 100 MW_e, and CFB units up to 400-600 MW_e. CFB boilers have proven feasibility to burn about 70 different fuels alone or in co-combustion mode. BFB boilers have proved their feasibility for biomass and waste fuels with similar characteristics especially in lower capacities, starting from 5 MW_{th} with well-processed fuel. A new enhanced CFB concept offers an even more competitive, flexible and environmentally friendly solution for combustion of low-grade fuels and different wastes, for smaller scale power plants (<10 MW_e).

6.3.2.3. Suspension burners

The suspension burning of pulverized wood in dedicated biomass boilers is a fairly recent development and is practiced in relatively few installations. Suspension burning has also been accomplished in limekilns and is being investigated by the utility industry for co-firing applications. The requirements for successful suspension firing, i.e. a feed moisture content of less than 15% and a particle size less than 1.5 mm, give higher boiler efficiencies (up to 80%) than firing wet wood chips of 50-55% moisture in a stoker grate or fluid bed system at 65% efficiency.

Higher efficiency also results in smaller furnace size. Offsetting the higher efficiency is the cost and power consumption of drying and comminution. In addition, special burners (i.e. scroll cyclonic burners and vertical-cylindrical burners) need to be used. Installations include the Oxford Energy 27 MW facility at Williams California, the ASSI Lövholmen Linerboard Mill in Piteå, Finland, the Klabin do Parana mill in Monte Alegre, Brazil, and the E.B. Eddy Mill in Espanola Ontario.

6.3.3. Cofiring with coal

6.3.3.1. Description

Biomass is economic source when the fuel is very low cost or free. Then efficiency is not a key economic criterion and, as a result, the existing biomass power plants have heat rates in the range from 13,000 to 20,000 Btu/kWh, or even higher, when coal-fired steam power boilers in the utility power industry have much better heat rates, in the range from 9,000 to 13,000 Btu/kWh. On the other hand, a number of major utilities worldwide are evaluating the cofiring of biomass in existing coal-fired power stations, mainly because of the environmental benefits that may accrue.

These benefits of biomass-coal cofiring, the firing of two dissimilar fuels at the same time in the same boiler, include the reduction in CO_2 emissions from the combustion of fossil fuels, the reduction of SO_2 formation through a decrease in fuel-bound sulfur, the reduction of NO_x formation through a reduction in fuel-bound nitrogen, and a means to address air toxics emissions. When co-firing with biomass, the percent CO_2 reduction for the power plant is approximately equal to the percent of the total boiler heat input that is obtained from biomass feedstocks.

Furthermore, potential benefits of co-firing with biomass fuels include obtaining a low cost fuel supply, increase fuel diversity for utilities, and providing an outlet for industrial customer residue products. Cofiring takes advantage of the best aspects of each technology, and makes it possible to achieve much better efficiency in converting biomass fuel into electric power, compared to the typical practice in existing boilers that fire 100% biomass as fuel.

Heat rates of 11,000 Btu/kWh can be achieved in cofiring, compared to 14,000 or higher in typical wood-fired power plants. On the other hand, tests and calculations both confirm that, when cofiring so that some 7% to 10% of the heat input is from biomass, the drop in overall boiler efficiency is in the range of 0.3 to 1.0 points out of the approximately 85% efficiencies typical of the coal-fired boilers in the tests. These numbers show that there is an efficiency penalty attributable to the biomass fraction being converted less efficiently than the coal fraction.

However, the numbers also show that it is a penalty that is small in comparison to the large difference between the existing biomass boilers now used for most biomass power and the existing coal-fired boilers in the utility power industry, a penalty that is in the range from 3% on the low end (approximately 0.3% times 100/10 divided by 0.85) to 16% on the high end (approximately 1.0% times 100/7 divided by 0.85).

6.3.3.2. Modifications and the related costs

The most critical items in the cost of a cofiring operation are the fuel cost and the capital cost of the modifications to the power plant to enable biomass fuel to be cofired with the coal. The cost-side economics of biomass cofiring are driven by whether or not fuel cost savings through biomass fuels displacing higher-cost coal can more than offset the capital cost to modify the plant, and any added labour and maintenance costs incurred to operate the cofiring system.

The fuel cost here is really the differential between the biomass fuel cost and the cost of the coal displaced by the biomass fuel. The capital costs to set up a cofiring capability divide into two classes, depending on whether the biomass is blended with coal or fired separately from the coal. Blending requires no separate flow and injection path for the biomass fuel and is usually much lower in cost, on the order of \$50/kW versus \$200/kW for separate feed. Note that these costs are expressed per unit of power capacity on biomass, not on total capacity of the unit.

Hence, a 100 MW_e boiler cofired at 10% by heat is getting 10 MW_e from the biomass fuel, and a \$200/kW cost of capital modifications for a separated feed system means a total of \$2,000,000 in capital invested to modify the plant. Per unit of total capacity of the plant, the unit cost is $20/kW. For a 250 MW coal-fired boiler with a blended fuel system added to enable the plant to cofire at 2% by heat, the capacity on biomass is 5 MW_e, and the unit capital cost of $50/kW gives a total of $250,000. Per unit of total capacity of the boiler, this is an expenditure of $1/kW.

For the most common utility coal-steam power plants, namely all those that fire pulverized coal, and are referred to as "PC boilers," the difference between blended and separate feed is associated with a major difference in the fraction of the heat input to the boiler that can be supplied by the biomass fuel. This fraction is often called as the "level" of cofiring. In the above cases, the blended feed example was at the 2% level, meaning 2% of the heat to the boiler is in the biomass fraction, based on heating values (in Btu/lb or kJ/kg) and mass flows of the coal and biomass fuels. The separated feed case in the example above was given as a 10% cofiring level.

These examples of 2% for blended feed and 10% for separated feed are useful and typical examples for cofiring in the common PC boilers. For the less-common cyclone type boilers there is an important difference, since these boilers fire crushed, as opposed to pulverized, coal. Cyclone-type boilers can successfully fire coal with larger particle sizes because they operate at very high temperatures. The burners are large horizontally oriented cyclone barrels where the large coal particles burn out in a swirl of liquid formed by molten ash on the walls of the barrels.

Because they are tolerant of larger sized fuel particles and do not require that fuel be pulverized to very small sizes, indeed because they do not even have the pulverizing mills that grind all fuel enroute to a PC boiler, cyclone power plants do not share the 2% limit on level of cofiring that applies to most PC power plants. In a cyclone boiler a 10% level can be achieved using the lower-cost blended fuel feeding approach. The blended fuel approach has lower costs on the operating side, as well as on the capital cost side.

In blended fuel feeding the blending of the biomass fuel with the coal can be done during one shift of the workday, and the fuel fed to the boiler throughout the day without further special labour. Separated feed has the advantage of being controlled to add or remove the biomass cofiring at any time, but that advantage is paid for by paying for an added operating staff member on each shift of the work day. Perhaps automated systems can be found to offset the need for an extra operator on all shifts, but such systems may add capital and maintenance costs that decrease or eliminate the operating cost savings.

6.3.4. Gasification-based biomass power production

6.3.4.1. System description

Biomass gasification, that is the conversion of biomass to a low- or medium-heating-value gaseous fuel, generally involves two processes. The first of them, the pyrolysis, releases the volatile components of the fuel at temperatures below 600°C via a set of complex reactions. Included in these volatile vapours are hydrocarbon gases, CO, CO_2, hydrogen, tars, and water vapour. Because biomass fuels tend to have more volatile components (70-86% on a dry basis) than coal (30%), pyrolysis plays a proportionally larger role in biomass gasification than in coal gasification.

The by-products of pyrolysis that are not vaporized are known as char, and consist mainly of fixed carbon and ash. In the second gasification process, char conversion, the carbon remaining after pyrolysis undergoes the classic gasification reaction (i.e. steam + carbon) and/or combustion (carbon + oxygen). It is this latter combustion reaction that provides the heat energy required to drive the pyrolysis and char gasification reactions. Due to its high reactivity (as compared to coal and other solid fuels), all of the biomass feed, including char, is normally converted to gasification products in a single pass through a gasifier system.

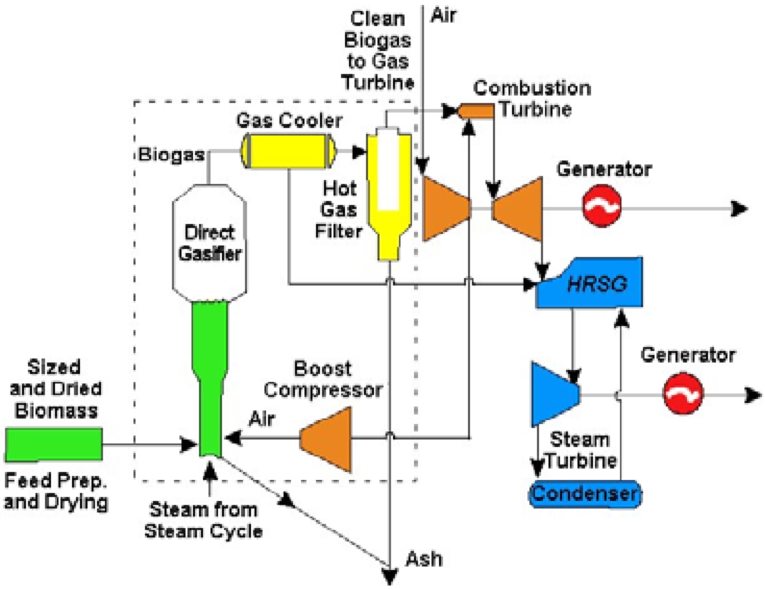


Figure 6.6. Biomass integrated gasification combined cycle (IGCC) system schematic

Depending on the type of gasifier used, the above reactions can take place in a single reactor vessel or be separated into different vessels. In the case of direct gasifiers, pyrolysis, gasification, and combustion take place in one vessel, while in indirect gasifiers, pyrolysis and gasification occur in one vessel, and combustion in a separate vessel. In the integrated gasification combined cycle (IGCC) system shown in figure 6.6, a high pressure, direct gasifier is depicted inside the dashed line. Also shown below are the other possible gasifier options, more specifically a low-pressure direct gasifier in figure 6.7 and an indirect gasifier in figure 6.8.

In direct gasification, air and sometimes steam are introduced directly to the single gasifier vessel. In indirect gasification, an inert heat transfer medium, such as sand, carries heat generated in the combustor to the gasifier to drive the pyrolysis and char gasification reactions. Indirect gasifiers operate near atmospheric pressure, while direct gasification systems have been developed at both atmospheric and elevated pressures. All the gasifier systems can be utilized in the larger system diagrammed in figure 6.6 and have been utilized in at least one recent system design study.

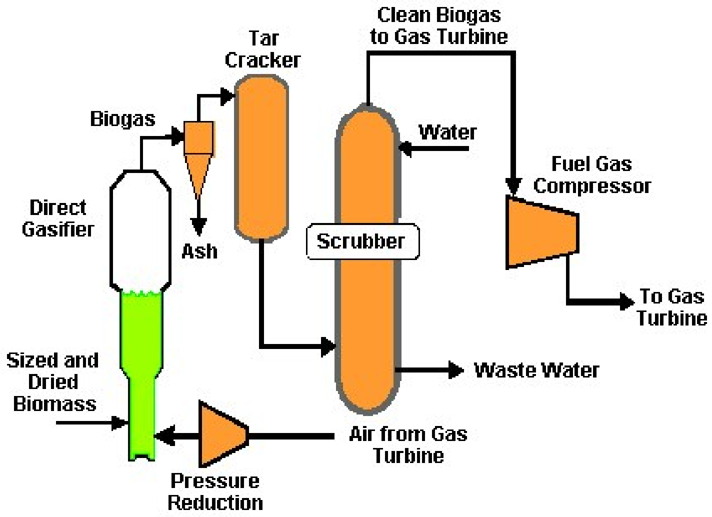


Figure 6.7. Low-pressure direct gasifier

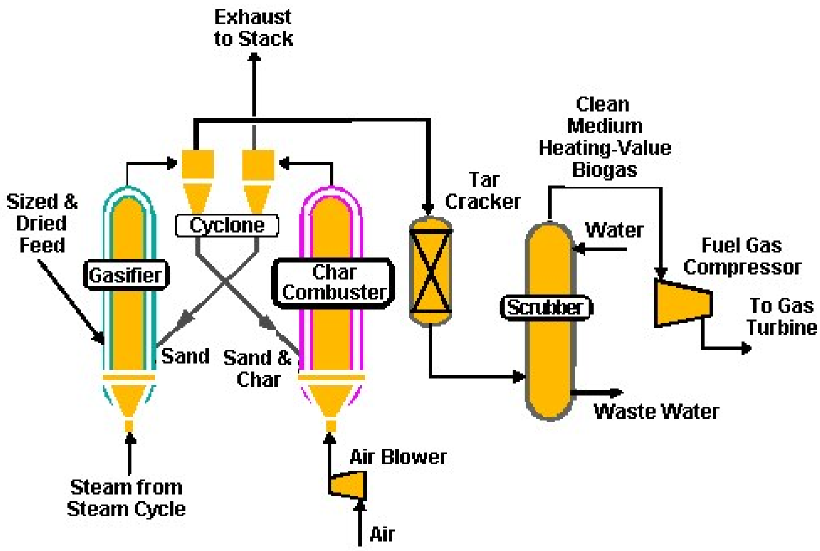


Figure 6.8. Indirect gasifier

However, there are several practical implications of each gasifier type. Due to the diluent effect of the nitrogen in air, fuel gas from a direct gasifier is of low heating value (5.6-7.5 MJ/Nm^3). This low heat content in turn requires an increased fuel flow to the gas turbine. Consequently, in order to maintain the total (fuel + air) mass flow through the turbine within design limits, an air bleed is usually taken from the gas turbine compressor and used in the gasifier. This bleed air is either boosted slightly in pressure or expanded to near atmospheric pressure, depending on the operating pressure of the direct gasifier.

The calorific value of the product gas can be increased to 12.8-13.8 MJ/Nm^3 through the use of oxygen instead of air; however, oxygen production is expensive. Since the fuel-producing reactions in an indirect gasifier take place in a separate vessel, the resulting fuel gas is free of nitrogen diluents and is of medium heating value (13-18.7

MJ/Nm^3). This heat content is sufficiently close to that of natural gas (~38 MJ/Nm^3), so fuel gas from an indirect gasifier can be used in an unmodified gas turbine without air bleed.

Gasifier operating pressure affects not only equipment cost and size, but also the interfaces to the rest of the power plant, including the necessary cleanup systems. Since gas turbines operate at elevated pressures, the fuel gas generated by low-pressure gasifiers must be compressed. This favours low temperature gas cleaning, since the fuel gas must be cooled prior to compression in any case. Air for a low-pressure gasifier can be extracted from the gas turbine and reduced in pressure (direct, low pressure gasifier) or supplied independently (indirect gasifier).

High-pressure gasification favours hot, pressurized cleanup of the fuel gas and supply to the gas turbine combustor at high temperature (~ 538ºC) and sufficiently high pressure for flow control and combustor pressure drop. Air for a high pressure, direct gasifier is extracted from the gas turbine and boosted in pressure prior to introduction to the gasifier. However, to take full advantage of operating at pressure, a number of ancillary systems must be developed.

Cooling, cold cleanup, and fuel gas compression add equipment to an indirect gasifier system and reduce its efficiency by up to 10%. On the other hand, gasifier and gas cleanup vessels rated for high-pressure operation and more elaborate feed systems add cost and complexity to high-pressure gasification systems, despite their higher efficiency. Results from several recent studies indicate that, at the moment, there is little discernable difference in cost of electricity between systems employing high and low pressure gasification.

The other major variable is reactor type. Gasification reactors operate under much of the same principles as comparable combustors and include fixed/moving bed units (updraft and downdraft), various fluidised bed systems, and entrained bed reactors. Of these, the fixed/moving bed is the simplest to construct, control and operate, and the downdraft system can produce a gas that requires only limited clean-up in relation to tar and particulates to make it suitable for combustion in internal combustion engines and gas turbines.

Another important feature of this unit is that, with the assistance of additives such as limestone and dolomite, large amounts of acid gas (hydrogen chloride and hydrogen sulphide) can be retained in the ash. Fluidised bed and entrained bed systems, on the other hand, although versatile in their operation, are generally more difficult to design, built and operate, are more expensive, and are currently considered inappropriate for small-scale applications of less than 1 MW.

The selection from a broad type of gasifiers for an application will be driven by economics, and will be a function of size, fuel type and availability. Figure 6.9 shows the likely selection by type and fuel capacity, though many of the technologies have yet to be proved at the scale indicated. Demonstration projects are now proving the potential of the technologies for biomass particularly at the larger scales. However, full commercial applications for power generation still carry high technical risks.

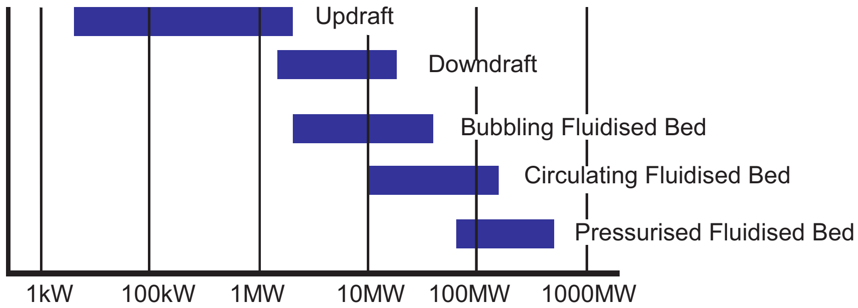


Figure 6.9. Fuel capacity of different types of biomass gasifiers (Rensfelt, 1997)

6.3.4.2. Power cycle options

Gasification and production of a clean fuel gas makes a wide array of power options possible, including the use of advanced power systems with higher efficiencies than those obtained from steam turbines. At the low cost end of the spectrum, gasifiers coupled to a high-efficiency, simple-cycle gas turbine offer simplicity as well as efficiencies competitive to the Rankine cycle. A fluidized-bed biomass gasifier (which does not necessarily require steam) integrated with a high-efficiency gas turbine may be the best combination for simple cycle operation.

Traditionally, poor part-load efficiency has limited the use of the simple cycle gas turbines to peak-load power generation. Following the trend established by both coal and natural gas for large-scale plants, combined gas and steam cycles along with their variants (e.g. Steam Injection Gas Turbine – STIG, and humid air turbine - HAT) offer power cycle efficiencies approaching 50% (6800 Btu/kWh). Looking slightly further into the future, fuel cells could offer efficiencies in this range, and could possibly push the ceiling even higher.

More specifically, natural gas-fired combined cycle plants are currently making inroads into the utility grid for intermediate and base load operation. These plants have efficiencies approaching 50% (6,800 Btu/kWh) and usually exceed 600 MW_e in output. The combined cycle technology is commercially available and can be expected to improve as turbine manufacturers compete for improved efficiency, NO_x control, and availability.

The steam-injected gas turbine is an adaptation of the combined cycle in which the exhaust gases from the turbine are used to generate steam in a heat recovery steam generator (HRSG). This technology offers flexibility for electricity/steam cogeneration applications. When process steam demand falls, the steam from the HRSG can be injected into the combustor and/or the turbine sections of the gas turbine. The steam injected into the turbine is additional mass which is used to help drive the turbine and which does not consume power at the turbine's compressor.

Since the specific heat of steam/air mixture in the turbine is twice that of air alone, more power can be extracted in the turbine section when using steam injection. Adding steam in the combustion zone of the turbine lowers both the flame and gas temperatures and prevents up to 80% of uncontrolled NO_x formation. The addition of compressor intercooling to the STIG cycle (ISTIG) can raise both thermal efficiency and shaft power output. The ISTIG, shown in figure 6.10, can double the output of a simple cycle gas turbine, while pushing its overall power cycle efficiency above 50%.

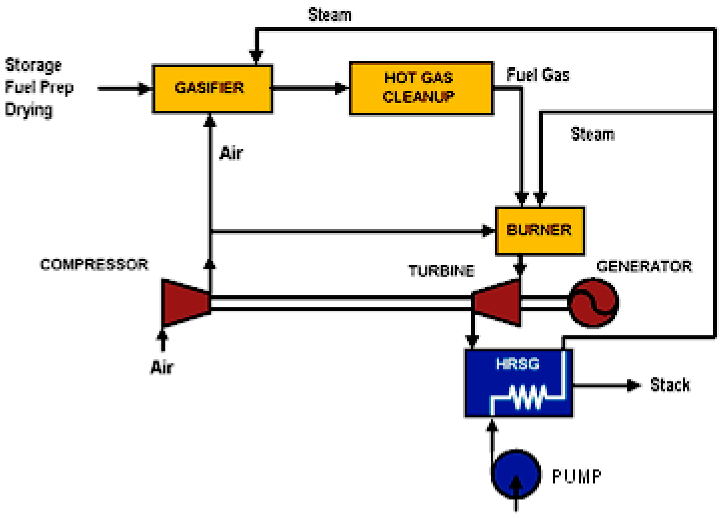


Figure 6.10. Integrated gasification steam injection gas turbine cycle

6.4. BIOPOWER MARKET POTENTIAL AND IMPACTS

6.4.1. Market position and potential

With an estimated 14,000 MW of annual worldwide installed generation capacity, biomass power is the largest source of non-hydro renewable electricity in the world. The biomass industry differs from many other renewables in that it encompasses both the farming and forestry communities and the power generation industry. This creates tensions and misunderstandings. There are often widely differing opinions on the merits of long-term fuel contracts and the contractual liabilities that these place on fuel supply companies (often quite small).

This situation has proved a major obstacle to the deployment of energy crops, and the industry is still finding forms of co-operation to deal with these differences that provide equitable returns for both sides of the industry. The greatest part of biomass to electricity schemes was developed in pulp and paper and forest industries, where significant synergies and the necessity of waste management were critical success factors. Beyond these applications biomass to electricity schemes have only been successfully deployed in countries where dedicated policies, including tax and subsidy policies, were implemented.

Off-grid, modular systems offer the most viable international market opportunity for bio-power. In the short term, a market for biomass electricity is most likely to be found where:

- biomass residues create a waste disposal problem;
- a low cost supply of biomass residue is combined with a strong growth in the demand for electricity; or
- where environmentally driven policies and global climate change concerns encourage deployment.

The situation in many developing countries corresponds to the first and second case. Although most biomass in these countries is used for cooking and space heating, a significant amount is also used in industry for process steam and power generation. These industrial uses are almost exclusively in the agro-processing and wood processing sectors. Up until recently the priorities for these generators have been the disposal of residues and the lowest capital cost commensurate with the required availability.

Efficiency has never been a priority because there has rarely been a customer for the surplus electricity that the improvements would create. Thus, efficiencies have typically been below 20% and often in single figures. However, as developing countries expand their electricity infrastructure, these agro-processing plants present an interesting opportunity to develop sources of low cost electricity by installing more efficient generation equipment. For example, a typical sugar mill could export 8 MW_e approximately by implementing simple improvements. This output could be doubled by the installation of more advanced technology.

Many forecasts predict that if appropriate policies are pursued and the technology is developed and disseminated, in the medium term future, biomass will account for significant proportions of electricity generation in many countries. An example of the moves in this direction can be found in Brazil, where parts of the country are expecting severe power shortages in the next few years due to the scarcity of low cost hydro schemes and the need for more environmentally sensitive schemes. Given the country's large biomass resource base and its sugar cane and alcohol industry, it is logical for the authorities to generate electricity from biomass.

As a demonstration of the possibilities, a 30 MW_e gasification power plant is to be built fuelled initially by chips from a eucalyptus plantation. The gasification technology will come from Sweden and the gas turbine from the USA. Also in Brazil, 150 sugar cane alcohol distilleries in Sao Paulo State with a power capacity of about 200 MW_e, using old, inefficient steam turbines, have agreed to invest in gas turbine technology to provide a capacity of about 3000 MW_e, from the same amount of cane, over the next fifteen years to the states' three power utilities.

In the U.S., which comes in the third market category, there are about 8000 MW_e of electricity from biomass capacity installed, using mainly biomass wastes with traditional conversion technologies. Under the National Biomass Power Program a further 6000 MW_e of electricity from biomass capacity were to be added by the end of 2000 in a collaborative strategy involving industry, the research and development community, regulators, potential users, and state and federal agencies. The DoE and EPRI forecast that by 2010 electricity from biomass capacity will have increased to, respectively, approximately 26,000 MW_e (USA) and 50,000 MW_e (world).

As regards the deployment in EU, electricity generation from biomass is significant in Sweden, Finland, Austria and Denmark, mainly in CHP schemes in pulp and paper industries followed by forest industry and in large district heating systems. Biomass is used for power generation to a lesser extent in other countries and usually in niche markets as co-generation or as a recent response to environmentally driven policy initiatives. As gasification and other advanced processes are still in the development and demonstration phase, most current deployment is conventional steam cycle technology. There is a minor amount of co-firing with coal in Sweden.

As regards wastes, the rate of deployment depends not only on the cost and availability of alternative treatment methods but also on national waste management policies. In the EU, for example, the adoption of the EC Landfill Directive, which will ban landfilling of organic material without prior treatment, would accelerate the deployment of MSW combustion facilities. If the EU achieves the intended diversion of 25-30% of waste to combustion by 2010, the potential power output is estimated to be in the range 2000-2400MW_e.

Outside the EU, improvements in waste management practices are also leading to an expansion of the market and to potential export opportunities. The principal non-EU markets are North America and Japan, which have a developed waste treatment infrastructure. By 2010 it is estimated that the world market will be equivalent to about 5500MW_e, creating a potential 22,000 direct jobs worldwide. The world market for landfill gas use is estimated to be equivalent to 4500 MW_e by the year 2010. So far, 15% of this has been developed, with over 50% of it in the USA and Canada.

6.4.2. Environmental impacts

Use of biomass for power generation involves complex environmental issues. There is general consensus on the global (greenhouse gas) benefits of using biomass, but these benefits are not well publicised and therefore poorly understood by decision makers and the general public. The key to successful biomass power development is to use the resource efficiently in modern conversion systems that maximize the energy produced and minimize the by-products of conversion processes.

Until the 20th century, in most parts of the world, using biomass to generate heat or to drive steam engines was the most common way to produce energy. However, historical methods of burning wood, field residues, or wood wastes and by-products have tended to be less efficient than modern conversion systems currently available and in development. In modern times, the combination of improved technological efficiencies, scientific advances, increased environmental awareness, and protection regulations have turned biomass conversion into a cleaner, more efficient process.

6.4.2.1. Air quality

Power generation using biomass or fossil fuels produces airborne emissions such as sulphur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2). Using Bio-power offers the following advantages:

- Reduced sulphur emissions: Most forms of biomass contain very small amounts of sulphur, therefore a biomass power plant emits very little sulphur dioxide (SO_2), an acid rain precursor. Coal, however, usually contains up to 5% sulphur. Co-firing biomass with coal can significantly reduce the power plant's SO_2 emissions compared to a coal-only operation. The amount of SO_2 reduced depends on both the percent of heat obtained from biomass and the sulphur content of the coal. There is approximately a one-to-one relationship between SO_2 reductions and the percent of total heat input from biomass. For example, using biomass for 5% of a coal-fired power plant's heat input would reduce SO_2 emissions by approximately 5%.
- Reduced nitrogen oxide emissions: Recent biomass cofiring tests at several coal-fired power plants worldwide have demonstrated that NO_X emissions can be reduced relative to coal-only operations. By carefully adjusting the combustion process, NO_X reductions at twice the rate of biomass heat input have been documented. In other words, if biomass is cofired at a 5% heat input rate then the power plant could achieve NO_X reductions of 10%. Pilot-scale tests have also shown that even more significant NO_X cuts can be achieved by using biomass in a re-burn configuration. Re-burn involves injecting up to 20% of a boiler's fuel above the primary combustion zone. It is emerging as an important NO_X control option for power plants.
- Reduced carbon emissions: Plants absorb CO_2 during their growth cycle. When managed in a sustainable cycle, like raising energy crops or replanting harvested areas, bio-power generation can be viewed as a way to recycle carbon. Thus, bio-power can be considered as a carbon-neutral power generation option.
- Reducing other emissions: Landfills produce methane gas, which is produced from decomposing biomass material. Decomposing animal manure, whether it is land-applied or left uncovered in a lagoon also generates methane. Methane (CH_4), which is the main component of natural gas, is normally discharged directly into the air, but it can be captured and used as a fuel to generate electricity and heat.
- Reduced odours: Using animal manure and landfill gas for energy production can reduce odours associated with conventional disposal or land applications.

6.4.2.2. Water quality

Animal manure can contain nitrogen, phosphorus, potassium, chlorine, and small amounts of sulphur, which can contaminate water. Normally, the manure is used as fertilizer or is processed in lagoons similar to those used at waste treatment facilities. Both of these land applications can cause the nutrients to leach into the groundwater or end up directly in a waterway through storm-water runoff. Using animal manure as a fuel source curtails water pollution by reducing this nutrient runoff and groundwater contamination.

6.4.2.3. Land use

Woody material and yard trimmings comprise approximately 20% of the total amount of non-hazardous waste entering a landfill. A portion of this material is contaminated and unsuitable for anything other than disposal. However, using the "clean" waste material as a fuel diverts the amount of material sent to landfills, thus extending their capacity/life and reducing the amount of discarded waste. This practice eliminates also methane emissions that would have resulted from the landfilled biomass.

Furthermore, energy crops are perennial plants grown on under-utilized agricultural lands. In general, they do not replace natural forests, grasslands, wetlands, or high value agricultural land. They require less herbicides and pesticides compared to row crops, so they reduce the chemical runoff into surface water and groundwater. The crops extensive root systems hold soil and minimize erosion, thus improving surface water quality. They can filter agricultural chemicals, keeping them from entering streams, and they can intercept nutrients that could migrate into groundwater.

6.4.3. Economic impacts

Rural economic development is one of the major benefits of biomass. Since biomass is bulky and costly to transport, biomass conversion facilities will be situated close to where the crop is grown. National energy security can also benefit from biomass, since defending the access to foreign oil is expensive. Thus, by diversifying the fuel supply, countries protect themselves, strengthen their own economies, and improve their balances of trade.

More specifically, farmers are looking for other cash crops or sources of revenue, while as the population expands beyond urban and suburban areas higher population densities raise the demand for electricity in rural areas. Bio-power projects can help meet both of these needs. Using crop residues as fuel resources can improve the economics of farming by reducing disposal costs and providing alternative sources of income.

The use of energy crops for power production opens a whole new market for agriculture that has the potential to provide a steady source of income for the farming community. For instance, the Electric Power Research Institute (EPRI) has estimated that producing 5 quadrillion Btu’s (British Thermal Units) of electricity on 20 million hectares of land would increase overall farm income by $12 billion annually (for comparison, the U.S. consume about 90 quadrillion Btu's annually).

On the other hand, building large base-load power plants is no longer desirable for meeting energy demand. This is especially true in more remote areas. Smaller bio-power facilities have less environmental impact and can operate with locally produced feedstocks. In concluding, using biomass delivers a triple benefit to rural people, namely it keeps the wealth nearby, it pays farmers for the production of biomass feedstocks, and it provides clean energy.

6.4.4. Barriers to entry

The principal barrier to the wide scale adoption of biomass electricity is the delivered cost of electricity, which can be up to three times the cost of competing power generated from fossil fuels. Whilst taxes and subsidies can make deployment possible, these should be maintained at acceptable levels and eventually removed. The overriding priorities are therefore to address the three elements that make up the unit cost of the electricity, namely capital, fuel and operation.

Modern conversion technologies (e.g. gasification and pyrolysis) offer great power generation efficiencies. However, these are commercially unproven and face many hurdles before becoming fully accepted and integrated into traditional energy markets, such as:

- Technology and O&M;
- Financing and costs;
- Fuel supply and procurement;
- Market and institutional acceptance.

Thus, although cofiring and gasification are proven technologies, which are currently being demonstrated at several utilities, significant remaining technological barriers include the following:

- Ash marketability – Various national and international standards do not allow for any organic matter content in ash to be used for concrete. Intense testing has revealed that cofiring ash does not affect the strength properties at reasonable percentages, and preliminary efforts are being made to change the standards.
- Corrosion – The high chlorine content in some herbaceous crops has caused corrosion of the heat exchanger. Sulphur additives may inhibit the release of the chlorine compounds; however, the resulting emissions may negate the positive effects of biomass.
- NO_x emissions – Generally, biomass cofiring results in lower NO_x emissions than those for coal; however, for certain crops the NO_x levels have been observed to increase. Biogas or natural gas stage reburn has proven effective in reducing the NO_x emissions.

Financial barriers to the use of biomass for power generation are of great importance. A large part of the cost is associated with the risk, actual and perceived, of unproven fuel supply (e.g. short-rotation coppice) and/or unproven conversion technology (e.g. gasification, pyrolysis, co-firing). An effective means of overcoming this is through the involvement of large, economically stable utilities; however, utilities themselves are focused on bottom line profits and wary of technologies with uncertain viability. These problems may be reduced through government incentives.

Fuel procurement has proven to be one of the more complex issues involved in establishing bio-power operations. Bio-power fuels are, at their best, in the form of clean woody by-products from primary forest products processing facilities such as sawmills or pulp and paper plants. However, when an appropriate facility is not located within a feasible transportation radius (usually less than 80 kilometres), alternate and reliable sources must be found. An important issue is the quality and quantity of materials delivered to the facility. These must be consistent and reliable in order for the site to function effectively.

Market and institutional acceptance are the most pervasive and challenging of the barriers to the use of bio-power, including many of the drivers and impediments relating to deregulation and global warming. Specifically, market drivers include:

- Renewable Portfolio Standards and other initiatives;
- Possible carbon trading credits;
- Cofiring as the lowest-cost means of achieving carbon reductions;
- Public demand for green power;
- Possible government incentives;
- Development of agricultural and rural economies.

These and other barriers must ultimately be overcome if any government decides to institute policies to establish large-scale biomass energy markets. Continuing R&D efforts are addressing some of the above problems, many of which are close to resolution. Moreover, various organizations worldwide are helping to accelerate the acceptance and deployment of biomass energy by promoting technology transfer and conducting extensive information dissemination, education, and outreach activities.

7.1. INTRODUCTION

The amount of power produced by renewable energy (RE) devices such as photovoltaic cells and wind turbines varies significantly on an hourly, daily and seasonal basis due to the variation in the availability of the sun, wind and other renewable resources. This variation means that sometimes power is not available when it is required and on other occasions there is excess power.

The variable output from renewable energy devices also means that power conditioning and control equipment is required to transform this output into a form (voltage, current & frequency) that can be used by electrical appliances. This chapter looks at the devices used to store, condition and control the output from renewable energy systems, including remote area power systems (RAPS) and grid-connected installations.

7.2. ENERGY STORAGE TECHNOLOGIES

7.2.1. Introduction

Energy storage can be integrated with renewable energy generation systems either in stand-alone or grid-connected applications. For stand-alone systems, a storage unit is essential to store electricity for use when there is a deficit in the renewable resources. For grid-connected systems, a storage unit adds value to intermittent renewable resources by facilitating a better match between the demand and supply.

In combination with renewable energy sources, electricity storage can increase the value of photovoltaic (PV) and wind generated electricity, by making supply coincident with period of peak consumer demand (figure 7.1). Electricity storage may facilitate large-scale integration of intermittent renewable resources such as wind and solar onto the electric grid. Energy storage systems complement renewable resources with siting flexibility and minimal environmental impacts.

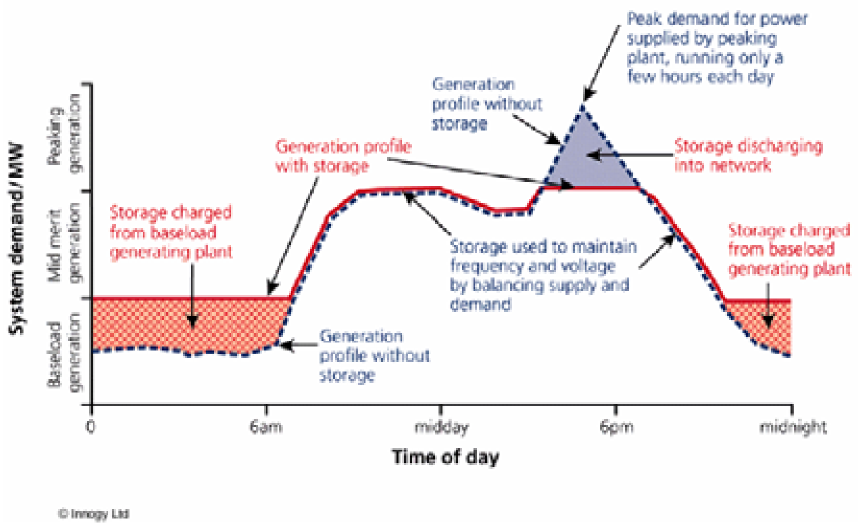


Figure 7.1. The concept of the energy storage

Storage can also play a flexible, multi-function role in the electricity supply network to manage resources effectively. As a generation resource, electricity storage can provide savings in operating costs or capital expenditure. Examples are: spinning reserve for temporary generation back up, frequency regulation for isolated utilities, capacity deferral of new generating facilities. Furthermore, strategically placed storage systems can increase the utilisation of existing transmission and distribution (T&D) equipment and defer or eliminate the need for costly T&D additions.

Energy storage can be used to reduce the stress on individual transmission lines that are near peak rating by reducing substation peak load. Among specific T&D benefits are: transmission line stability for synchronous operation to prevent system collapse, voltage regulation for consistent voltage within 5% of the set point and deferral of construction or upgrade of T&D lines, transformers, capacitors banks and substations. Opportunities may develop for Independent System Operators to deploy storage to help balance regional loads as restructuring proceeds.

Finally, energy storage can serve customers as a controllable demand-side management option that can also provide premium services, including power quality for sags or surges lasting less than 5 seconds, uninterruptible power supply for outages lasting about 10 minutes, and peak demand reduction to reduce electricity bills. A number of energy storage technologies have been developed or are under development for electric power applications. Each of these technologies will be shortly summarised in this part.

7.2.2. Battery technology

In recent years, much of the focus in the development of electric energy storage technology has been centred on battery storage devices. In a chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery. Currently there are a variety of battery energy storage technologies in use and under development.

Ongoing R&D activities will lead to significant improvements in the cost and performance of battery storage systems. At present, flooded lead acid and VRLA (Valve Regulated Lead Acid) batteries are commercially available, as well as some alcaline batteries (NiCd, NiMH). Zinc bromide and lithium batteries are two advanced batteries under development. Each of these technologies has particular strengths and weaknesses.

7.2.2.1. Lead acid batteries

Basically, flooded lead-acid battery technology for renewable energy storage systems is the large-scale application of a technology similar to that found in automobile batteries. Flooded lead acid batteries (figure 7.2) are manufactured in large numbers for many uses and their operating characteristics and technology are well understood by manufacturers. However, they have several key limitations:

- they require a frequent maintenance to replace water lost in operation;
- they are heavy with a reduced portability;
- the expected reduction of cost is limited.

The strengths of flooded lead acid batteries centre around their relatively long life span, durability and the commercial availability of the technology. This allows flooded lead acid battery customers to better justify their acquisitions and to amortise the cost of their systems over a long period. Flooded lead-acid batteries are the most common batteries found in PV applications.

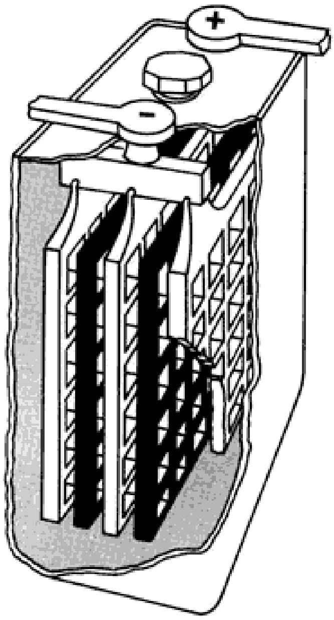


Figure 7.2. Schematic of a lead acid battery

VRLAs use the same basic electrochemical technology as flooded lead-acid batteries, but these batteries are closed with a pressure-regulating valve, so that they are essentially sealed. In addition, the acid electrolyte is immobilised. This eliminates the need to add water to the cells to keep the electrolyte functioning properly, or to mix the electrolyte to prevent stratification. The oxygen recombination and the valves of VRLAs prevent venting of the hydrogen and oxygen gases and the ingress of air into the cells.

The battery subsystem may need to be replaced more frequently than with the flooded lead acid battery, increasing the levelised cost of the system. The major advantages of VRLAs over flooded acid cells are:

- the dramatic reduction in the maintenance necessary to keep the battery in operation;
- the battery cells can be packaged more tightly because of the sealed construction and immobilised electrolyte, reducing the footprint and weight of the battery.

The disadvantages of VRLAs are that they are less robust than flooded lead-acid batteries, and they are most costly and shorter-lived. VRLAs are perceived as maintenance free and safe, and have become more popular for standby power supplies in telecommunications applications, as well as for uninterruptible power supplies in situations where special rooms cannot be set aside for the batteries.

7.2.2.2. Alcaline batteries

Nickel-cadmium (NiCd) batteries are used routinely in communication and medical equipment and offer reasonable energy and power capabilities. They have longer life cycle than lead-acid batteries, can be operated at very low temperatures (even down to -50°C) and can be recharged quickly. The battery has been used successfully in developmental Electric Vehicles. The main problems with NiCd batteries are high raw material costs, recyclability, the toxicity of cadmium, and temperature limitation on re-chargeability.

Nickel-metal hydride batteries are currently used in computers, medical equipment and other applications. They offer energy and power benefits and their components are recyclable. The main challenge with NiMH batteries are their high cost, the high temperature they crate during charging, the need to control hydrogen loss and their low cell efficiency.

7.2.2.3. Advanced Batteries

Among the advanced batteries that may support renewable energy applications is the zinc/bromide system. It uses a flowing aqueous zinc bromide electrolyte, with metallic zinc being deposited on the negative electrode, while the bromide produced at the positive is stored in external tanks. The advantages of zinc/bromide battery technology are low cost, modularity, transportability, low weight and flexible operation. Because of the chemical nature of the reactants and room temperature operating conditions, the casing and components can be constructed from low cost and lightweight moulded plastic and carbon materials.

The major disadvantages of zinc/bromide batteries centre around the maintenance requirements, including upkeep of pumps needed to circulate the electrolyte, and the somewhat lower electrical efficiency. Also, the zinc deposited during the charging process must be completely removed periodically. Other advanced batteries include the lithium-ion and lithium-polymer batteries that operate at or near ambient temperatures and may become appropriate for renewable energy applications.

Rechargeable lithium batteries have already been introduced into the market for consumer electronics and other portable equipment in small button and prismatic cylindrical size. The advantages of lithium batteries include their high specific energy (four times that of lead acid batteries) and charge retention. However, scaling up to the sizes, power levels and cycle life required for large applications remains an exacting challenge.

7.2.2.4. Comparison of battery types

Lead-acid is the most common used battery type in RE applications because it is cheap and widely available. Nickel cadmium batteries are used in cold climates such as the Polar Regions. Under normal operating conditions, the lifetime of each type is equivalent. However, under severe operating conditions a nickel cadmium cell lasts longer for the following reasons:

- its plates do not easily corrode,
- it does not suffer from sulphation and stratification.

For the foreseeable future tubular and flat plate lead acid will dominate the market. Pocket plate nickel cadmium batteries are also well suited to RE applications, as they operate over a large range of temperature and can be discharged to less than 10% of the nominal capacity. However, they are more expensive and so are only be used when high reliability or severe climatic conditions are expected. The full range of operational characteristics of various battery types is provided in table 7.1.

Table 7.1. Characteristics of different battery types

Type	Temperature of operation	Specific energy (Wh/kg)	Number of cycles	Specific power (W/kg) permanent/30s	Energy efficiency (charge – discharge)	Cost/kWh (€/kWh)
Pb/acid/PbO_2	-20°C - +50°C	25 - 45	300 -1500	80 / 150	0.75 - 0.85	110 - 230
NiCd – NiMH	-40°C - +40°C	25 - 65	1000 - 2000	75 / 250	0.6 - 0.75	400 -1200
Zn-Br	Ambient	60 - 70	500	90 / 110	0.65 - 0.7	300
Li polymer	+60°C - +90°C	110 -150	300 - 600	50 / 250	0.90	150 – 200*
Li ion	0°C - 50°C	80 -120	200 - 1000	50 / 200	0.85	250 – 400*

*cost objectives when at an industrial level

7.2.2.5. Battery sizing

There are different approaches to sizing batteries for RE applications:

- For stand-alone applications, some system developers have sized batteries to provide from 3 to 7 days of back-up.

- Sizing strategy for grid-connected applications depends on the uses of the system and the tariffs available from the local utility. For example, power quality applications require batteries sized to provide nearly instantaneous full-power discharges for only 15 minutes of back-up. A peak shaving application for a RE system may require the battery to boost the output of the generator to meet peak loads for 1-2 hours a day.

  If the differential between peak and off-peak electric rates is not significant, then the battery can be sized for one hour of operation and the facility owner can purchase power from the grid when the RE unit is not available. However, if the differential between peak and off-peak is significant, then an economic analysis should be undertaken to determine the optimum size of the battery system.

A number of developers optimise the RE installation, but not the battery system, opting for 7-10 hours of battery back-up in the event of outages. In many cases, RE installations require only minimal battery back-up to add value to RE generated electricity. If the transmission system is heavily loaded, batteries can store renewable energy that would be lost during hours when transmission service is constrained, delivering the electricity later.

7.2.3. Pumped hydro

Pumped hydro has been in use since 1929, making it the oldest of the central station energy storage technologies. In fact, until 1970 it was the only commercially available storage option for generation applications. Conventional pumped hydro facilities consist of two large reservoirs, one located at base level and the other situated at a different elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Such a pumping storage installation, at the site of Turlough Hill in Ireland, is shown in figure 7.3.

Figure 7.3. Aerial view of the upper and lower reservoirs of the pumping storage installation at the Turlough Hill (Ireland) (© ESB)

Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines that generate electrical power as high as 1000 MW. The barriers to increase use of this technology include high construction costs and long lead times, as well as the geographic, geologic and environmental constraints associated with reservoir design. Currently, efforts aimed at increasing the use of pumped hydro storage are focused on the development of underground activities.

7.2.4. Compressed air energy storage (CAES)

CAES plants use off-peak energy to compress and store air in an airtight underground cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. Currently, manufacturers can create Compressed Air Energy Storage machinery for facilities ranging from 5 to 350 MW. Studies have concluded that such a technology is competitive with combustion turbines and combined cycle units, even without attributing some of the unique benefits of energy storage.

7.2.5. Flywheels

Flywheels are currently being used for a number of non-utility related applications. Recently, however, researchers have begun to explore utility energy storage applications. A flywheel storage device consists of a flywheel that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel (see figure 7.4).

The use of magnetic bearings and a vacuum chamber helps reducing energy losses. A proper match between geometry and material characteristics influences optimal wheel design. As a result, engineers have focused on the development of materials with high working strength-to-density ratios. Flywheels have been proposed to improve the range, performance and energy efficiency of electric vehicles. Development of flywheels for utilities has been focused on power quality applications.

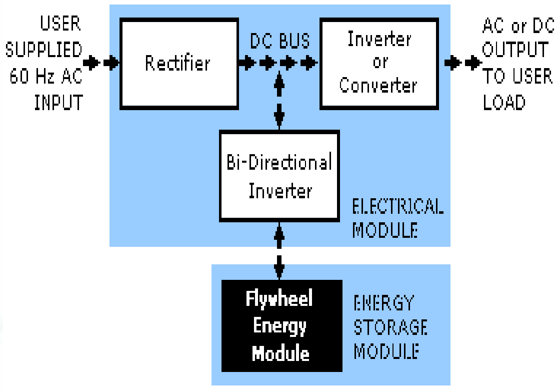


Figure 7.4. Schematic view of a flywheel energy module and its operation

7.2.6. Superconducting magnetic energy storage

A Superconducting Magnetic Energy Storage (SMES) system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. To maintain the coil in its superconducting state, it is immersed in liquid helium contained in a vacuum insulated cryostat. The energy output of such a system is much less dependent on a discharge rate than batteries. SMES systems also have high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation.

Although research is being conducted on larger systems in the range of 10 to 100 MW, recent focus has been on smaller devices in the range of 1 to 10 MW. Micro systems devices are available for power quality applications. Figure 7.5 provides a schematic view of a SMES 3 MW unit output of real power with a response time <0.5ms. This unit can be connected to transmission grid from 69 to 500 kV.

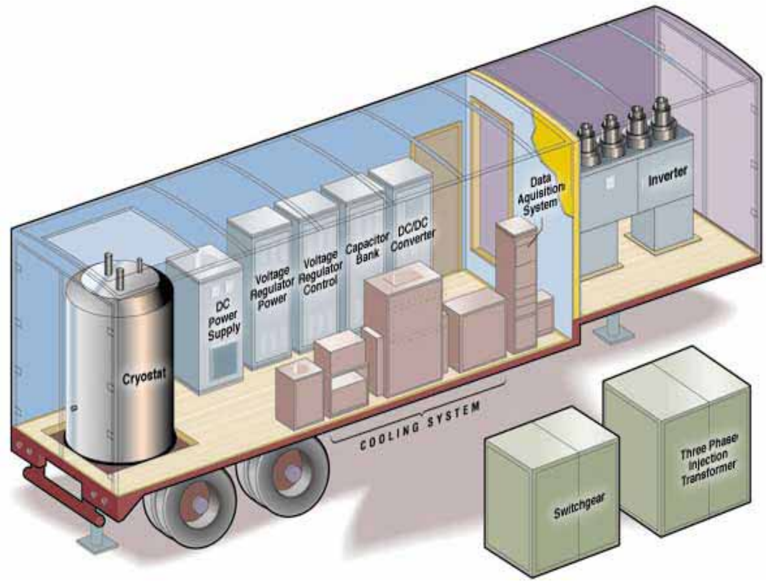


Figure 7.5. Schematic view of a 3 MW unit output SMES

7.2.7. Advanced electrochemical capacitors

Super-capacitors (also known as ultra-capacitors) are in the earliest stages of development as an energy storage technology for electric utility applications. An electrochemical capacitor has components related to both a battery and a capacitor. Consequently, cell voltage is limited to a few volts. Specifically, the charge is stored by ions in a battery. But, as in a conventional capacitor, no chemical reaction takes place in energy delivery. An electrochemical capacitor consists of two oppositely charged electrodes, a separator, electrolyte and current collectors.

Capacitance	2700 Farads (-10% / +30%)
Voltage	2,5 V
Rated current	625 A (5 s discharge rate to 0.5V)
Size	161 x 61.5 x 61.5 mm
Weight	725 g
Temperature	-40°C to 70 °C
Leakage	6 mA (after 72 hours)

Figure 7.6. View of a commercialised super-capacitor and its characteristics

Presently, very small super-capacitors (see figure 7.6) in the range of seven to ten Watts are widely available commercially for consumer power quality applications and are commonly found in household electrical devices. Development for larger scale capacitors has been focused on electric vehicles. Currently, small-scale power quality (< 250 kW) is considered to be the most promising utility use for advanced capacitors.

7.3. BATTERY CHARGE CONTROLLERS (REGULATORS)

The table included in the Annex summarizes the key features of each energy storage system. Batteries, flywheels, SMES and advanced electrochemical capacitors lend themselves to distributed utility applications, while pumped hydro and CAES are large, centralized installations. All cost estimates are for complete systems with power conditioning subsystems (PCS), controls, ventilation and cooling facilities, and other balance of plant components. In the case of renewable energy generation technologies, the most appropriate storage systems appear presently to be batteries.

Batteries have been installed in stand-alone PV and wind systems for more than two decades throughout the world. Batteries support renewable generation in at least four size ranges:

(a) less than 1 kW - rural electrification,

(b) 1 to 5 kW - residential,

(c) 10 to 100 kW - commercial, industrial or village, and

(d) more than 1 MW - generation of grid support.

Much of the activity funded by the PV industry has focused on rural or residential scale applications with oversized battery back-up, while much of the activity funded by the battery manufacturers has focused on the industrial scale applications with low battery back-up.

Batteries are not specifically designed for RE systems, even if research activities are under way to take into account the specific behaviour of the storage unit, namely in stand-alone RE systems. Most of the batteries used in current small PV systems were actually designed for use in deep-cycle electric vehicle or recreational vehicle applications, where the recharge is carefully controlled and complete for every cycle. In all cases, to protect the battery bank from over-charging and over-discharging, a battery charge controller should be used.

7.3.1. The concept

The lifetime of a battery depends on the strict respect of the operating conditions specified by the manufacturer. A charge controller is used to guarantee that the conditions are met, which are described by limiting values. Its main function is to protect the battery against overcharging and deep discharging; in doing so, the charge controller cannot avoid interruptions to the operation of the RE system when the limiting values are reached, namely by disconnecting a load when the discharge voltage limit has been reached.

The management of the battery state of charge for control purposes is usually done through voltage measurements, even if some methods are developed to refine this matter of fact through Ampere-hours counting or SOC algorithm utilisation. Most of RE systems including a lead acid battery storage have a control system in which voltage thresholds have been fixed to protect the battery:

- A high voltage threshold to avoid battery overcharge leading to electrolyte hydrolysis and plates corrosion. This threshold is frequently called High Voltage Disconnect.
- A low voltage threshold to avoid battery deep discharge, often called Low Voltage Disconnect.
- Two intermediate thresholds to reconnect the battery to the system: High Voltage Reconnect and Low Voltage Reconnect.

7.3.2. Overcharge protection

In order to ensure full charging of the energy storage, lead-acid batteries are charged according to a so-called IV characteristic. At the beginning of the charging process, the battery receives maximum charging current, but when the end-of-charge voltage is reached, the mean charging current slowly drops off to zero, while the voltage is maintained at a constant level (figure 7.7). This method allows full charging of the battery. The end-of-charge voltage depends on the battery type. For 12V lead acid batteries with liquid electrolyte serving in stationary installations, the producers recommend an end-of-charge voltage of roughly 14.4 V.

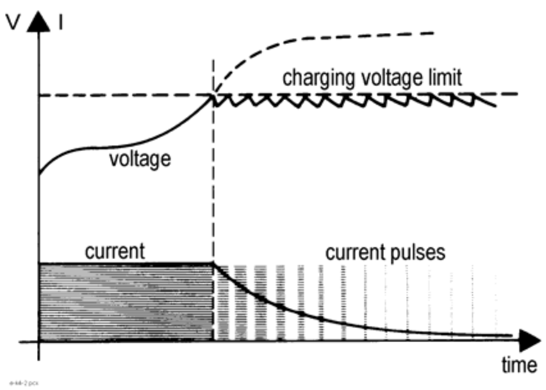


Figure 7.7. Voltage and current profiles during charging

If the battery of the RE system is not installed in a room with nearly constant temperatures but is instead exposed to substantial temperature variation, the best way to ensure a long service life coupled with high economic efficiency is to adapt the overload-protection switching thresholds (end-of-charge voltage, release threshold for two-step control) to the temperature of the battery and its surroundings. Otherwise, the battery may sustain damage due to overcharging at elevated temperatures and, on the other hand, will not be able to provide its full nominal capacity at lower temperatures.

A temperature coefficient of -4 to -5 mV(K·cell) makes a good rule of thumb for determining the battery's "temperature-compensated" end-of-charge voltage. Thus, the end-of-charge voltage of a 12-V battery (6 cells), which amounts to 14.4 V at 20°C, should be lowered to 13.8 V for a service temperature of 40°C. Due to charge/discharge cycling, batteries with liquid electrolyte eventually develop different acid-density zones in their electrolyte. This detrimental phenomenon can be avoided by keeping the electrolyte well-mixed.

Gassing of the electrolyte caused by time limited overcharging produces bubbles of oxygen and hydrogen that guarantee the mixing of the different layers of acid densities. At present, most of the development in different management strategies have been undertaken to prevent the battery from overcharge, while optimising the system behaviour. The most easy one is a simple disconnection of the RE generator when the battery reaches a voltage threshold which is in the case of lead acid batteries about 2.4 Volts/cell.

In order to avoid such a disconnection, some controllers are managing the battery recharge in a floating mode, allowing a low current to recharge the battery when the HVD is reached so that the voltage never exceeds the HVD. Some regulators present a “boost charge” function that is used when the LVD is often reached in order to fight against the electrolyte stratification and help the recombination of lead sulphate in lead or lead dioxide.

This “boost charge” allows raising the HVD up to 2.5 or 2.7 Volts/cell. The difference between these regulators concerns essentially the “boost charge” frequency. Some of them use this function when the LVD is reached. Nevertheless, this kind of recharge must not be too frequent as it can create other degradations such as corrosion and shedding. Battery manufacturers suggest to use this “boost charge” once every three weeks.

Another regulation strategy (PWM: Pulse Width Modulation) has been developed, based on the results of a Sandia Laboratories study, modulating the recharge current delivered by a PV array leading to:

- a better recombination of the lead sulphate crystals,
- a better recharge efficiency,
- a longer life time of the battery,
- a decrease in the battery gazing by limiting the recharge period.

This regulation strategy starts in the first phase with a typical recharge (full PV array current) until a given battery voltage. Then, the current is modulated: a mean constant current is applied to the battery with a variable period.

7.3.3. Deep discharge protection

As soon as the battery's voltage drops below the LVD, the load is disconnected from the battery and cannot be reconnected until the battery has been adequately recharged. It is very important to choose the correct cut-off voltage. To avoid deep discharging in any case, the cut-off voltage must be adapted to the discharging current (table 7.2).

Table 7.2. Discharge voltage limits for lead-acid batteries

Discharge current I_D[1] [-]	Discharge voltage limit V_D [V]
I_{10}	1.80 - 1.85
I_{20}	1.85 - 1.90
I_{50}	1.90 - 1.95
I_{100}	1.95 - 2.00

If charge controllers with a fixed end-of-discharge threshold are used this value should not be below 1.9V/cell, i.e. 11.4 V for a 12 V battery. It is recommended that this threshold is stable for all temperatures. To prevent the disconnection of the load due to short high current pulses, e.g. starting of a motor, the load cut-off should be retarded for at least some seconds. Charge controllers are exposed to many sources of damage during both installation and operation, and in order to function correctly, they should include the forms of protection described in the following.

7.3.4. Protection against external influences

Protection against moisture: A distinction must be made between direct contact with water (rain, water spray) and high air humidity. The housing of the charge controller must be well sealed to protect against the entry of water (high IP protection class, IP 65 where possible). Where the air humidity is high, a housing with a certain degree of air circulation is suitable. Further, protection can be achieved by adequate spacing between the electronic components, appropriate choice of the board material and lacquering the board.

Protection against incorrect operation: The most common mistake when installing a charge controller is reversing the polarity of the connections. Thus, it is necessary to protect the inputs to the solar generator and the battery against reverse poling with so-called free-wheeling diodes and a suitable fuse.

Protection against over-voltage: Both the input and the output of the charge controller should be protected against short-term voltage peaks.

[1] It is common practice to define the rated capacity at 20°C temperature by discharging the battery by means of a constant discharge current for 10 hours, i.e. I_{10}. In photovoltaic applications often quite lower currents occur for e.g. I_{100}, which is the current referring to 1/100 of the rated batteries capacity. Thus, with a rated capacity of 100 Ah, I_{10} is 10A and I_{100} is 1A.

Protection against overloading: On the input side, it is possible that the module current rating is exceeded, e.g. when additional light is reflected onto the solar module. Corresponding reserves should therefore be built into the charge controller. On the output side, a fuse should protect against overloading.

7.3.5. Main types of charge controllers

Two main types of charge controllers can be distinguished, namely:

- Series controller: With a so-called series controller, as illustrated in figure 7.8, the connection between the solar generator and the energy storage unit is interrupted when the charging limit is reached. Relays, bipolar transistors or MOS-FET can be used for the disconnection. The series regulation principle originated in classical charging technology and is also used in grid-connected charging devices. It is often told that, the disadvantage of this principle in comparison to the other principle is that the series controller lies in the losses that occur at the switch.

  Since the development and application of semiconductor switches with very low "on"- resistance this is no longer true. The charging losses of both types of controller are now in the same range. Critical under certain circumstances is, however, that with completely exhausted batteries the closing of the charging circuit may be not possible any more, leading to the complete destruction of the battery. The load is disconnected from the battery to protect it against deep discharge, when the voltage falls below the deep discharge limit.

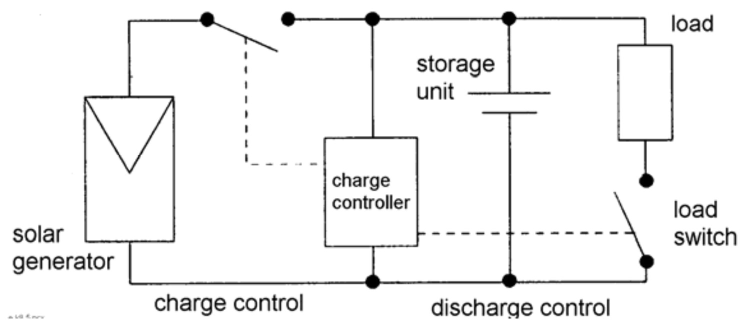


Figure 7.8. Charge controller with series regulation

- Shunt controller (short circuit controller): When advantage is taken of the specific properties of solar cells, a control principle can be applied which avoids the disadvantages of series regulation. Thus, in the circuit illustrated in figure 7.9, the solar generator is simply short-circuited via an electronic switch when the battery is fully loaded. The voltage across the switch or transistor then falls almost to zero.

  However, this loss does not affect the energy balance of the photovoltaic system, as it only occurs when the battery is fully charged and the solar energy is not needed anyway. In contrast to most series controllers, this procedure functions reliably even when the battery capacity is completely exhausted (voltage < 9 V), as the short circuit switch does not have to be activated until the battery has been recharged. A blocking diode is necessary to prevent the battery from being short-circuited. During the night it serves also against discharge via the solar generator.

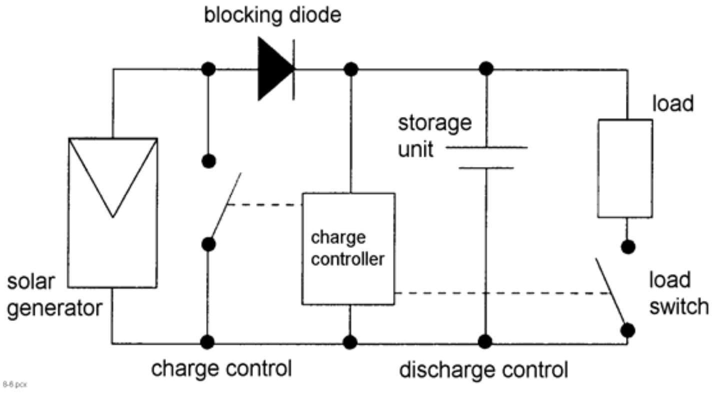


Figure 7.9. Charge controller with short circuit regulation (shunt principle)

- PWM controllers: These regulators use a high frequency switching technique. The regulator switches the control device on and off quickly. When the batteries are discharged the unit will be switched fully on. As the battery is reaching a fully charged state the unit will start switching the control device on and off in proportion to level of charging required. When the battery is fully charged no current will be allowed to flow to the battery. In solar systems the PWM technique is used in series with the solar modules. In wind turbine systems this technique uses a shunt (dump) load to divert excess energy away from the batteries

7.4. INVERTERS FOR GRID-CONNECTED SYSTEMS

7.4.1. Necessity

Renewable energy systems often provide low voltage, direct current (DC) from batteries, solar panels or wind generators. To use this DC power directly requires special non-standard appliances that may be available for camping and other portable or low power applications. Some appliances, such as fridges are relatively expensive. Electricity available from the main electricity grid is provided as alternating current (AC), so most appliances are manufactured to suit this supply. The electrical energy used by the appliance is referred to as the load on the system.

On the other hand, a PV system installed on a house roof for generating some of the electricity required uses the public electricity grid for storage (figure 7.10). If more solar electricity is generated than currently needed, the surplus can be fed into the grid. Conversely, during overcast weather and at night, grid electricity can be drawn to supply the household. During a power blackout, the grid-connected photovoltaic system does not provide power to the household, because it needs the grid to determine the frequency and the voltage.

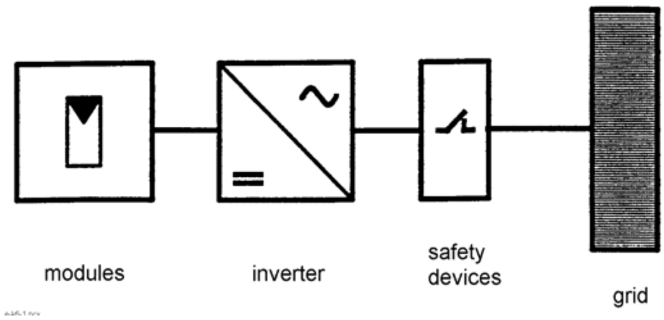


Figure 7.10. Schematic circuit diagram for grid-connected photovoltaics

Moreover, grid-connected RE systems typically consist of the following components, as can be seen in figure 7.10, where a grid-connected photovoltaic system is shown:

- the generating unit,
- an inverter,
- the safety circuit (grid connection).

The inverter is the heart of the system. It converts the direct current from the modules to alternating current. The planning of a grid-connected RE system begins with the choice of a suitable inverter. This determines the system voltage on the DC side and the generator can then be configured according to the input characteristics of the inverter.

7.4.1.1. Fundamental characteristics of grid-connected inverters

The inverter is the most important component of a grid-connected RE system after the generator. Its task is to convert the direct current generated by the RE converter to 50 Hz alternating current conforming to the grid. In contrast to inverters intended only for stand-alone operation, those intended for parallel operation must respond just as well to the grid characteristics as to the generator performance. As all of the current flows through the inverter, its properties fundamentally affect the behaviour and operating results of the RE system.

Apart from the efficient conversion of direct to alternating current, the inverter electronics also include components that are responsible for the daily operation mode. In the case of PV systems, they ensure that operation starts at the right time in the morning as soon as the solar cells deliver enough power. Unsuccessful start attempts require energy from the grid and should be avoided by good controls. During the day, the optimum working point on the I-V characteristic curve shifts according to the fluctuations in solar radiation and module temperature.

Intelligent control by the inverter includes maximum power point (MPP) tracking, that is the continuous readjustment to the most favourable working point. This is used with photovoltaic modules to optimise the match between the panels and the battery bank. This technique uses a DC to DC converter with circuitry that measures the incoming power from the module and adjusts the voltage so that the maximum power is being sent to the battery bank independent of the battery bank voltage.

Protective devices are also integrated into the inverter, which automatically disconnect the system if irregularities in the grid or the RE generator occur (figure 7.10). Some inverter models are additionally equipped with data loggers and measurement computers, which allow the power, voltage, current and other operating parameters to be recorded continuously. These data can be read out at intervals via a serial interface with a laptop computer and analysed.

Grid-connected inverters can operate according to different principles:

- The inverter output is conceived as a regulated current source. The variation with time of the supplied electricity is regulated such that it corresponds to the variation of the prevailing grid voltage. If the grid voltage deviates significantly from a sinusoidal waveform, this waveform will also be imitated by an inverter operating on this principle.
- Regardless of the waveform of the grid voltage, the inverter supplies internally regulated, sinusoidally modulated current to the grid, which flows synchronously to the grid voltage.
- The inverter attempts to improve the imperfect waveform of the grid voltage by supplying electricity with the appropriate waveform. This succeeds better when the connected grid has a lower power (higher impedance) than with strong grids.

7.4.1.2. Requirements on grid-connected inverters

In the case of PV systems, as a typical example, the requirements on grid-connected inverters are the following:

- Automatic operation start in the morning.
- High partial load efficiency.
- Defined overload operation.
- Operation at the maximum power point (MPP) of the PV generator.
- Power supply for the internal control electronics from the solar generator side.
- Low ripple on the solar generator voltage.
- Inverter tolerance of short circuit and open circuit conditions.
- Adequate instrumentation, simple operation by the user.
- Automatic disconnection from the grid on voltage or frequency deviation.
- Galvanic separation of the PV generator from the grid.
- Earth connection monitoring integrated into the inverter.
- Power factor: cos φ> 0.9.
- Low harmonic content in the AC power supplied to the grid.

7.4.2. Types of grid-connected inverters

There are several basic types of grid-connected inverters, which all have different properties:

- Grid-commutated inverters (thyristor devices).

- Self-commutated inverters with pulse-width modulation and low frequency (LF) transformer.
- Self-commutated inverters with pulse-width modulation and high frequency (HF) transformer.

7.4.2.1. Grid-commutated inverters

Grid-commutated inverters are relatively inexpensive, because their components are derived from existing thyristor devices for drive unit technology. These inverters are simple and robust, being constructed of standard components. They normally supply three-phase power to the grid. Inverters for the higher power range (> 100 kW) are almost all constructed according to this principle.

Some of the characteristics of thyristor inverters are the following:
- The thyristor can turn on the current but not turn it off.
- The grid voltage is needed for commutation.
- The inverter has the characteristics of a current source.
- High harmonic content, because the electricity is supplied to the grid in blocks (rectangle or trapezium).
- Reactive power drawn from the grid, because the current is out of phase with the grid voltage (ignition angle).
- Grid voltage interruptions cause inverter stalling.

7.4.2.2. Self-commutated inverters with pulse-width modulation and a 50 Hz transformer

With self-commutated inverters, the grid voltage is not needed to switch off the power semiconductors. Thus, these devices can also be used in stand-alone operation. The final power block is equipped with fast semiconductor switches:

- bipolar transistors;
- MOSFET (power field effect transistors with insulated gate);
- IBGT (bipolar transistors with insulated gate).

In self-commutated inverters, the sinusoidal form of the output current is achieved by pulse width modulation with a high frequency. In the lower power range (1 - 5 kW), specifically optimised inverters for photovoltaics are on the market. They are usually equipped with MOSFET transistors and have an intrinsically low harmonic content, so that additional filters are not needed. It is possible to keep the distortion factor below 1% with the switching configurations that are usual today.

The operating principle of this type of inverter is illustrated in figure 7.11. The voltage of the solar generator is laid with variable pulse width and alternating polarity on the grid transformer via the bridge circuit, consisting of four electronic switching components. The pulse width is controlled such that the AC side has a minimum harmonic content.

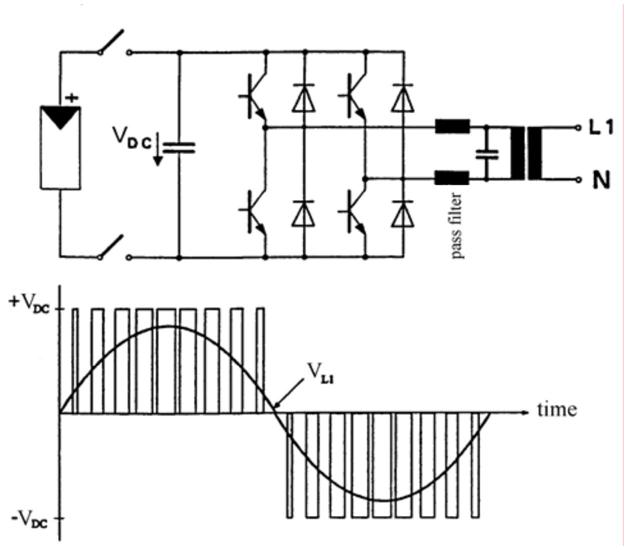


Figure 7.11. Self-commutated inverter with pulse width modulation

7.4.2.3. Self-commutated inverters with pulse-width modulation and an HF transformer

All of the previously described inverters include a 50 Hz transformer for potential separation and voltage matching. A toroidal transformer was used in the optimised devices to reduce the iron losses. The incorporation of HF transformers was a further attempt to reduce the internal consumption. It also allowed the weight and dimensions to be reduced. Ferrite transformers ensure the galvanic separation of the grid and the solar generator here. The inverter circuit illustrated in figure 7.12 avoids the large and heavy 50 Hz transformer by using smaller ferrite transformers.

The inverter consists of several stages:

- <u>HF inverter</u>: The direct current from the solar generator is transformed in a self-commutated inverter to high-frequency alternating current. The switching frequency is 10,000 to 50,000 Hz. The MPP control with pulse width modulation also occurs at this stage. The HF transformer ensures the galvanic separation of the solar generator and grid potentials. Because of the high frequency, the HF shell cores are only about as large as a fist. They consist of ferrite material, which is sensitive to impact.
- <u>HF rectifier</u>: The high-frequency alternating current from the transformer is rectified in this stage. The diodes used here must be able to switch the high frequencies with particularly low losses.
- <u>Filter circuit</u>: The pulse width modulation voltage is smoothed to a sinusoidal form in this low-pass filter.
- <u>50 Hz bridge</u>: Every second sinusoidal half-wave is inverted and connected to the grid here via cylindrical induction coils. As this stage is directly at the grid voltage, attention must be paid to the dielectric strength of the thyristors or IBGT's used.

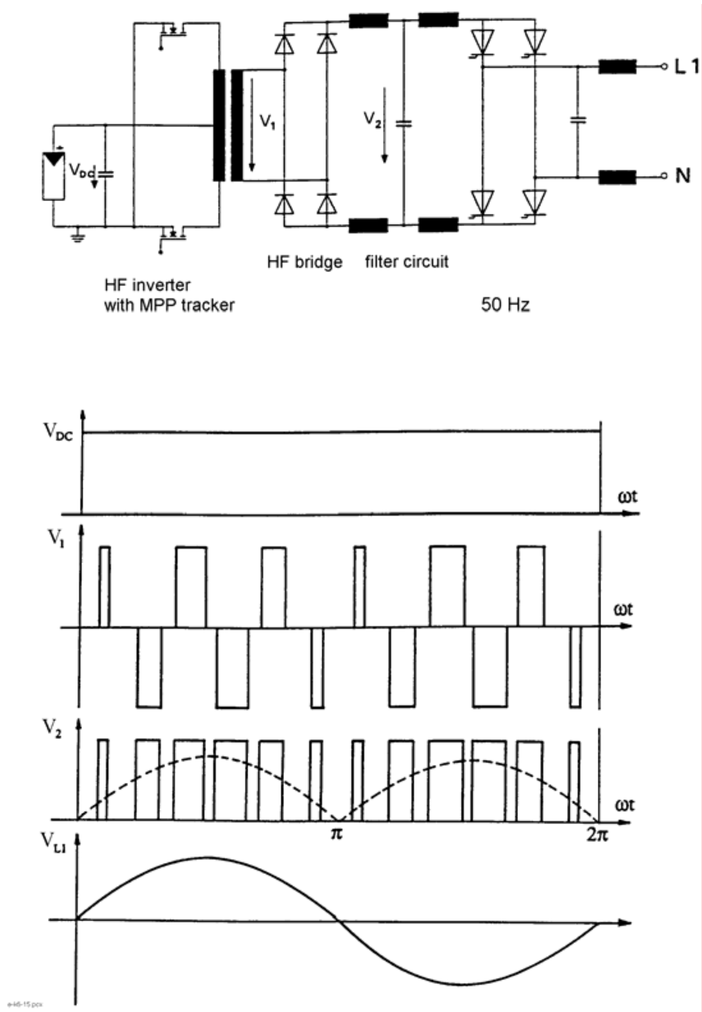


Figure 7.12. Switching principle of an inverter with an HF transformer

7.5. SYSTEM CONTROLLERS

In systems with a number of power sources sophisticated system controllers are required. These controllers are usually computer controlled, with inputs indicating the state of the system being fed into the controller and then the microprocessor makes changes to the system operation if necessary. The functions performed by system controllers include:

- disconnecting or reconnecting renewable energy sources;
- disconnecting or reconnecting loads;
- implementing a load management strategy;
- starting diesel generators if battery voltage is too low or if load becomes too high;
- synchronising AC power sources (e.g. inverters and diesel generators);
- shutting systems down if overload conditions occur;
- monitoring and recording of key system parameters.

7.5.1. Controllers for stand-alone wind-diesel applications

These units provide supervisory control of diesel generators and wind turbines to provide seamless utility-grade power in remote locations. Their modular, pre-integrated design allows them to adapt to a variety of applications without expensive custom engineering. The controllers combine a proven, robust microprocessor control module with refined control software. The result of their reliable control and monitoring functions is stable, high quality, utility grade power.

The controller features are the following:

- Proven, mature technology from the generator control industry.
- Easy integration of a variety of system elements, including synchronous condensers, rotary converters, electrical storage components, and critical/non-critical load controls (custom hardware design costs are eliminated).
- Automatic generator-only operation in the event of a failure (the loss of the control system will not result in a loss of power).
- Flexible system architecture able to accommodate the range of existing diesel generator and wind turbine control packages.

During their operation these controllers will switch a wind/diesel hybrid system between four states of operation. In times of no wind, the system will operate “diesel only”, bringing generators on and off line for maximum fuel efficiencies. When there is enough wind to produce power, the controller will reduce the output of the diesel generators to match the load. If the wind increases just to the point where the wind turbine can match the load by itself, the controller will set one diesel generator to a minimum level and dump excess wind power to a secondary heat load.

The addition of battery storage would allow the generator to be shut down in this state. When the wind power is ample enough to allow a margin of safety, the controller will switch off the last diesel generator and use the heat load to absorb the excess power production. The heat load is variable, and acts along with the synchronous condenser or rotary converter to maintain power stability. The controller ensures seamless transitions between operating states and the most efficient use of both diesel fuel and the wind resource.

The controller consists of a range of digital based control modules especially designed for power control applications. These are:

1. The *wind/diesel controller* handles the sequencing (On/Off control) of power units (e.g. wind turbines, diesels, storage systems, synchronous condensers, rotary converters and dump loads). The wind/diesel controller is aware of loading on the diesel generator sets, power output of the wind turbines, and status of the secondary load controller. From this information, the wind/diesel controller makes state change decisions for the major power system components in the overall system.
2. *Wind power controller*: The turbine manufacturer provides normal control of the wind turbine generator. The wind power controller sends a “permission to

operate” signal to the wind turbine controller to allow it to start, and interfaces with the turbine controls to monitor its operation.

3. *Secondary load controller*: The secondary load controller is designed to switch a set of binary dump loads in order to match the total electrical demand to the power being generated. The secondary load controller will act as the prime bus frequency control during operation at high levels of wind power penetration.
4. *Energy storage controller*: The energy storage controller is a software module to provide overall supervisory and state control to an electrical power storage system such as a battery bank. The ESC will provide load support during wind-only operation.
5. *Engine/generator modules*: Each engine must have an engine control system and an electronic governor. These are typical hardware components on all diesel genset units and control basic engine functions. Each generator must have an automatic voltage regulator as part of its standard equipment. Engine control system will provide the engine sequencing, synchronizing, and load and reactive power sharing between generators.
6. *Synchronous condenser controller*: It consists of a synchronous generator with a clutched pony motor for starting, and an automatic voltage regulator. A standard power controller with software adaptations carries out the synchronization and control of the unit. In applications with battery storage the synchronous condenser would be replaced with a rotary converter. The rotary converter would take on the functions of the synchronous condenser, plus battery charging and inverting.
7. *Communications processing module*: This is a PC based industrial computer platform that will collect data from the various control platforms. It is possible to configure this subsystem with a monitor running a local operator interface. The communications processing module acts as a data collection and storage device through which operating data can be retrieved via remote link. By using a PC platform the form of remote communications is transparent. The communications processing module allows an electric utility or other remote provider to connect in real time to the control system. It is able to communicate using the public switched telephone network, internet, radio modem, microwave modem, satellite modem, or cellular phone.
8. *Networked I/O*: To enable comprehensive control of ancillary site requirements such as environmental systems, thermal systems, or specific dump load applications such as electric heaters, desalinisation or ice making, the system architecture should allow additional I/O and processing to be added to either the Modbus or Echelon communications networks. This feature makes the overall control architecture flexible enough to meet a variety of applications without requiring custom parallel control systems or adversely affecting the cost of individual components.

7.5.2. High penetration AC bus wind-diesel systems

High penetration AC bus wind/diesel systems (figure 7.13) have complex control requirements, and significant engineering development effort is still required. AC bus architecture appears to be the more cost-effective choice for larger (> 100 kW) hybrid power systems. System integration is the key. The individual components of an AC system can be as reliable as those of a DC system.

The basic control principles of AC bus hybrid power systems are the following:

1. The frequency is controlled by maintaining a balance of real power between:
    - dump loads;
    - control power to/from energy storage;
    - diesel load, according to the type of generator:
        - ordinary diesel;
        - variable speed diesel;
    - controllable output variable speed wind turbines.
2. The voltage is controlled by maintaining a balance of reactive power using:
    - diesel generator voltage regulator;
    - synchronous condenser;
    - static VAR compensator.

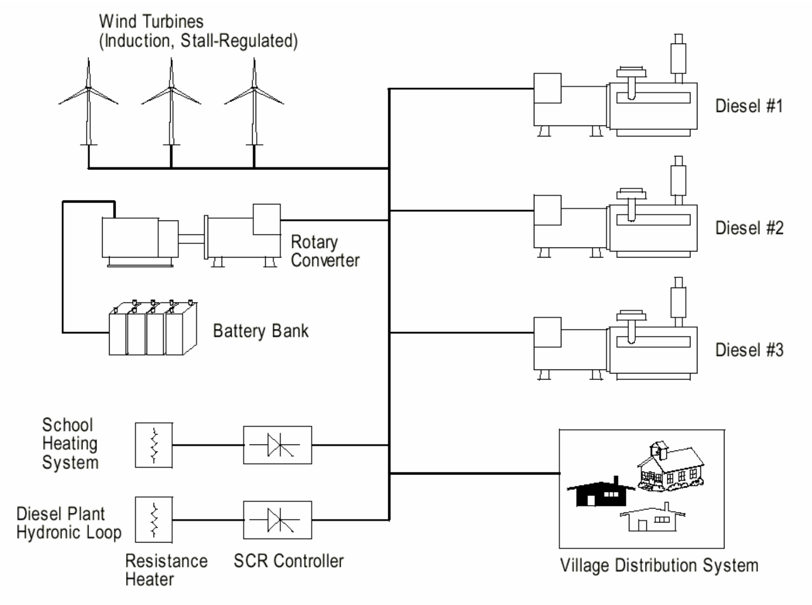


Figure 7.13. Example of an AC bus hybrid system including the controls

7.5.3. DC bus systems

DC bus hybrid systems, as the one shown in figure 7.14, have different control requirements that typically include:

- Battery over-voltage - wind & PV regulators.
- Battery under-voltage (load shedding) – inverter.
- Battery equalization - wind & PV regulators.
- Back-up generator start / stop - inverter or DC source centre.
- Centralized controller, which monitors all sources and loads, is not necessary.
- Most controls triggered by DC bus voltage (battery bank voltage).

- State-of-charge monitors or energy counting (e.g., net Ampere-Hours) controls don't work as well.
- Some people prefer to have manual back-up power, controlled by local operator.

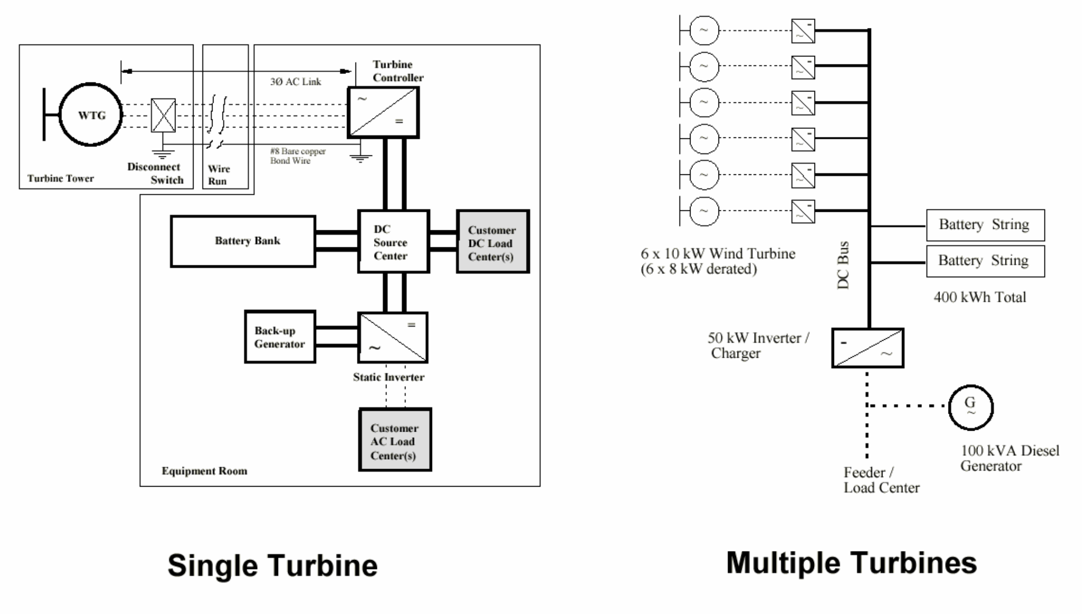


Figure 7.14. A DC bus system architecture

APPENDIX

Energy storage technology profiles

Technology	Facility size range	Potential/actual applications for electricity production	Efficiency	Commercially available	Estimated system costs
Batteries	From 100W to 20 MW	- Spinning reserve - Integration with RES - T&D applications - Power quality - Peak shaving	0.7 - 0.9	Yes (Lead-acid, alcaline) No (Zinc/bromide, lithium)	200 - 300 €/kW (range of kW) 750 - 1000 €/kW (10s MW, 2 hrs) 500 - 600 €/kW (10s MW, 0.5 hr) 400 - 600 €/kW (2 MW, 10-20 sec)
Pumped Hydro	Up to 2.1 GW	- Load levelling - Spinning reserve	0.75	Yes	300 - 500 €/kW
CAES	25 MW to 350 MW	- Peak shaving - T&D applications - Spinning reserve	0.7	Yes	350 - 500 €/kW (commercial plant estimates)
Flywheels	kW scale	Power quality	0.7 - 0.9	Yes (Steel, low rpm) No (Advanced composite)	Steel: 300 €/kW (1MW, 15sec) Advanced: 6 000 €/kW (~1 kW) 3 000 €/kW (~20 kW)
SMES	From 1 - 10 MW (micro SMES) To 10-100 MW	- T&D applications - Power quality	0.9 - 0.95	Yes (micro SMES) No (larger units)	500 - 1000 €/kW (1-2MW, 1sec)
Ultra capacitors	7 - 10 W commercial 10 - 20 kW prototype	Power quality	0.9 - 0.95	Yes (Low voltage, standby power) No (Power quality)	500 €/kW

8.1. INTRODUCTION

The Community's target of doubling the current share of renewables by 2010, thus attaining a 12% contribution to the EU's gross inland consumption, is generally agreed to be a realistic goal and a necessary first step to comply with the international commitments of environmental protection. Despite the remarkable technological progress achieved recently and the increasing competitiveness of RE technologies, the large-scale integration of renewable energies into the European energy system is not straightforward.

Available technical options are capable of satisfying ambitious targets only if considered from an integral planning perspective and used in combined schemes aiming at maximising efficiency. This means that significant changes have to be made in existing energy infrastructures for accommodating RES in an optimised way. Moreover, if in the long term renewables are intended to play a prominent role in the total energy supply, a radical renewal of energy infrastructures has to take place.

In concept, RE systems and schemes can be envisaged to consist only of RE technologies for up to 100% local power supply from centralised RE systems and integration of dispersed RE schemes into the existing power supply. In practice, the power supply will often include fossil fuel energy sources for support and backup, in particular when RE systems are introduced in supply systems with existing fossil fuel power plants. Besides, RE technologies when used on their own have shortcomings when compared to the ability of traditional fossil fuel generation technologies to supply firm power with accepted high capacity value.

Therefore, in order to utilise the full potential of RE technologies, they may be used together in an integrated way comprising hybrid schemes. Such integrated systems could consist of RE generating technologies in combination with other RE technologies and energy storage and/or power conditioning technologies. They can be used in different layouts (centralised systems for local power supply or dispersed schemes for regional power supply) adapted to the conditions and possibilities of each specific location, so that to ensure firm and reliable power.

Ultimately, RE systems could develop into completely RE based schemes that include new types of energy carriers, such as Hydrogen, in combination with new ways to supply and manage the end user's energy demand. During the last decade it has been widely recognised that technical progress is a necessary but not sufficient condition for the large-scale integration of RES. Regarding the cost of renewable technologies, existing market imperfections still limit the establishment of fair competition with conventional systems.

This situation may severely threaten the further development of RE generated electricity in the emerging internal electricity market and, therefore, undermine compliance with the targets set in the White Paper on RES and the Kyoto commitments. The proposal of the Commission for a Directive "on the promotion of electricity from renewable energy sources in the internal electricity market" provides a sound framework for minimising relevant risks.

Furthermore, recent experiences in different EU countries or regions clearly demonstrate that there are ways to a successful implementation of RES systems, even in a rapidly liberalising market. In addition, the new constraints regarding environmental protection and sustainable development establish a very positive framework, favouring the option of RES against conventional energy sources.

8.2. RE TECHNOLOGIES IN EUROPE

8.2.1. Present situation

There is presently a significant increase in the interest shown by governments, planners, utilities and private investors for including RES technologies in the energy supply portfolio. A long-term goal of European policy is a significant contribution (12 % at year 2010) from European based renewable energy, which specifically for the power sector is planned to reach 22.1% of the gross electricity consumption by 2010 (12.5% excluding large hydro). This goal is influenced by rising concern regarding externality costs (CO_2 - related and others).

Today's most promising RE technologies are based on wind, biomass and solar energy for electricity production as well as for heat production. Currently, RES applications mostly deal with one RE technology at a time, such as wind parks, PV systems, etc. To date international Research and Development (R&D) in hybrid RE systems has mostly concentrated on wind/diesel systems. It is envisaged that future R&D programmes will concentrate more on RE systems in which several RES technologies are integrated.

The R&D effort in the field of RES is in accordance with national and European policies on energy, and the EU Framework programmes have made available considerable allocations of funding for developing RES technologies and increasingly in hybrid technologies. Complementary national R&D programmes also exist, with emphasis on different RES topics, according to national resources and preferences. RE technologies are not yet fully competitive with existing energy-supply technologies on purely commercial considerations, i.e. when externalities are not included in the comparison.

However, it is generally anticipated that the new RE technologies (wind, PV, solar thermal, biomass, etc.) will be increasingly economically competitive with fossil and nuclear plant and some, such as wind, fully competitive within a time horizon of 10 to 20 years. In high-wind locations, wind is already competitive. In a second stage, the above effort was complemented by promotional activities aiming at creating a "critical mass" for a dynamic market development.

Stable, favourable framework conditions, reflecting the environmental and social benefits of RES are characteristic for this stage. Most recently, promotional systems (already applied or under discussion) emphasise market elements (competition, fiscal incentives) and indicate a third promotional stage. "Indirect" support measures, mainly favourable electricity feed-in tariffs and low-interest loans have risen considerably in recent years, becoming significantly more important than "direct" support tools (grants, subsidies, etc.).

In fact, the "support" share included in payments for RES electricity injected into the grid is the major individual support tool (965 M€ per year). Total RES support in the EU, on regional and national level, is actually about 1.7 B€, for a total expenditure (support plus corresponding private investment) of about 2.9 B€. In the Commission's White Paper, annual investments of about 6.8 B€ were estimated in order to reach the aim of a 12% RES share in energy supply in 2010. Evidently, in spite of the progress achieved, substantial additional efforts will be needed in the future.

8.2.2. RES strategies

The only renewable source of energy that has been exploited on a significant scale before 1990 is hydro, basically large hydro. Since then, growth has been significant for all new renewable energies, between 15-30% over year. This evolution is due to various support measures of governments and of the Community. However, the overall contribution to the EU electricity market still remains small, around 3% when excluding large hydro. If the European countries want the RES to play a substantial role in the energy supply, they need the industry to invest in renewable energy technologies.

This will only happen if industry representatives have confidence in reliable, favourable long-term framework conditions. Such conditions will only exist if governments set clear targets, identify and remove non-technical barriers, and, finally, give financial support. The majority of governments have adopted RES promotion strategies as an integral part of their national energy policy. These strategies were published in the form of documents.

The Commission's White Paper has motivated Member States' governments to prepare corresponding Green (Ireland) or White Papers (Spain, Italy). Such documents typically include targets and pluriannual Action Plans addressing issues such as the installation of the RES systems, as well as administrative, legal and other promotional measures and activities. On the other hand, several countries (Austria, Finland, Sweden) traditionally have a high share of RES in their energy balance, mainly based on large hydro power stations and biomass.

Although the RES share in these countries is considerably higher than the 12% adopted as EU wide target by 2010, national policy aims at increasing the RES contribution further. Denmark, the Netherlands, Greece and Spain are examples of countries starting with a low RES share in the seventies, and then adopting medium and long-term objectives and action plans with environmental (greenhouse gas reduction) targets. Their national surveys show that such targets, based on a broad political consensus and acceptance level, have progressive and stimulating effects.

As an example, in Spain the targets for the year 2000 had already been overtaken by almost 200% (including installations under construction) by the end of 1997. Austria has no national, but rather regional targets. One region (Upper Austria) even has the ultimate goal of 100% RES supply in coming years. Among the countries without national targets (at least for the time being) are Germany and France, the countries with the highest energy consumption in the EU. Two federal German states have targets exceeding that of the White Paper (Bavaria: 13% of primary energy by 2000, and Schleswig-Holstein: 25% of final energy demand by 2010).

8.2.3. The electricity market

The 19th of February 1997, the Directive 96/92/EC on the Internal Market in Electricity entered into force. Each country had 2 years to adapt it into national legislation. After the Directive on price transparency (90/377/EG) from 29.6.1990 (for electricity and gas) and the one on electricity transit (90/547/EG) from 20.10.1990, this Directive marks the last step to the liberalisation of the electricity sector in the European Union.

This Directive establishes common rules for the generation, transmission and distribution of electricity. It lays down the rules relating to the organisation and functioning of the electricity sector, notably:

- access to the market,
- the criteria and procedures applicable to calls for tender and the granting of authorisations,
- the operation of systems.

The Directive indicates the minimum goal to be achieved:

- In February 1999, the national market share that should have been opened to competition was to be calculated on the basis of the Community share of electricity consumed by final customers consuming more than 40 GWh per year (on a consumption site basis, including auto-production). The resulting average Community market opening, at that date, should have been approximately 23%.
- The share of the national market opened to competition will be increased progressively over a period of six years. In 2000 the Community consumption threshold is reduced from 40 GWh to 20 GWh annual electricity consumption and in 2003 it will be further reduced to 9 GWh.

Member States specify those customers inside their territory that have the legal capacity to contract electricity, given that all final consumers consuming more than 100 GWh per year (on a consumption site basis and including auto-production) must be included in the above category. These customers are called "eligible customers". Distribution companies, if not already specified as eligible customers, have the legal capacity to contract for the volume of electricity being consumed by their customers designated as eligible within their distribution system, in order to supply them.

In March 2000, four European Member States have opened up their electricity market fully, namely Sweden, Finland, Germany and United Kingdom. Denmark has almost entirely opened it (90%). Belgium, Greece and Ireland have had, due to the specific technical characteristics of their electricity systems, an additional period of respectively 1, 2 and 1 year to apply the obligations ensuing from the Directive.

Greece opened the electricity market in February 2001 (34.5%), and Belgium and Ireland started to open up their markets on 19th February 2000 by 33 and 30% respectively. France has chosen for a minimal liberalisation, with almost a year of delay. It opened its market as late as in January 2000, to a rate of 30%. The other Member States have different market opening levels ranging from 30 to 45% (Austria 30%, Italy 35%, Portugal 30%, The Netherlands 32%, Spain 42%).

8.2.4. Integrated RE projects

There is a growing realisation that RE technologies should be applied in combination with each other, to supplement each other and to improve capacity values. Today, the situation is that few manufacturers aim specifically at systems, but there are suppliers of Hybrid Wind/Diesel systems (i.e. systems with wind and diesel generation, together with another RE technology, typically PV) with development strategies that aim at integrating RE systems.

Although there is no widespread application of integrated RE systems, a number of pilot plants and demonstration projects have been implemented. Their operation adds to the increasing body of experience being accumulated. The development and application of integrated RE systems presently aims at supplying electricity to grids, heat for use in (district) heating and as process heat, and energy carriers such as biogas and biofuels (and in the long run hydrogen from electrolysis).

The integration of renewable energy in the urban environment using passive and active systems has also been considered during the last few years. A number of pilot projects for modern urbanisation ("solar city" concepts), which take into account new climatic techniques in order to develop a new solar and bio-climatic architecture, have been designed.

Attention has also been paid to the possibilities of producing water using integrated RE systems specifically in regions like the Mediterranean where the natural water supply is limited. A new way of producing water in a sustainable manner and of a cost that people can afford is currently being investigated. There is a simultaneous development of planning tools in terms of system models on various levels, predicting resources and output, but practically no standards or agreed evaluation criteria are established.

8.3. INTEGRATION ISSUES

A number of technical options exist, which can be used for the exploitation of RES according to the specific situation in each region and the availability of local resources. However, for increasing technical efficiencies and maximising the degree of RES penetration, new effective solutions have to be promoted. These basically consist of exploiting the synergies between different RE technologies and between RE and conventional ones, including energy management and energy storage and/or power conditioning technologies. In addition, the massive RES utilisation in existing infrastructures, which may have unwanted impacts and layouts, should be adapted to the conditions of each specific location so as to ensure guaranteed and reliable supply.

8.3.1. Electricity production with RES

Several technical issues are related to the electricity production using high penetration levels from renewables. These are briefly described in the following paragraphs.

8.3.1.1. The intermittent character of some RES

Considering their technical characteristics, electricity production units can operate either continuously or intermittently. Wind, solar and wave applications produce a rather intermittent energy output, whereas biomass, hydro and conventional units can operate continuously. Obviously intermittent sources cannot reliably cover peak loads, unless the produced energy is stored in a storage system. It must be noticed that biomass plants for electric conversion operate like conventional units and so their integration does not affect the stability of the electrical system.

On the contrary, for the introduction of wind farms and solar thermal of high capacity in an electrical system it is prerequisite that suitable studies for both the steady state and the dynamic behaviour of the system to be performed. The level of intermittency varies between different RE technologies. Also, it is important to bear in mind the difference between predictability and intermittency. Some renewables, for example tidal, are intermittent but predictable. Solar PV is intermittent and predictable to some extent. Both these sources are more intermittent than wind, as the variability in output is greater - there are (predictable) periods when both solar and tidal plant fall to zero.

Although the power output from individual wind turbines demonstrates significant short-term variability, when turbines are grouped together within a wind farm - and better still when many wind farms are spread over a wide area - the combined effect is much smoother. The overall output of wind rarely changes rapidly enough to cause a problem for a system that must be able to cope with sudden and substantial losses of power, as described above. The rate of change in wind output is much smaller than installed capacity, and very small indeed over a short time-scale.

German data derived from 1500 turbines totalling around 350 MW showed that the mean hourly gradient was plus or minus 1% of the installed capacity. The maximum changes observed in one hour were a 23% decrease and a 14% increase. Over 4-hourly intervals the maximum changes were larger, at plus or minus 50%. Similar results were obtained from a study of six wind farms in Northern Ireland. Over half-hourly intervals the magnitude of wind power fluctuation was shown to be mostly within the 0-10% range and very unlikely to exceed 20%. There has been much more attention to the prediction of wind energy output in Denmark.

At present Danish utilities use two models for this purpose, but in April 2000 it was intended to merge the two to give a superior method, to be implemented across all utilities. Some winds, such as sea breezes or other thermally induced winds, follow a pattern that correlates well with natural peaks in demands - when the wind picks up as the sun goes down, for example. In hot climates a similar situation occurs with PV, in that higher solar radiation creates a demand for air conditioning. In cooler climates the opposite is true; demand is highest in the winter, at around 5:30 p.m., when the sun is down.

8.3.1.2. Problems associated with the power demand security and the dynamic performance of hybrid systems

The typical hybrid systems are consisted of a diesel generator, a photovoltaic generator and possibly other generators, such as wind converters, hydroelectric turbines, etc., complement each other in supplying power. A battery bank and possibly other units for short-term energy storage ensure that power is available at all times. Power is distributed to the loads with AC voltage of the usual frequency and amplitude.

Deployment of hybrid systems using exclusively Renewable Energy sources requires further storage capacity. In order to cope with the large variety of applications and differing power requirements, increasing the reliability and adaptability of the technology is fundamental for promoting the widespread application of hybrid systems using large amounts of renewable energies.

8.3.1.3. Energy and load management

The operation of power systems with increased renewable energy penetration can be achieved by applying sophisticated algorithms capable to forecast load and renewable power. The aim should be to maintain high degree of reliability and security against dynamic disturbances. The development of an adaptable advanced control system that will achieve optimal utilisation of multi-renewable energy sources, by advising operators of possible actions, is thus necessary.

Technical constraints imposed by Renewable Energy sources availability and variability, as well as by thermal power units technical characteristics would be reduced by the deployment of an advanced control system, which will ensure the stability of the electrical system. Rather than attempting to match the power generation to the consumer demand, the philosophy of 'load management' involves an inversion of approach and taking action to vary the load to make it match the power available.

When assessing the possible use of load control, consumers' attitude should be taken into consideration. Consumers should tolerate a complex tariff structure and co-operate in staggering their loads. The incentive always is extremely cheap electricity for the consumers during the hours of low demand and the result may be the smoothing of the daily power curve, low energy production cost, limited storage requirements, and the use of a very high proportion of the generated energy.

8.3.1.4. Energy storage options

The nature of the electrical load, the variability of renewable sources and the characteristics of the electrical grid introduce the need of energy storage. Energy storage devices show the same variety as the technologies for direct use of energy. Energy storage is distinguished to short, medium and long term. Under a technical point of view, storage technologies can be grouped with respect to the forms of energy being used, mechanical, thermal and electrical.

The main available options include batteries, hydraulic/pneumatic accumulators, flywheels and pumped storage. Special applications such as water desalination could also be used as indirect storage.

8.3.2. Classification of integrated RE systems

It is obvious that there exists an immense variety of areas differing in a large number of parameters such as size, population density, climatic conditions, building styles, cultural patterns, resources availability and, of course, energy system characteristics. However, what is of particular interest when examining the prospects for RES integration in an area can be reflected in a small number of characteristics:

- energy consumption density per area unit, compared to RE availability;
- availability and kind of energy infrastructure;
- power consumption pattern;
- size.

Different combinations of RE technologies can be used according to the type and size of the energy system to which they are going to be integrated. They can be classified as integrated RE systems for:

- single consumers and small groups;
- stand alone and isolated grids;
- local energy supply;

- regional energy supply.

A brief presentation of the above systems is provided in the following.

8.3.2.1. Single consumers and small groups

Photovoltaics have proven their success in supplying small and very small consumers. Solar home systems consisting of PV modules, batteries and charge controllers up to approximately 100 Watts have become one of the most well established applications. In cases where more power is required, wind energy converters and biomass plants often become more attractive due to their economic performance. In case of grid absence, a storage system or/and a conventional generation back-up is needed. A low power stand-alone DC system is presented in figure 8.1, where the genset is used only for emergency, when there is a shortage in RE supply. The inverter is optional. Hydro and wind systems can be located at some distance.

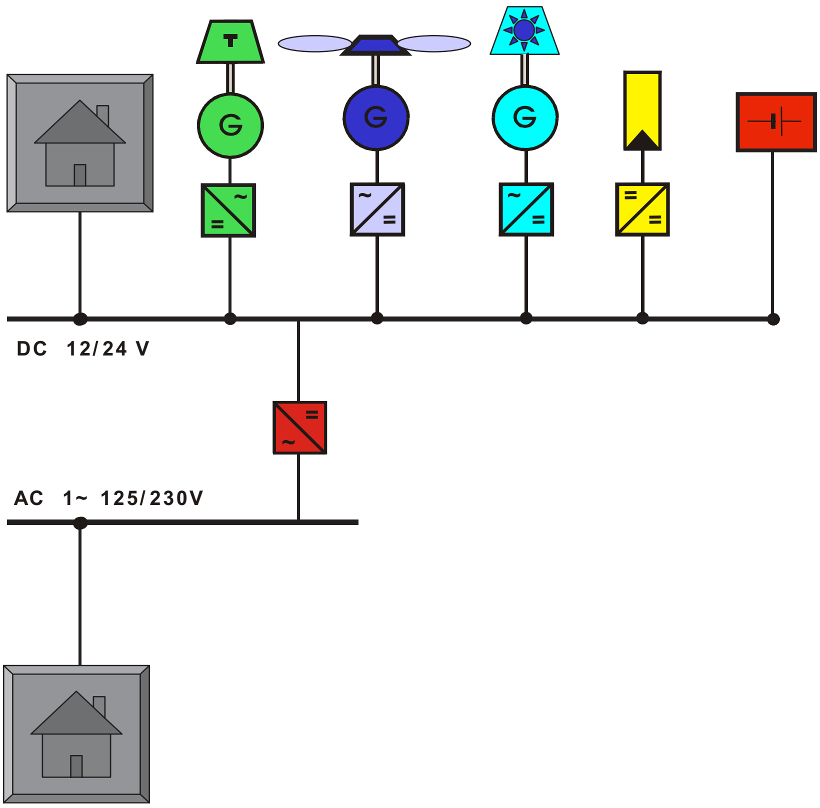


Figure 8.1. Schematic of a low power stand-alone DC system
(Source: ISET)

8.3.2.2. Stand-alone and isolated grids

In general, the decentralised electrification of local communal and regional structures by erecting or expanding stand-alone grids presents a very important potential for the large-scale deployment of renewable energies worldwide. Solar applications, wind energy converters and biomass plants are suggested for medium loads and local power supply. The weak or autonomous grid requires storage systems in order to approve the system reliability. In figure 8.2 such a system is shown, its power size ranging from 1 to 10 kW. Compared to the previous one (fig. 8.1), this arrangement can be considered as a pre-electrification solution, giving the possibility to be connected to a bigger grid at a later stage.

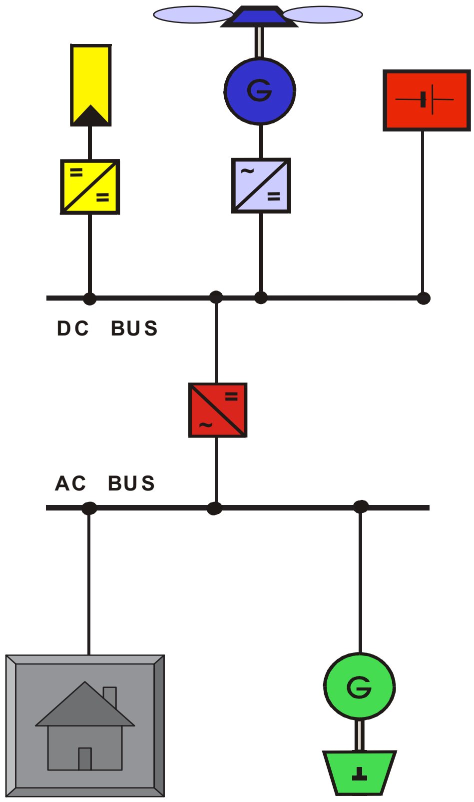


Figure 8.2. A stand-alone system in the range from 1 to 10 kW
(Source: ISET)

8.3.2.3. Local energy supply

In this category a differentiation between rural and urban areas can be made. The differentiation is based on the comparison of the energy consumption density with RES availability. In the urban areas the RES input is much smaller than the consumption density. The main RE source is the sun with a limited availability of the other RE resources. In the case of rural areas the RES input is in the range of the energy consumption density. Usually there is a significant availability of several RE resources (solar, wind, biomass, hydro).

8.3.2.4. Regional energy supply

These systems constitute large-scale applications of all the available technologies. Big hybrid systems are mainly wind/diesel systems, such as the one shown in figure 8.3, which presents the layout of the existing network supplying the Greek island of Kythnos (a photovoltaic park is also present there). The selection among possible alternatives depends on the following parameters:

- the social acceptance;
- technical reliability;
- the availability of resources;
- the economic effectiveness;
- environmental protection issues.

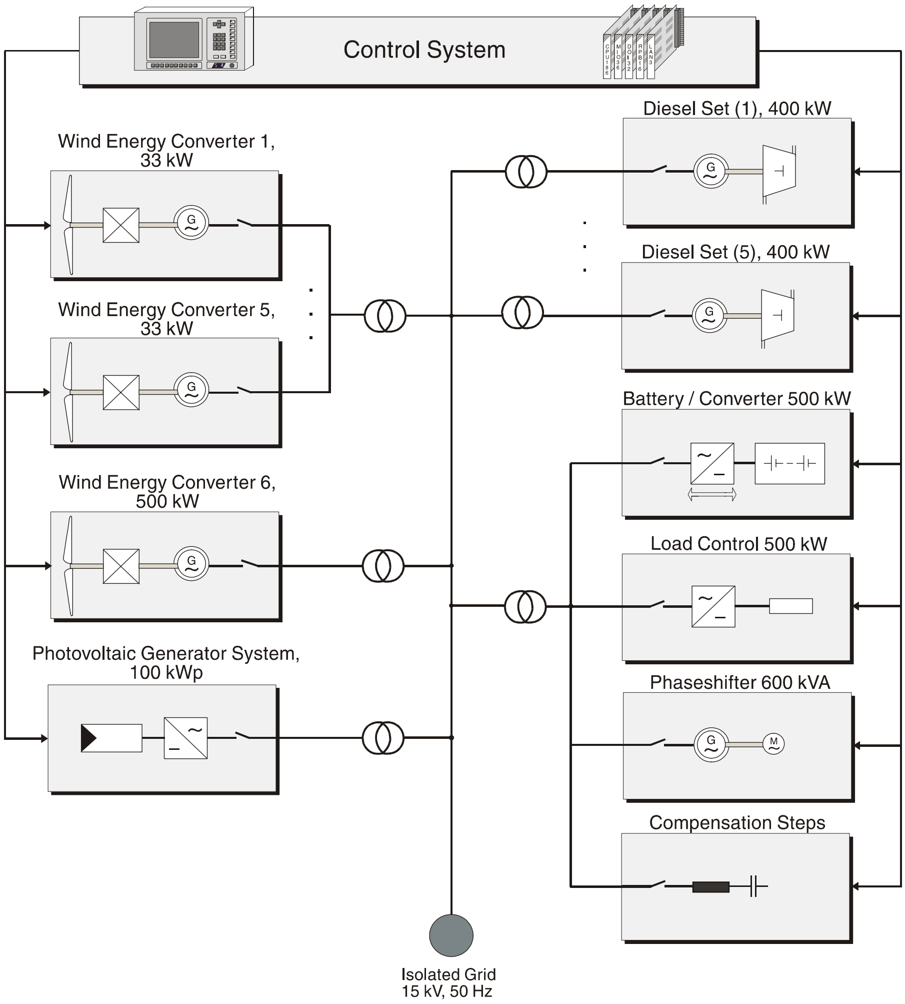


Figure 8.3. The network of the island of Kythnos (Greece) hybrid power system (Source: ISET)

The objectives of such systems are:

- to cover the demand in a sustainable way,
- to exploit the available renewable energy sources,
- to use the most mature and cost-effective RES technologies.

Additional objectives for electricity production are:

- to cover the maximum average net hourly production;
- to provide the electrical system with an adequate safety margin.

8.3.3. Transmission and distribution system

RE systems, such as wind turbines or small hydro, are usually located in rural or upland areas, where the electrical connection to the nearest electricity substation can be weak, and where local demand for electricity may be much less than the RE system generation capacity. One way of defining the "strength" of the electricity network is by the fault level. The fault level is a measure of the current that will flow when there is a fault on a network.

The fault level at the end of a long electricity circuit is much lower than at the centre of an interconnected network, for example in a town or industrial development. At a low fault level site, the impact of the RE systems can be great enough to disturb other local consumers. For this reason, it is sometimes necessary to reinforce the network, or connect the RE converters to a higher voltage or stronger part of the network further away. This will increase costs. Higher-voltage systems such as the 400 kV or 275 kV transmission systems have high fault levels. In general, the lower the voltage, the weaker the system will be.

For most of Europe, in rural areas the distribution system voltages are 132, 33 and 11 kV. The 11 kV system is the most extensive, but in rural areas is unlikely to support more than one to three megawatts (MW) of generation. In rural or upland areas, it is most likely that the nearest point on the local electricity network is an overhead line, rather than underground cable. Any overhead line with only two wires is carrying a single-phase system and will normally require reinforcement, if generators are to be installed.

8.3.3.1. Interface issues

Interface issues include harmonics, reactive power supply, voltage regulation, and frequency control.

<u>Harmonics</u>: Harmonics are undesirable distortions of the utility AC sinusoidal voltage and current waveforms. Harmonics are of concern due to potential damage to both utility distribution and customer load equipment. Some first-generation wind power plants installed in the early 1980s employed older, alternative conversion systems, such as those using 6-pulse thyristor bridge configurations without external harmonic correction or filtering, resulting in the production of lower order harmonics.

Advanced converter systems available today produce output with very little harmonic distortion, well below that specified in the relevant Monitoring Power Quality standards. With the addition of harmonic correction devices and the current trend towards the use of advanced power electronics in variable-speed wind turbines, harmonics are no longer a significant utility concern.

<u>Reactive power supply</u>: Early RE plants using induction generators were installed with inadequate hardware for reactive power compensation. As a result, utilities experienced increased line losses and difficulty controlling system voltage. RE plant operators were economically incented to improve the quality of power injected into

the electricity system when utilities began to charge for excessive VAR (reactive power) support.

Utilities now require small power producers that use induction generators to provide near unity power factor at the point of interconnection. Nevertheless, power electronics technology used with modern, variable-speed wind turbines has demonstrated a full range of power factor control under all operating conditions, even with the wind turbine shut down.

Voltage regulation: Taking as an example wind turbines, when they are running their output power varies second by second, depending on the strength and turbulence of the wind. The effect of the tower as the blades rotate past it also introduces a periodic disturbance in the power output, which is greater at high wind speeds. In the case of RE conversion systems, these power fluctuations cause voltage variations on the local electricity network, termed flicker.

Limits on the flicker any connected equipment can cause are defined in relevant references and are set to avoid disturbance to other consumers. Flicker is only likely to be a problem for small groups or single RE converters, especially large machines connected at lower voltages. For instance, stall-regulated wind turbines produce less disturbance than pitch-regulated turbines, while variable-speed wind turbines have very little effect.

Difficulty in controlling voltage regulation is accentuated when the RE plant is located in a remote area and connected to the utility through transmission lines originally designed to service only the load in the area. Solutions considered by utilities include new transmission lines, alternative line arrangements, the addition of static or adaptive VAR controllers, and RE plant curtailment. Based on an economic analysis of each of these alternatives, studies have determined that the least cost option is to curtail RE plant production and to compensate RE plant operators accordingly.

Frequency control: Utilities operating RE power plants connected to weak, isolated grids can have difficulty maintaining normal system frequency. For example, system frequency varies when gusting winds cause the power output of wind plants to change rapidly. While maintaining normal system frequency has not been a problem in the windfarm areas of California for instance, it has been well documented on various island systems.

An EPRI study showed that a reduction in capacity or an increase in demand of 10 MW per minute, caused by a combination of a RE system output changes and/or unscheduled load changes, would cause utility's load-following generation plant to trip, resulting in a loss of ability to regulate system frequency within acceptable limits. The report concludes that, in order to accommodate more renewables, the utility system would require:

- the use of modern RE converters with power electronic control and interface to the grid (e.g. the power electronic system can be controlled to limit wind turbine output during gusty or strong wind periods) and/or
- automatic generation control with additional spinning reserve.

In other cases, the short-term variations in RE plant output are small relative to normal load fluctuations and therefore do not significantly impact the ramping and cycling duties of available system regulating capacity.

8.3.3.2. Operational issues

Operational issues include operating reserve, unit commitment and economic dispatch, system stability, and transmission and distribution system impacts.

<u>Operating reserve</u>: Utilities carry operating reserve to assure adequate system performance and to guard against sudden loss of generation, off-system purchases, unexpected load fluctuations, and/or unexpected transmission line outages. Operating reserve is further defined to be spinning or non-spinning reserve. Typically, one-half of system's operating reserves are spinning, so that a sudden loss of generation will not result in a loss of load, with the balance available to serve load within 10 minutes. Any probable load or generation variations that cannot be forecast have to be considered when determining the amount of operating reserve to carry.

The exact point at which the integration of intermittent generation such as wind begins to degrade system economics is unclear, but the technical literature suggests that it is at penetration levels in excess of five percent. Intermittency is becoming an increasing concern to utility operators in California, particularly during low demand periods, since wind plant penetration is beginning to reach this level. As markets for electricity become more competitive, the ability to forecast and control the RE resource will increase the value of renewables to utilities.

<u>Unit commitment and economic dispatch</u>: Unit commitment is the scheduling of specific power plants on the utility system to meet expected demand. Units are committed to the schedule based on generation maintenance schedules, generator start-up and shutdown costs, minimum fuel burn requirements, and seasonal availability of intermittent resources, such as hydro and wind. This schedule is usually made at least 24 hours in advance. The most conservative approach to unit commitment and economic dispatch is to discount any contribution from interconnected RE resources.

In fact, wind plant output may be fairly predictable, as in the case of the Altamont Pass region of California, due to seasonal and diurnal wind resource characteristics observed over many years of wind farm operation or as a result of wind resource monitoring programs. Further research is needed to develop the capability to accurately forecast RE plant output on an hourly basis over time periods ranging from one day ahead to one week.

System stability: Large wind turbines typically have low-speed, large-diameter blades coupled to an electric generator by a high-ratio gearbox. This feature results in a large turbine inertia and low mechanical stiffness between turbine and generator, which gives large wind turbines excellent transient stability properties. Operating experience with wind power plants in California confirms that wind turbine transients due to speed fluctuations or network disturbances have not resulted in system stability problems, but this is not the case with all RES.

Transmission and distribution system impacts: RE systems can affect transmission and distribution systems by altering the design power flow or causing large voltage fluctuations. Also, "islanding", in which a RE plant might energize a line that otherwise would be dead, has been a concern. Operating experience with wind power plants has not shown system protection or safety to be an issue. Cases that may have led to islanding in the past have been identified, and hardware and detection schemes have been tested and approved. In some cases, the installation of direct transfer trip equipment is designed to trip the RE systems to prevent them from islanding.

8.3.4. Levels of integration

The level of RES penetration is highly influenced by the type and the degree of adaptation of the current energy infrastructure. Three (3) levels can be distinguished indicating to which extend RES can contribute to the total energy supply. These levels are also indicative for the time and changes required coming to a significant RES contribution and are defined as follows:

- I-1: maximum level of integration without changing current energy infrastructure;
- I-2: maximum level of integration with optimised energy infrastructure to accommodate RES;
- I-3: maximum level of integration with a new energy infrastructure.

These three levels should be interpreted rather as a range of shares than as crisp numerical figures. In newly built energy systems, the energy infrastructure can be designed from the very beginning as to effectively accommodate RES. Thus, level I-3 can practically be reached in a short term. On the contrary, in existing energy systems with a highly developed energy infrastructure, it will take decades before renewables can play a significant role in the energy supply system. About 40% of the energy is consumed in urban areas with highly developed infrastructure.

For achieving a considerable contribution of RES on the energy balance, serious planning steps have to be taken at this moment. Defining the limits of RE penetration in a power system, in order to avoid inadmissible disturbances to its operation, is a complicated issue, dependent on many and diverse parameters, not always clearly defined. In the following, a method for the estimation of the RE penetration limits in small power systems is outlined.

In a first step, the different scenarios regarding the possible RE installations have to be selected, taking into account the operational conditions of the power system during the minimum load demand of the year. For each of these scenarios, the impact on the distribution network must be examined, considering constant frequency and voltage at the bus-bars of the system. The dispersion of RE systems on the network is generally in favour for the operation of the small power system, and must be taken into account. Usually three scenarios (max-min-mean penetration) are chosen and the analysis of each one includes the following:

a) The operation of the power station under different conditions is simulated for a time period (e.g. one month or year) taking into account the corresponding load time series and the estimated RE power production. The necessary “spinning reserve” of the conventional units, because of the RE uncertainty added up to the uncertainty of the load change, is of primary importance. It can be expressed as follows:

$$P_{SR} = \mu P_W + \lambda P_L \qquad (8.1)$$

where μ and λ are coefficients expressing the error in the estimation of the expected RE power P_W and load P_L, in a time interval equal to that required for starting a new conventional power unit (e.g., μ =0.4 and λ =0.1).

Consequently, the problem can be formulated as follows. For each time interval *t* (e.g. every 1min) the following relation must be satisfied:

$$P_L = \sum_{i=1}^{n} P_{Di} + P_W \pm P_S \qquad (8.2)$$

where P_{Di} is the power produced by the unit *i*, and P_S is the stored power (if energy storage equipment exists), subject to the restrictions:

$$\sum_{i=1}^{n} P_{Di} + P_{SR} = \sum_{i=1}^{n} \alpha_i P_{NDi}$$

$$\beta_i P_{NDi} \le P_{Di} \le \alpha_i P_{NDi}$$

where α_i and β_i are coefficients expressing the loading margins of unit *i*, the nominal power of which is P_{NDi} (e.g., α_i=1.1 and β_i=0.2, for a specified duration). Other technical constrains must also be taken into account, such as the time intervals required for starting and stopping a unit, etc.

Table 8.1. Application results

	SCENARIO		
	1	2	3
ENERGY (kWh) Load consumption	2330588	2330588	2330254

Loss of energy	-	-	334
Diesel production	2330588	2002122 (86%)	1712623 (73.5%)
W.T. production	-	328461 (14%)	617631 (26.5%)
Spilt energy	-	22941 (1.0%)	259786 (11.1%)
OIL CONSUMPTION			
- Medium fuel oil (kg)	582582	502311	429078
- Gas fuel oil (kg)	4789	5573	8872
- Specific oil consumption (kg/kWh)	0.252	0.254	0.256
N^o OF DIESEL START/STOP	40	49	67

In Table 8.1 the results of the application of a computer program based on the above principles are presented. The main operational characteristics are the following:

- Diesel power station:
  - Installed capacity: 3 * 2700 kW
    2 * 1200 kW
  - Max/Min demand: 4800 / 1800 kW
- Wind Parks:
  - Scenario 1: Without WT
    2: 7*100 kW+8*55 kW=1140 kW
    3: 1*1140 kW+8*225 kW=2940 kW
- Simulation period: One month.

It is remarkable that in case of low wind penetration (as in scenario N^o 2, where the penetration levels are 1140/4800=24% in power or 14% in energy) there is no "Loss of energy", that is the system is always able to meet the demand. On the contrary, in case of high wind penetration (as in scenario N^o 3: 2940/4800=61% in power or 26.5% in energy), an important loss of energy occurs although a relatively high wind margin is used, resulting in a spilt wind energy percentage of 11% of the total consumption. On the other hand, there is no considerable change in the specific oil consumption of the diesel units, but there is an important increase in the number of Start/Stops.

b) The above analysis is made considering normal operating conditions. The behaviour of the system under "abnormal conditions" must also be examined, by simulating the following cases:

(1) Fast changes of the wind power, following wind gusts or connection-disconnection of the wind turbines.

(2) Short-circuits on the distribution network.

The analysis can be made by computer simulation of the behaviour of the system, for selected disturbances. Disturbances of type (1) are dealt with by the reaction of the regulating means of the conventional power units (such as the speed and voltage regulators), whereas for disturbances of type (2) the role of the protective means is of primary importance. The proper modelling of the operation and reaction of all this equipment is crucial for the accurate and reliable simulation of the behaviour of the system.

8.4. ECONOMICS OF RENEWABLE ENERGY SYSTEMS

Economic issues refer to all the parameters influencing the competitiveness of RES with respect to conventional fuels or energy forms and are widely considered as the primary factor determining the rates of RES market penetration. There are several aspects to be considered in relation with these issues, which are all inter-dependent and should be treated through a systematic integral approach.

8.4.1. Costs and prices

Costs and prices are the main driving forces of the market defining the competition between different energy alternatives. Despite the impressive cost reductions having accompanied the technical upgrading and the fast deployment of RE technologies in the market, most large-scale RE applications are still more expensive than competing sources of heat and electricity generation. The expected further drop of production costs along with their market penetration is not likely to make RES able to compete with conventional fuels/technologies in the short-to medium run.

Besides, such a procedure is very slow, exactly because of the multiple barriers hindering market penetration, among which the unfair pricing system. Prices are the signals reflecting the costs of producing goods and their utility for society. If not all costs are accounted for and utility factors are ignored, then prices give the wrong signal to the market. This is especially true for RES, since their use is associated with significant environmental and social benefits that are not taken into account in market decisions.

Moreover, conventional fuels and technologies are still benefited –directly and indirectly- of important public subsidies that further deepen existing cost differences. Electricity companies are generally more interested in buying electricity during the periods of peak load (maximum consumption) on the electrical grid, because this way they may save using the electricity from the less efficient generating units. According to a study on the social costs and benefits of wind energy by the Danish AKF institute, wind electricity may be some 30 to 40% more valuable to the grid, than if it were produced completely randomly.

In some areas, power companies apply variable electricity tariffs depending on the time of day, when they buy electrical energy from private RE systems owners.

Normally, RE systems owners receive less than the normal consumer price of electricity, since that price usually includes payment for the power company's operation and maintenance of the electrical grid, plus its profits. The widely accepted inefficiencies of the current costing and pricing mechanisms are therefore the main obstacle to be overcome in order to establish fair competition rules.

8.4.2. Factors affecting the costs of Renewables

8.4.2.1. Transmission issues for RE technologies

The tariffs for transmission access and services are coming under review as the electric power industry evolves from a regulated to a competitive environment. The structure of the transmission tariff will determine the allocation of transmission costs to the users of the transmission system, and ultimately, to the respective consumers. The structure of the transmission tariff can impact the prices of transmission for different generation technologies and energy sources, which could affect the economics of these technologies.

The transmission tariff is designed to recover both the marginal and fixed costs of the transmission system. The marginal cost of transmission for completing any given power transfer, including losses, ancillary services (i.e., capacity reserves), and any congestion cost, is typically a small fraction of the embedded cost included in transmission tariffs. The transmission tariff also sets prices well above the marginal cost to recover the fixed cost of the transmission system. The methodology used to recover fixed costs (in excess of marginal cost) can impact the price of electricity, thereby potentially affecting competition among generation suppliers.

For example, certain transmission tariffs could result in a distant generation supplier paying "pancaked" transmission rates to several transmission providers, the sum of which greatly exceeds the marginal cost of transmission. The most common type of transmission tariff is postage stamp pricing. A postage stamp rate is a fixed charge per unit of energy transmitted within a particular zone, irrespective of the distance that the energy travels. Other transmission tariffs include megawatt-mile and congestion pricing. Megawatt-mile rates explicitly reflect the cost of transmission based on both the quantity of power flow and the distance between the receipt and delivery points.

Congestion pricing is used to allocate the available transmission capacity by increasing the price to users of the transmission lines as maximum transmission capacity is reached. Currently, transmission tariffs are based on contract path pricing. A contract path rate is one that follows a fictional transmission path agreed upon by transaction participants. However, contract path pricing does not reflect actual power flows through the transmission grid, including loop and parallel path flows. Flow-based pricing schemes can be used as an alternative to contract path pricing.

Tariffs that include charges for firm (take-or-pay) transmission capacity or transmission distance will increase the cost of transmission for generating units having low capacity factors (e.g., due to intermittency of operation, as with wind-powered facilities) or with increasing transmission distance (e.g., remotely located facilities, as with biomass powered facilities). Under these tariffs, systems utilizing certain renewable energy technologies having inherently low capacity factors, large distance from load centers, and intermittent operation will incur relatively higher transmission costs than other technologies.

How competitive RES technologies ultimately become will depend on the cost of RES technologies to produce electricity, including transmission prices, incentives that mandate consumption or reduce the cost of generation, and the price elasticity of consumers' demand for green power. High prices for transmission services, added to the cost of renewable generation, could reduce the demand for RES even with green pricing programs. However, a transmission tariff that results in high transmission prices in certain geographic areas may create an opportunity in those areas for distributed generation by using RES to compete with central station power plants.

8.4.2.2. Distributed generation

During the early development of the electric power industry, electricity was provided using distributed generation, sometimes called distributed resources, where generation occurs near or at the site of electricity demand. Although distributed generation has been replaced by large central-station power plants—made possible by the development of an adequate, reliable, and efficient transmission system—it may be staging a comeback under deregulation. Generation will be priced competitively under deregulation, but transmission and distribution (T&D) will continue to be regulated.

T&D regulation is undergoing substantial changes, with transmission owners required to open access to transmission lines, and the transmission services undergoing a transition to "unbundling" of services and prices. Under unbundled services, transmission owners must provide a clear and specific tariff for a variety of transmission access services (e.g., point-to-point vs. network related, interruptible vs. non-interruptible charges) and a variety of dispatching and power management services (e.g., capacity reserves, voltage control, and administration).

Distributed generation may have opportunities in niche markets to be competitive with the cost of electricity from central stations, which includes cost of transmission (including losses and ancillary reserves), operating power substations, and distribution lines and equipment for delivery to end users. T&D costs can vary greatly among locations with the unbundling of rates. T&D costs may be relatively low for customers receiving power from plants close to major transmission lines or substations. For customers located far away from main transmission lines, or in constrained areas of the grid, T&D costs may be a multiple of the average costs.

Distributed generation may prove to be attractive in areas where it can defer T&D investment or where it can improve reliability to the consumer. Small-scale renewable generation technologies that have seen significant cost reductions and improvements in operating characteristics may be competitive and provide benefits (e.g., environmentally friendly, minimum land use) not available from large central generating stations. In the future, fuel cells, wind turbines, solar panels, and some biomass technologies may meet these criteria.

8.4.2.3. Reactive power charges

Most RE systems (wind, hydro, etc.) are equipped with asynchronous generators, also called induction generators. These generators require current from the electrical grid to create a magnetic field inside the generator in order to work. As a result of this, the alternating current in the electrical grid near the generator will be affected (phase-shifted). This may at certain times decrease (though in some cases increase) the efficiency of electricity transmission in the nearby grid, due to reactive power consumption.

In most places around the world, the power companies require that RE systems be equipped with switchable electric capacitor banks that partly compensate for this phenomenon (for technical reasons they do not want full compensation). If the system does not live up to the power company specifications, the owner may have to pay extra charges. Normally, this is not a problem that concerns RE system owners, since the experienced manufacturers routinely will deliver according to local power company specifications.

8.4.2.4. Capacity credit

To understand the concept of capacity credit, it is better to look at its opposite, power tariffs. Hence, large electricity customers are usually charged both for the amount of energy (kWh) they use, and for the maximum amount of power (kW) they draw from the grid, i.e. customers who want to draw a lot of energy very quickly have to pay more. The reason they have to pay more is that it obliges the power company to have a higher total generating capacity (more power plants) available. Power companies have to consider adding generating capacity whenever they give new consumers access to the grid.

But with a modest number of RE systems in the grid, these systems are almost like "negative consumers", which means that they postpone the need to install other new generating capacity. Many power companies therefore pay a certain amount per year to the RE system owner as a capacity credit. The exact level of the capacity credit varies. In some countries it is paid on the basis of a number of measurements of power output during the year. In other areas, some other formula is used. Finally, in a number of areas no capacity credit is given, as it is assumed to be part of the energy tariff. In any case, the capacity credit is usually a fairly modest amount per year.

8.4.3. Taking into account environmental externalities

The use of fossil fuels for heat and electricity production is accountable for substantial environmental deterioration. In particular, atmospheric emissions are widely known to produce serious impacts on the environment, which are insufficiently taken into consideration in energy decisions. This is because air quality and other environmental assets are considered as public goods and are not priced by the existing market mechanism.

Thus, the price of conventional energy sources does not include the costs imposed on society due to the various environmental impacts on human health and on the natural and social environment (e.g. crops, forests, water resources, natural ecosystems, buildings, cultural monuments). During the last decade, intensive efforts have been undertaken for estimating the external costs associated with energy production and use. All relevant studies (among which the ExternE project of the European Commission) have proved that environmental externalities of many conventional technologies may exceed the corresponding private costs.

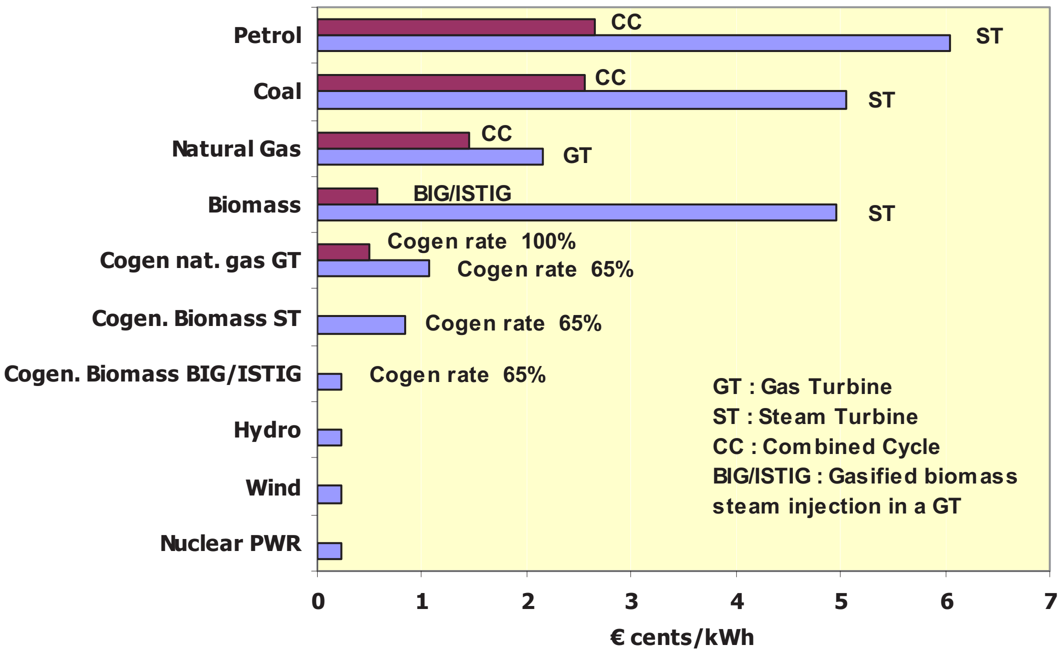


Figure 8.4. Environmental externalities of the electricity production in Europe (Source: ExternE study for DGXII)

The largest components of these external costs (see figure 8.4) refer to the global warming effect and to mortality and morbidity effects due to atmospheric pollutants. It is clear that RES, which are exempt from all types of atmospheric emissions, are unequally treated in the current market place and that internalisation of external costs would significantly alter present perceptions about the relative economic attractiveness of competing energy technologies.

8.4.4. Supporting Renewables

There is a wide range of renewable energy technologies: some provide electricity, others heat; some are small scaled and decentralised, other are in the multi-MW-range; some are economically competitive, other still need additional support; some are "classical", others are in an experimental stage. This diversity needs flexible, "tailor-made" promotional instruments. To do so, different forms of support are possible.

The main support schemes are:

- Subsidies for research and development.
- Capital investment or loans to investments.
- Guaranteed prices coupled with a purchase obligation by the utilities: The level of the guaranteed prices vary considerably from country to country with, on average, regulation in Germany, Denmark, Spain and Italy offering the highest prices to RES power producers.
- Tendering system: Under this approach, the State decides on the desired level of RES, according to the source mix (wind, biomass, solar, waste, etc.) that public policy dictates. It then places a series of tenders for the supply of the electricity, which would thereafter be supplied on a contract basis. The electricity is then sold by the authority responsible for organising price through a non-discriminatory levy on all domestic electricity consumption.
- Voluntary green pricing schemes: Consumers can voluntary opt to pay a premium for renewable electricity. The consumers pay part or full extra costs that the generation of RES entails.
- Standard/consent procedures and regulation in building codes and design guidelines: The objective is to reduce or streamlining planning barriers. For example, the obligatory designation by local authorities of eligible zones for RES development (as in Denmark) also facilitates renewable growth.
- Support via the tax system:
  - exemption forms or refunds of energy taxes where they exist (Finland where the electricity tax is reimbursed, Denmark where the CO_2-tax is reimbursed, Sweden where an environmental bonus is given to wind power producers),
  - lower VAT rates on some RES systems, like solar energy systems in Greece and Portugal,
  - tax exemptions for investments in small scale RES power systems,
  - introduction of SO_2 and NO_x taxes as in Denmark and Sweden, which especially favours the development of wind and hydro power.

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