Hybrid Energy Systems

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Glossary

biomass Any organic material that is used as a fuel.
deferrable load An electrical load that must be supplied a certain amount of energy over a specified time period in an isolated electrical network, but that has some flexibility as to exactly when.
diesel generator A device for producing electricity through the use of a diesel engine.
dump load A device used to dissipate power in order to maintain stability in an isolated hybrid energy system.
fuel cell A device for continuously producing electricity through a reaction between hydrogen and oxygen.
hybrid energy system A combination of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that, when integrated, overcome limitations that may be inherent in either.
load (1) An energy consuming device; (2) the cumulative power requirement due to a number of devices connected to an electrical network.
maximum power point tracker A DC-DC converter whose function is to maximize the power produced by a variable voltage DC generator, such as PV panels or a wind turbine, connected to a fixed voltage bus.
optional load An electrical load which can be supplied by excess power in an isolated electrical network but need not be supplied if no excess power is available.
penetration The instantaneous power from the renewable generator divided by the total electrical load being served in an isolated electrical network.
photovoltaic panel (PV) A semiconductor-based device that converts sunlight to electricity.
renewable energy source An energy source that is derived ultimately from the sun, moon, or earth's internal heat.
supervisory control A central control system whose function is to ensure proper operation of all the devices within a hybrid energy system.
weak grid An electrical network whose operational characteristics can be affected by the presence of a generator or load connected to it.
wind turbine A device that converts the power in the wind to electrical or mechanical power.

The term hybrid energy system refers to those applications in which multiple energy conversion devices are used together to supply an energy requirement. These systems are often used in isolated applications and normally include at least one renewable energy source in the configuration. Hybrid energy systems are used an alternative to more conventional systems, which typically are based on a single fossil fuel source. Hybrid energy systems may also be used as part of distributed generation application in conventional electricity grid. The most general definition is the following: "Hybrid energy systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either." This definition is useful because it includes a wide range of possibilities and the essential feature of the multiplicity of energy conversion. This article focuses on stationary power systems, where at least one of the energy conversion devices is powered by a renewable energy source (which, in the context of this article, is one based ultimately on the sun).

1. INTRODUCTION TO HYBRID ENERGY SYSTEMS

A considerable interest has emerged in combined or 'hybrid' energy systems. In the context used here, that refers to an application in which multiple energy conversion devices are used together to supply an energy requirement. These systems are often used in isolated applications and normally include at least one renewable energy source in the configuration. Hybrid systems are used as an alternative to more conventional systems, which typically are based on a single fossil fuel source.

1.1 Definitions

Hybrid energy systems have been defined in a number of ways. The most general, and probably most useful, is the following:

"Hybrid energy systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either."

This definition is useful because it includes a wide range of possibilities and the essential feature of the multiplicity of energy conversion. Note that this broad definition does not necessarily include a renewable energy based device and allows for transportation energy systems. In the present discussion, however, we focus on stationary power systems, where at least one of the energy conversion devices is powered by a renewable energy source (which is one based ultimately on the sun, moon, or earth's internal heat).

For the purpose of comparison, it is useful to consider briefly the nature of conventional energy systems that are normally used where hybrid system might be used instead. There are basically three types of conventional systems of interest: (1) large utility networks, (2) isolated networks, and (3) small electrical load with dedicated generator.

Large utility networks consist of power plants, transmission lines, distribution lines and electrical consumers (loads). These networks are based on alternating current (AC) with constant frequency. Such networks are frequently assumed to have an infinite bus. This means that the voltage and frequency are unaffected by the presence of additional generators or loads.

Isolated electrical networks are found on many islands or other remote locations. They are similar in many ways to large networks, but they are normally supplied by one or more diesel generators. Generally, they do not have a transmission system distinct from the distribution system. Isolated networks do not behave as an infinite bus and may be affected by additional generators or loads.

For many small applications, it is common to supply an electrical load with a dedicated generator. This is the case, for example, at construction sites, highway signs, and vacation cabins. These systems are also normally AC but have no distribution system.

1.2 Applications for Hybrid Energy Systems

There are numerous possible applications for hybrid power systems. The most common examples are (1) remote AC network, (2) distributed generation applications in a conventional utility network, and (3) isolated or special purpose electrical loads.

The classic example of the hybrid energy system is the remote, diesel-powered AC network. The basic goal is to decrease the amount of fuel consumed by diesel generators and to decrease the number of hours that they operate. The first addition to "hybridize" the system is to add another type of generator, normally using a renewable source. These renewable generators are most commonly wind turbines or photovoltaic panels. Experience has shown, however, that simply adding another generator is not sufficient to produce the desired results. Accordingly, most hybrid systems also include one or more of the following: supervisory control system, short-term energy storage, and load management. Each of these will be described in more detail. An example of a typical hybrid energy system, in this case a wind/diesel system, is illustrated in Fig. 1.

During the 1990s, management of many large electrical networks changed so that it is now possible

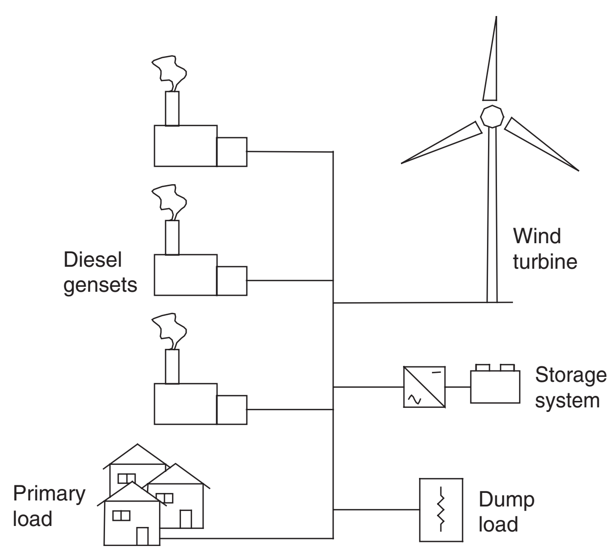

FIGURE 1 Schematic of wind diesel system with storage.

for individuals or businesses to add generation in the distribution system of the utility. This is known as distributed generation (DG). Distributed generation can have a variety of purposes, but in any case, it is sometimes desirable to combine a number of energy conversion devices together with the distributed generator. This results in a hybrid energy system in the distributed generation application.

Hybrid systems can be of particular value in conjunction with an isolated or special-purpose application. One example is that of using photovoltaic panels, together with some battery storage and power electronic converters to supply a small amount of energy to a load in a remote location. Other examples include water pumping or water desalination. In these applications, electrical loads may take a range of forms. They may be conventional AC, DC, or even variable voltage and variable frequency.

1.3 Impetus for Hybrid Energy Systems

There are a variety of reasons why a hybrid system might be used. An important reason is the reduction of fossil fuel use. Fossil fuel can be costly, especially in remote locations where the cost of transporting the fuel to the site must be considered. In many remote locations fuel oil must be stored, often for an entire winter. Reducing the amount of fuel use can reduce storage costs.

An isolated hybrid power system can be an alternative to power line construction or power line upgrade. Hybrid power systems, because they include so many components, tend to be relatively expensive. When they can be used as an alternative to power line construction, the savings can help compensate for the cost of the hybrid system.

Under some conditions a power line already exists, but is not capable of carrying the desired current. This could occur, for example, when a new load is added. In this case, the hybrid system would be a type of distributed generation. The hybrid system would only need to provide the difference between the total load and what the existing lines could carry. The presence of the existing line could simplify the design of the hybrid system, in that it need not necessarily be required to set the power line frequency and might not have either storage or dump loads (q.v.).

Distributed generation has advantages in a number of situations, and, in some cases, the overall benefit is enhanced by using a hybrid system. One common application for distributed generation is combined heat and power (CHP). In this case, waste heat associated with fossil fuel combustion is used for space or process heating, thereby increasing the overall energetic efficiency of the fuel use.

Use of hybrid systems can result in local environmental benefits. In particular, diesel generators (in isolated applications) should run less often and for shorter periods. This will reduce locally produced air pollution and noise, as well as reducing risks associated with fuel transport.

2. *CHARACTERISTICS OF HYBRID ENERGY SYSTEMS*

The characteristics and components of a hybrid system depend greatly on the application. The most important consideration is whether the system is isolated or connected to a central utility grid.

2.1 Central Grid Connected Hybrid Systems

If the hybrid system is connected to a central utility grid, as in a DG application, then the design is simplified to a certain degree and the number of components may be reduced. This is because the voltage and frequency are set by the utility system and need not be controlled by the hybrid system. In addition, the grid normally provides the reactive power. When more energy is required than supplied by the hybrid system the deficit can be in general be provided by the utility. Similarly, any excess produced by the hybrid system can be absorbed by the utility. In some cases, the grid does not act as an infinite bus, however. It is then said to be “weak.” Additional components and control may need to be added. The grid connected hybrid system will then come to more closely resemble an isolated one.

2.2 Isolated Grid Hybrid Systems

Isolated grid hybrid systems differ in many ways from most of those connected to a central grid. First, they must be able to provide for all the energy that is required at any time on the grid or find a graceful way to shed load when they cannot. They must be able to set the grid frequency and control the voltage. The latter requirement implies that they must be able to provide reactive power as needed. Under certain conditions, renewable generators may produce energy in excess of what is needed. This energy must be dissipated in some way so as not to introduce instabilities into the system.

There are basically two types of isolated grid hybrid systems which include a renewable energy generator among their components. These are known as low penetration or high penetration. In this context, "penetration" is defined as the instantaneous power from the renewable generator divided by the total electrical load being served. Low penetration, which is on the order of 20% or less, signifies that the impact of the renewable generator on the grid is minor, and little or no special equipment or control is required. High penetration, which is typically over 50% and may exceed 100%, signifies that the impact of the renewable generator on the grid is significant and special equipment or control is almost certainly required. High-penetration systems may incorporate supervisory control, so-called dump loads, short-term storage, and load management systems.

Two important considerations in an isolated system are whether the system can at times run totally on the renewable source (without any diesel generator on) and whether the renewable source can run in parallel with (i.e., at the same time as) the diesel generator. It is most common for one or the other to be possible (and normal). It is less common that both modes of operation are possible. This latter system offers the greatest fuel savings but is more complicated.

2.3 Isolated or Special Purpose Hybrid Systems

Some hybrid systems are used for a dedicated purpose, without use of real distribution network. These special purposes could include water pumping, aerating, heating, desalination, or running grinders or other machinery. Design of these systems is usually such that system frequency and voltage control are not major issues, nor is excess power production. In those cases where energy may be required even when renewable source be temporarily unavailable, a more conventional generator may be provided. Renewable generators in small isolated systems typically do not run in parallel with a fossil fuel generator.

3. TECHNOLOGY USED IN HYBRID ENERGY SYSTEMS

A wide range of technology may be used in a hybrid energy system. This section describes some of them in more detail than was done in previous sections. Devices to be discussed include energy consuming devices (loads), rotating electrical machinery, renewable energy converters, fossil fuel generators (often, but not always, diesels), energy storage devices, power converters, control systems, and load management devices. Some of the various possible devices and arrangements that may be found in hybrid energy system are illustrated in Fig. 2. The primary focus here is on isolated network hybrid systems, but much of the technology applies to other types of hybrid systems as well.

3.1 Energy Consuming Devices

Hybrid energy systems typically use the same types of energy consuming devices that are found in conventional systems. These include lights, heaters, motors, and electronic devices. The combined energy requirement of all the devices is know as the total load, or just load. The load will typically vary significantly over the day and over the year. An example of a load varying over a year on an isolated island is shown in Fig. 3.

3.2 Rotating Electrical Machinery

Rotating electrical machinery is found in many places in a hybrid energy system. Most such machines can function as either motors or generators, depending on the application. This section focuses on the generating function.

3.2.1 Induction Generators

The induction generator has been the most common type of generator used in wind turbines. They are also occasionally used with other prime movers, such as hydro turbines or landfill gas fueled internal combustion engines. More information on induction machines is provided elsewhere in this encyclopedia, so they will not be discussed in detail here. As far as hybrid systems, however, there are two important considerations. First of all, induction machines require a significant amount of reactive power. This is not a fatal problem, but it does affect the design of the system in a number of ways.

The second consideration is starting. When an induction machine is brought on line from stand still, it requires much higher current than when operating normally. Provision must be made to ensure that the hybrid system has the capability of starting any induction motors or generators that it connected to it.

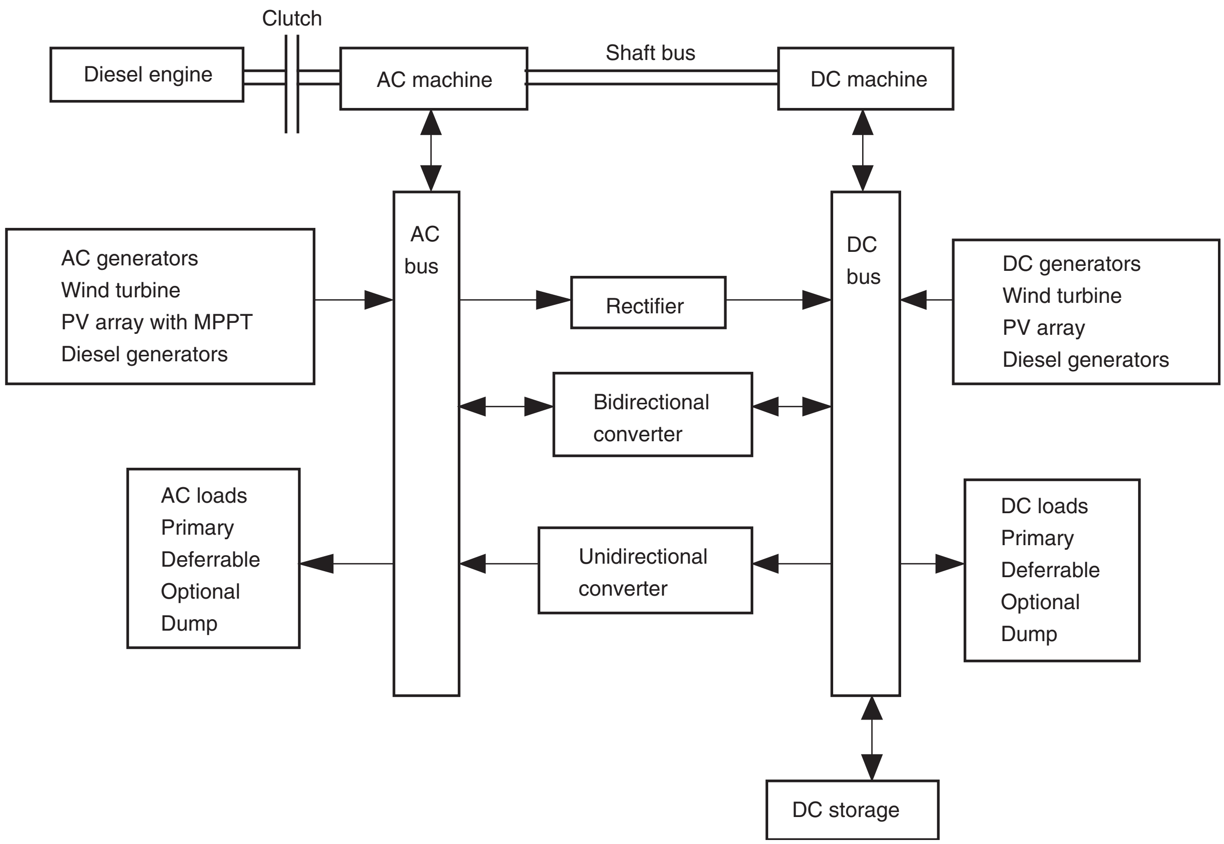

FIGURE 2 Devices and arrangements in hybrid energy systems.

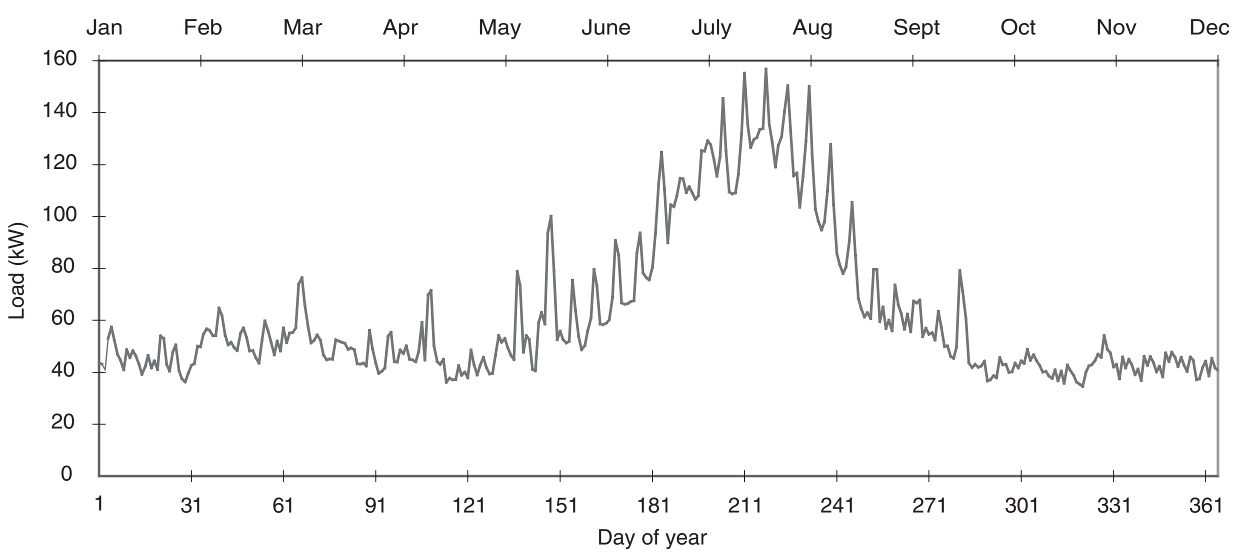

FIGURE 3 Daily electrical loads on Cuttyhunk Island, Massachusetts.

3.2.2 Synchronous Generators

Synchronous generators (SG) may also be used with a variety of prime movers. These generators are discussed in detail elsewhere in this encyclopedia. In hybrid system applications SGs are of one of two types: those with electromagnetic fields and those using permanent magnets. The first type, operating with a voltage regulator, can maintain the voltage on the electrical network and provide reactive power required by other devices in the system. Permanent magnet SGs are often used in small wind turbines. Such generators cannot maintain voltage and so are normally used in conjunction with power electronic converters.

A synchronous machine can be brought on line so that it will run in parallel with other generators. When this is done, particular attention must be taken so that the various generators are in phase with each other.

3.3 Renewable Energy Generators

Renewable energy generators are devices that convert energy from its original form in the renewable energy source into electricity. Renewable energy generators that are most likely to be found in hybrid energy systems include wind turbines and photovoltaic panels. Some hybrid energy systems use hydroelectric generators, biomass fueled generators, or fuel cells. It should be noted that many renewable energy generators include rotating electrical machines acting in the generating mode, which is also called a generator. It should be clear from the context what is meant.

3.3.1 Wind Turbines

Wind turbines are devices that convert the energy in wind into electricity. A typical wind turbine is shown in Fig. 4. The main parts of a wind turbine are the rotor, the drive train (including the generator), main frame, tower, foundation, and control system. The rotor consists of the blades and a hub. The blades serve to convert the force of the wind to a torque that ultimately drives the generator.

The two most important features of a wind turbine as far as a hybrid energy system is concerned are the type of generator and the nature of the rotor control. Most wind turbines use induction generators, although some use synchronous generators. In either case the generator may be connected directly to the electrical network or it may be connected indirectly through a power electronic converter.

There are two main forms of rotor control on wind turbines: stall control and pitch control. The most important function of rotor control is to protect the wind turbine from high winds. In hybrid systems, rotor control is also important because it affects on how energy flows are regulated within the hybrid system. Under some conditions (with pitch control), the rotor can be controlled to facilitate start up or to reduce production when full output is not required.

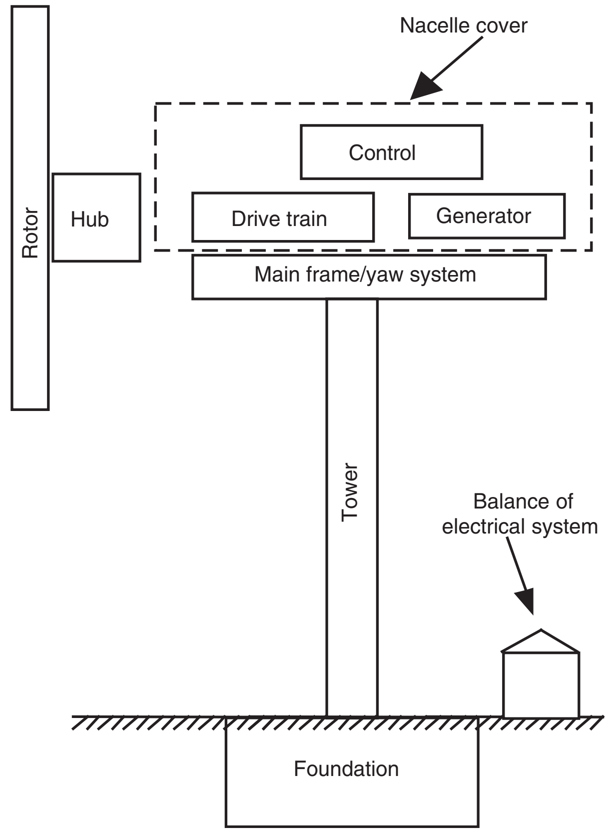

FIGURE 4 Components of typical wind turbine.

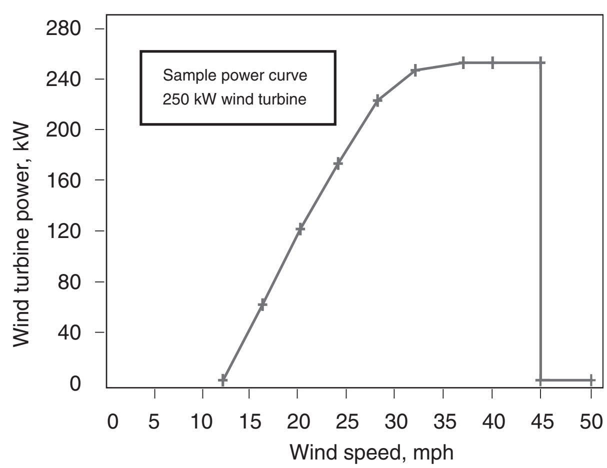

FIGURE 5 Typical wind turbine power curve.

Details on rotor control may be found elsewhere in this encyclopedia or in Manwell *et al.*

The power generated by a wind turbine varies in relation to the wind speed. That relation is summarized in a power curve, a typical example of which is illustrated in Fig. 5.

3.3.2 Photovoltaic Panels

Photovoltaic (PV) panels are used to produce electricity directly from sunlight. PV panels consist of a number of individual cells connected together to produce electricity of a desired voltage. Photovoltaic panels are inherently DC devices. To produce AC, they must be used together with an inverter.

Most PV cells are made from crystalline silicon. PV cells produce current in proportion to the solar radiation level (up to a certain voltage). The current/voltage relation of a typical silicon cell at a fixed level of solar radiation is shown in Fig. 6. Since power is proportional to the product of current and voltage, the power from a PV cell will continue to increase until the current begins to drop.

Because the maximum voltage from individual cells is less than 1 V, multiple cells are connected together in series on a PV panel.

The actual radiation level at any given time at a particular spot on the earth's surface will vary significantly over the year and over the day. See Section 5 for more details. More information on PV panels themselves is provided elsewhere in this encyclopedia.

3.3.3 Hydro Turbines

Hydropower is one of the oldest forms of electricity production and is used in large electricity networks as well as small ones. Small hydroelectric plants are used in isolated systems in many parts of the world. Hybrid systems, which include hydroelectric plants with other forms of generation, are relatively rare, but they do occur. The most common of these are in locations where the resource varies significantly over the year, and there is not enough water in certain seasons. A diesel generator is then used instead of the hydroelectric generator during those seasons. The primary requirements of a hydroelectric plant are a continuous source of water and a change in elevation. More information on hydroelectric generators is provided elsewhere in this encyclopedia.

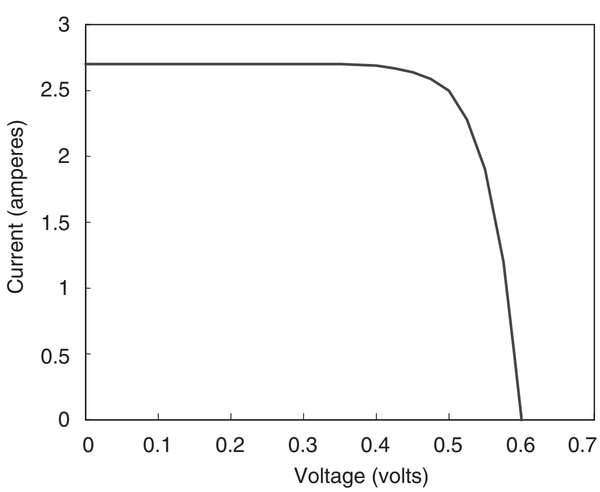

FIGURE 6 Photovoltaic cell current versus voltage.

3.3.4 Biomass Fueled Generators

Biomass fueled generators are occasionally used in hybrid energy, though most often when they are employed in isolated networks they are the only power plants used. Biomass fueled generators are quite similar to conventional coal or oil fired generating plants, except for the combustors themselves and the fuel handling equipment.

Biomass is any organic material which is used as a fuel. For purposes of power generation, the most common sources of biomass include wastes from wood products or the sugar cane industry. Other agricultural wastes are sometimes used as well.

Biomass generators are sometimes fueled with landfill gas. Such generators most commonly employ an internal combustion engine as a prime mover. Occasionally fuel cells have been used.

3.3.5 Fuel Cells

Fuel cells can be used in hybrid power systems, and are expected to become more common as their costs drop. Fuel cells ultimately run on hydrogen, but in many cases the input fuel is some other gas, such as natural gas or landfill gas.

Fuel cells can be thought of as a continuous battery. The fundamental reaction is between hydrogen and oxygen, the product of which is water and electric current. The reaction takes place in the vicinity of a membrane, which serves to separate the various components of the electrolyte and the electrodes. The electrodes are the terminals of the fuel cell and carry the current into an external circuit. Like batteries, fuel cells are inherently DC devices. Fuel cells can be used in an AC network if their output is converted to AC via an inverter.

When natural gas or landfill gas is used as the fuel, it must first be used to produce hydrogen. This is done in a reformer.

There are a number of different designs for fuel cells. They include proton exchange membrane (PEM), solid oxide, and molten carbonate. More information on fuel cells is presented elsewhere in this encyclopedia.

3.4 Fossil Fuel Generators

Fossil fuel generators are commonly used in hybrid energy systems. In fact, most isolated power systems at the present time are based on fossil fuel, using internal combustion engines as prime movers. Most medium-sized and larger isolated systems use diesel engine/generators. The smallest systems sometimes use gasoline. Some very large isolated power systems sometimes use conventional oil-fired steam power plants. They will not be discussed here, however.

3.4.1 Diesel Engine/Generators

Diesel engine generators are discussed elsewhere in this encyclopedia, so they will only be summarized here. Emphasis is given to those aspects of relevance to hybrid energy systems.

Diesel generators typically consist of three main functional units: a diesel engine, a synchronous generator with voltage regulator, and a governor.

The fuel injection system is an important part of the diesel engine. Its function is to inject the proper amount of fuel into the proper cylinder at the appropriate time in the cycle. The timing of the injection is determined by the design of the engine itself; the amount of fuel is determined by the governor.

The diesel engine is normally connected directly to a synchronous generator. A voltage regulator ensures the proper voltage is produced. The frequency of the AC power is directly proportional to the engine speed, which in turn is controlled by the governor.

Historically diesel generators have employed "droop" type governors. A set of flyballs is driven by the engine, so the speed varies in proportion to the engine speed. Through a set of linkages, the amount of fuel that can be injected at any time is varied according to how far the operating speed differs from (or "droops") from nominal. As the electrical load on the generator increases, the droop increases and more fuel is injected. Diesel generators are now more likely to have electronic governors without droop, but the function is the same.

An important consideration regarding diesel generators is their fuel consumption, both at full load and part load. Diesel fuel consumption is frequently described in terms of electricity produced per gallon of fuel consumed. Full load values ranging from a low of 8 kWh/gallon to 14 kWh/gallon have been reported.

Diesel engine generators are often called on to follow the load. That means that their output must be equal to the system load (or to the system load less the production of any other generators that might be on; this is called the net load). As the load may go up and down, so must the electricity generated. This is known as part load operation. Generally, the conversion efficiency is less at part load than at full load. Fuel consumption over the full range of operation is summarized in fuel curves. In these curves, fuel consumption is graphed against power. Figure 7 shows a typical example.

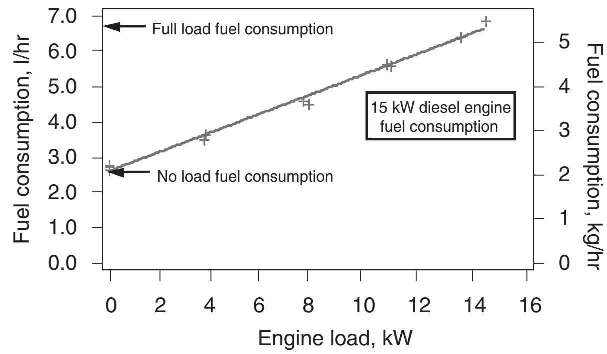

FIGURE 7 Typical diesel engine generator fuel curve.

Regardless of efficiency considerations, manufacturers normally recommend that diesel generators not be run below some specified minimum power level, known as the minimum load. Typically, the minimum recommended load is between 25% and 50% of rated. Engines run for long periods at levels below the minimum recommended can experience a number of problems.

3.4.2 Gasoline Generators

Gasoline generators are sometimes used for very small hybrid energy systems applications. These generators have the advantage that they are readily available throughout the world and are relatively expensive. They are similar in many ways to diesel generators, except that use spark ignition, and have lower compression ratios. They also typically use carburetors rather than fuel injection. The main disadvantage of gasoline generators is that they are less efficient than diesel.

3.5 Energy Storage

Energy storage is often useful in hybrid energy systems. Energy storage can have two main functions. First of all, it can be used to adapt to a mismatch between the electrical load and the renewable energy resource. Second, it can be used to facilitate the control and operation of the overall system. There are basically two types of energy storage, convertible and end use. Convertible storage is that which can readily be converted back to electricity. End-use storage can be applied to a particular end-use requirement but may not readily be converted back to electricity.

3.5.1 Convertible Storage

There are a number of convertible storage media, although only a few of them have been used frequently in hybrid energy systems. The most commonly used form of convertible storage is the battery. Less commonly used, but frequently discussed, forms include pumped hydroelectric, flywheels, compressed air, and hydrogen.

3.5.1.1 Batteries Batteries are the most commonly used form of convertible storage for hybrid energy systems. They have been used both for short term (less than 1 hour) and long term (more than 1 day) storage. A number of types of batteries have been developed. The most common type of storage battery for hybrid applications is the lead acid battery. Nickel cadmium has also been used occasionally. Batteries are discussed elsewhere in this encyclopedia, so only those aspects most relevant to hybrid energy systems are summarized here.

As far as hybrid energy systems are concerned, there are five important performance characteristics of batteries: (1) voltage, (2) energy storage capacity, (3) charge/discharge rates, (4) efficiency, and (5) battery lifetime.

Batteries by their nature are DC. Individual batteries are made up by a number of cells in series, with each cell nominally two volts. Complete batteries are typically 2, 6, 12, or 24 Volts. The actual terminal voltage will depend on three factors: (1) state of charge, (2) whether the battery is being charged or discharged, and (3) the rate of charge or discharge.

The energy storage capacity is primarily a function of battery voltage and the amount of charge it can hold and then return. Charge is measured in units of current times time (Ampere-hours). The amount of charge that is stored in a battery at any particular time is often described with reference to its full state by the term “state of charge” (SOC). Discharging and charging back to a given level (normally fully charged) is referred to a cycle. The total amount of charge that a battery can hold is primarily a function of the amount of material used in the construction.

Battery capacity is normally specified with reference to a specific discharge rate. This is because the apparent capacity of batteries actually differs with charge and discharge rate. Higher rates result in smaller apparent capacities.

As energy storage media, batteries are not 100% efficient. That is, more energy is expended in charging than can be recovered. Overall efficiencies are typically in range of 50 to 80%.

An important characteristic of batteries is their useful lifetime. Experience has shown that the process of using batteries actually decreases their storage capacity until eventually the battery is no longer useful. The important factors in battery life are the number of cycles and the depth of discharge in the cycles. Depending on the type of battery, the number of deep cycles to which a battery can be subjected ranges from a few thousand down to hundreds or even tens of cycles. The cycle life of a typical battery is illustrated in Fig. 8.

3.5.1.2 Pumped Hydro One form of convertible storage that has been applied in some hybrid energy systems is pumped storage. In this case, water is pumped from one reservoir at a low elevation up to one at a higher elevation. The amount of energy that can be stored is a function of the size of the reservoir and the difference in elevation. The overall efficiency of the storage is a function of the efficiency of the pumps and turbines (which may be the same devices) and the hydraulic losses in the pipes connecting the two reservoirs. The use of pumped storage is limited by the lack of sites where such facilities can be installed at a reasonable price.

3.5.1.3 Flywheels Flywheels can be used to store energy in a hybrid system. A flywheel energy storage system consists of the following components: (1) the flywheel itself, (2) an enclosure, usually evacuated to minimize frictional losses, (3) a variable speed motor/generate to accelerate and decelerate the

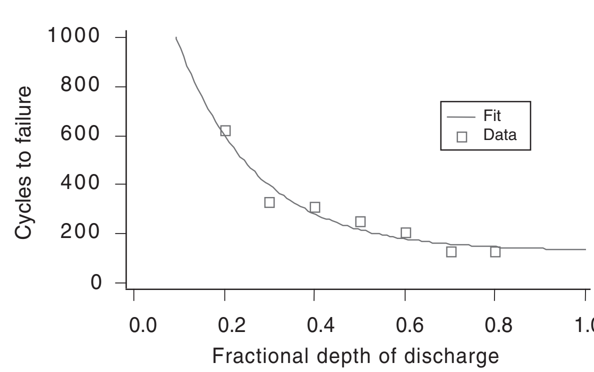

FIGURE 8 Battery cycle life.

wheel, and (4) a power electronic converter. Energy is absorbed when the wheel is accelerated up to its maximum speed and is released when the wheel is decelerated to some lower speed. A power electronic converter accompanies the flywheel and motor/generator because the input and output power to and from the motor/generator is typically variable voltage and variable frequency AC. Flywheels typically store relatively small amounts of energy, but they can absorb or release the energy at high rates. Thus in hybrid power systems they can be used to smooth short term fluctuations in power (on the order of seconds or minutes) and they can facilitate system control.

3.5.1.4 Compressed Air Compressed air can be used for storage in hybrid systems, and some experimental prototypes have been built. Efficiency is relatively low, however, and this method of storage has not been widely used.

3.5.1.5 Hydrogen Hydrogen can be produced by the electrolysis of water, using a renewable energy source for the electricity. The hydrogen can be stored indefinitely and then used in an internal combustion engine/generator or a fuel cell to generate electricity again. This method of storage appears to have a lot of potential, but it is still quite expensive.

3.5.2 End-Use Storage

End-use storage, as opposed to convertible storage, refers to the situation in which some product is created through the use of electricity when it is available. The product is then stored and made available when it is needed. Load management schemes often incorporate some end-use storage. Three examples are given next.

3.5.2.1 Thermal Energy A common form of end-use storage is thermal energy, most often in the form of hot water. Hot water can be used for space heating applications, domestic hot water, swimming pools, and so on. Hot water can be stored relatively inexpensively in insulated water tanks. Depending on the location of the water tanks relative to the end use, the efficiency of the storage can be quite high.

3.5.2.2 Pumped Water Pumped water is another form of end-use storage. This form of storage has a long history of use in conjunction with windmills. In this application, water for any plausible purpose is pumped into a reservoir or storage tank, usually elevated, from which it can be released as needed. When the storage is elevated, then the water can flow by gravity to the point of use, so no further input of externally produced energy is required.

3.5.2.3 Pure Water Another, less common form of end-use storage is the production and then storage of pure water from salty or brackish water. Depending on the quality of water at the input of the process, ultrafiltration, reverse osmosis, or vapor compression evaporation may be used to produce the pure water. All of these are energy intensive, so the implicit energy density of the storage is high.

3.6 Power Converters

For any hybrid energy system to function properly, it is common that one or more power converter be incorporated into the system. These are either electromechanical or electronic devices.

3.6.1 Electromechanical Power Converters

There are at least two types of electromechanical power converters that have been used in hybrid energy systems. They include the rotary converter and the synchronous condenser.

3.6.1.1 Rotary Converter A rotary converter is an electromechanical device that converts AC to DC or vice versa. When it is converting AC to DC it is a rectifier. When operating the other way it is an inverter. The rotary converter consists of two rotating electrical machines that are directly connected together. One of them is a DC machine; the other is an AC machine. Either of them can run as a motor or generator depending on the intended direction of power flow. The AC machine can be either an induction machine or a synchronous machine. Which is used will depend on the requirements of the system.

Rotary converters have the advantage that they are a rugged and well-understood technology that has been around for many years. Their disadvantage is that their costs are high and their efficiencies are lower than are electronic devices that can serve the same purpose.

3.6.1.2 Synchronous Condenser Synchronous condenser is the name given to a synchronous machine that is connected into an electrical network to help in maintaining the system voltage. The synchronous machine in this case is essentially a motor to which no load is connected. A voltage regulator is connected to the synchronous machine and functions in the same way as described previously. Synchronous condensers are used in hybrid energy systems when there are, for at least some of the time, no other synchronous machines connected. This is often the case in those systems that include diesel generators but that are intended to allow all the diesels generators to be turned off under some circumstances. For example, a synchronous condenser could be used in a wind/diesel system in which the wind turbines used induction generators and could at times supply all of the electrical load. The diesel could then be turned off, but the synchronous machine would be needed to supply the required reactive power to the induction generators and maintain system voltage in the process.

3.6.2 Electronic Power Converters

A wide range of electronic devices has been developed and adapted for use in hybrid energy systems. Many of them serve similar functions to the electromechanical devices described previously, but have a number of advantages, such as lower cost, higher efficiencies, and greater controllability. The devices of greatest interest include rectifiers, inverters, dump loads, and maximum power point trackers.

3.6.2.1 Rectifiers A rectifier is a device that converts AC to DC. The primary functional elements are diodes, which only let current pass one way. By suitable layout of the diodes AC in a single or three-phase circuit is converted to a rippling, but single direction, current. Capacitors may be used to smooth the resulting current.

3.6.2.2 Inverter An inverter is a device that converts DC to AC. The primary switching elements are either silicon controlled rectifiers (SCRs) or power transistors (IGBTs). They are arranged in a bridge circuit and switched on (and off, in the case of transistors) in such a way that an oscillating waveform results. Some inverters operate in conjunction with other devices that set the system frequency. These are referred to as line commutated. Other inverters have the capability to set frequency themselves. These are called self-commutated.

3.6.3 Maximum Power Point Trackers

Another electronic device that may be used in hybrid energy systems, particularly ones with photovoltaic panels is the maximum power tracker. This device is DC-DC converter than can be partially thought of as a DC transformer. Its function to provide a particular desired output voltage to the rest of the system, while adjusting the voltage at the input to allow the maximum power production by the generator that is connected to it. In the case of photovoltaic panels, the voltage at the input will be the maximum power point voltage corresponding to the incident solar radiation level. Maximum power point trackers have also been used with small wind turbines.

3.7 Dump Loads

A dump load is device that is used to dissipate power in order to maintain stability in an isolated hybrid energy system. Dump loads are used primarily to maintain power balances. They may also be used to control frequency. The most common use of a dump load is in isolated wind/diesel systems where the penetration of the wind energy generation is such that instantaneous power levels sometimes exceed the system load less than minimum allowed diesel power level. The dump load control can sense the excess power and dissipate whatever is required to ensure that the total generated power is exactly equal to the actual system load plus that which is dissipated. The dump load is virtually a requirement in high penetration wind/diesel systems using stall controlled wind turbines, because adjusting the power is impossible. When pitch controlled turbines are used it may be possible to dispense with the dump load, since power can be limited by pitching the blades.

3.8 Supervisory Controller

Many hybrid systems, especially the more complex ones, have a supervisory controller to ensure proper operation of all the devices within the system. The possible functions of a supervisory controller are illustrated in Fig. 9. The controller itself consists of three main functional units: (1) sensors, (2) logical unit, and (3) control commands.

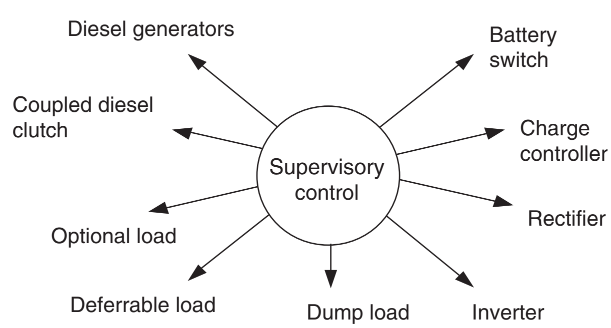

FIGURE 9 Supervisory controller functions.

Sensors are distributed throughout the system. They provide information on power levels, operating conditions, and so on. The information gathered from the sensors is directed to the logical unit. The logical unit is based on a computer or microprocessor. It will make decisions based on an internal algorithm and the data from the sensors. Algorithms can be fairly simple or quite complex.

The decisions made by the logical unit are referred to as dispatch decisions, since their function relates to dispatching of the various devices in the system. Dispatch in this sense refers to turning a device on or off, or in some cases to setting its power level. The dispatch instructions from the supervisory controller are sent to controllers of the various devices in the system.

4. ENERGY LOADS

The energy supplied by a hybrid system can be categorized in a variety of ways. The first has to do whether the energy supplied is electricity or heat. Within the electrical category, electricity loads are often divided into primary and secondary loads. Primary loads are those that must be served immediately. Secondary loads are associated with load management, and they may be further divided in what are known as deferrable and optional loads. Deferrable loads have some flexibility in when they are served, while optional loads are those which are only served if there happens to be sufficient excess energy available to do so. Regardless of type, it may be noted that loads frequently vary significantly from one season to the next as well as over the week and over the day, as was discussed earlier.

5. RENEWABLE ENERGY RESOURCE CHARACTERISTICS

It is worth considering briefly the time varying nature of the various renewable resources that might be used in a hybrid system, because that nature will affect the design and operation of the system.

5.1 Wind

The wind resource is ultimately generated by the sun, but it tends to be very dependent on location. Over most of the earth, the average wind speed varies from one season to another. It is also likely to be affected by general weather patterns and the time of day. It is not uncommon for a site to experience a number of days of relatively high winds and for those days to be followed by others of lower winds. The daily and monthly average wind speed for an island off the coast of Massachusetts, illustrating these variations, is illustrated in Fig. 10. The wind also exhibits short-term variations in speed and direction. This is known as turbulence. Turbulent fluctuations take place over time periods of seconds to minutes.

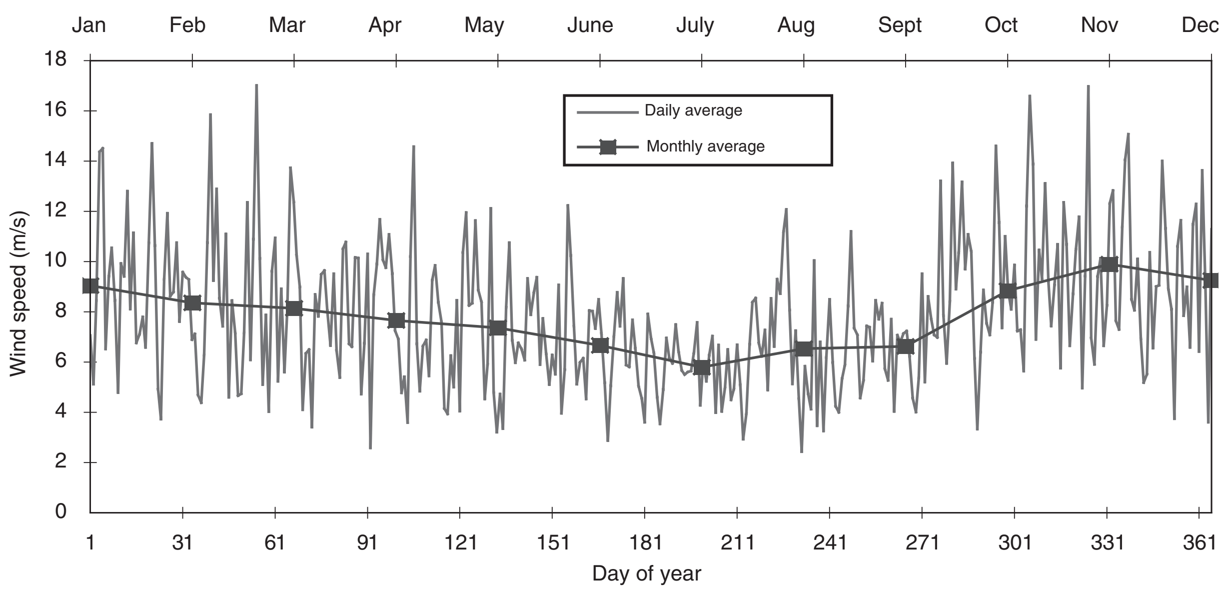

FIGURE 10 Daily and monthly wind speeds on Cuttyhunk Island, Massachusetts.

5.2 Solar Radiation

The solar radiation resource is fundamentally determined by the location on the earth's surface, the date, and the time of day. Those factors will determine the maximum level of radiation. Other factors, such as height above sea level, water vapor or pollutants in the atmosphere, and cloud cover, decrease the radiation level below the maximum possible. Solar radiation does not experience the same type of turbulence that wind does, but there can be variations over the short term. Most often, these are related to the passage of clouds. Figure 11 illustrates the solar radiation over a 5-day period in December in Boston, Massachusetts.

5.3 Hydropower

The hydropower resource at a site is a function of the amount of flowing water available (discharge) in a river or stream and the change in elevation (head). The head is usually relative constant (affected only by high water during storms), but the amount of water available can vary significantly over time. The average discharge is determined by rainfall and the drainage area upstream of the site on which the rain falls. Discharge will increase after storms and decrease during droughts. Soil conditions and nature of the terrain can also affect the discharge. Short-term fluctuations are normally insignificant.

5.4 Biomass

Sources of biomass are forest or agricultural products. The resource is ultimately a function of such factors as solar radiation, rainfall, soil conditions, temperatures, and the plant species that can be grown.

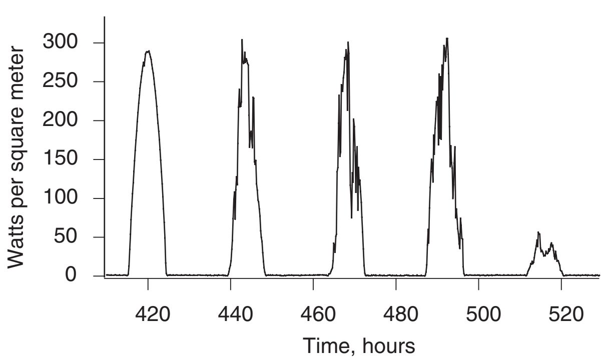

FIGURE 11 Hourly solar for 5 days radiation in Boston, Massachusetts.

6. DESIGN CONSIDERATIONS

The design of a hybrid energy system will depend on the type of application and the nature of the resources available. The primary consideration is whether the system will be isolated or grid connected. Other important considerations include (1) how the various generator types will be intended to operate with each other, (2) excess power dissipation, (3) use of storage, (4) frequency control, (5) voltage control, (6) possible dynamic interactions between components. Many of the possible technologies were discussed previously and will not be repeated here.

6.1 Load Matching

In the design of an isolated hybrid system with renewable energy source generators one matter of particular concern is known as load-matching. This refers to coincidence in time (or lack thereof) of the renewable resource and the load. The match between the two will affect the details of the design and will also determine how much of the energy that can be generated from the renewable energy source can actually be used. When too much is available, some of it may have to be dissipated. When too little is available, either storage or a conventional fueled generator will be needed.

Under ideal circumstances, the energy requirement will match the available resource. Often, however, that is not the case. In many islands of the world, for example, the largest loads are during the summer tourist season, but the wind resource is greatest in the winter. Figures 3 and 10 above illustrated a typical example of this for the load and wind, respectively.

When there is a mismatch between the resource and the load, the system must be designed to function properly under all conditions. For example, a wind/diesel system designed for the situation shown in Figs. 3 and 10 would most likely be designed so that wind energy could supply most of the load in the winter, keeping most or all of the diesel generators off for long periods, but in the summer, the diesels would continue to run and the wind turbines would serve as fuel savers. Figure 12 illustrates the possible energy flows for a 50-second period for a hypothetical wind/diesel system on an isolated island. The system illustrated has a primary load, an optional heating load, a dump load, a wind turbine, and multiple diesel engine/generators, at least one of which must always remain on.

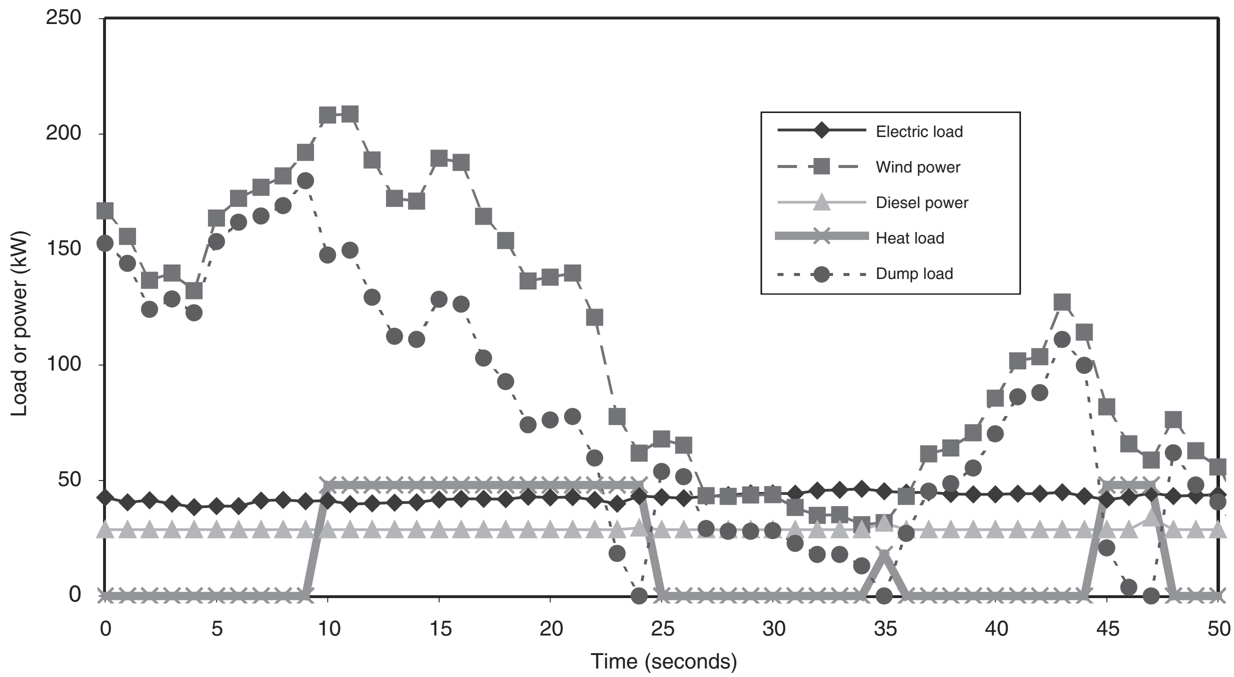

FIGURE 12 Power flows in hypothetical wind/diesel system.

7. ECONOMICS

Whether or not a hybrid energy system is actually used, and what it looks like, is strongly related to the economics of the system. In particular, will the cost of energy from the hybrid system be lower than that of a more conventional alternative? The cost of energy of a hybrid system is determined primarily by two factors: the cost of the system and the amount of useful energy that is produced. Other factors that are also important include the value of the energy, the cost of conventional energy, lifetime of the system, maintenance costs, and financial costs.

The cost of a hybrid energy system is first of all affected by the cost of the individual components that make up the system. Installation of the components and integrating them into a functioning unit will also contribute to the total cost. Generally, the renewable energy generators themselves are the most expensive items. For example, at the present time, wind turbines cost on the order of $1000 to $2000/kW, depending on the size. Photovoltaic panels cost on the order of $6000 to $8000/kW. Diesel generators are also costly, but considerably less so than wind turbines. Costs of $250 to $500/kW are typical. Lead acid batteries cost $100 to $200/kWh.

The energy that can be produced by a renewable energy generator will depend on the type of generator, its productivity at different levels of the resource, and the distribution of the occurrences of those levels. For example, a wind turbine will produce different amounts of power depending on the wind speed. If the average wind speed each hour over a year is known, this information can be combined with the data in the turbine power curve to predict the total energy that the turbine could produce. Similar curves describe the output of photovoltaic panels. These curves, combined with hourly data on the solar resource, can be used to predict the total annual energy from the panels.

When a renewable energy generator is operating in a hybrid energy system, predicting the useful energy is not as simple as it would appear, based on the previous discussion. First of all, because of a likely mismatch between the available resource and the load, it is may be that not all of the energy can be used when it is available, except in very low penetration systems. When not all of the load is supplied by the renewable generator, the rest is made up a conventional generator. Because of the difficulty in determining the amount of useful energy produced by the renewable energy generators in a hybrid system and predicting the actual fuel savings, detailed computer models are frequently used to facilitate the process.

The value of energy in a hybrid energy system is related to the nature of the energy produced, the cost of the alternatives, and the vantage point of the operator of the system. For example, the operator of an island diesel power system, considering installing a wind turbine, would want to know that the cost of the turbine would be offset by the decrease in diesel fuel purchased.

Economics of hybrid energy systems are typically evaluated by a technique known as life cycle costing. This method takes account of the fact that hybrid energy systems have relatively high initial costs but long lifetimes and low operating costs. These factors, together with various financial parameters, are used to predict present value costs, which can then be compared with costs from the conventional alternatives.

8. TRENDS IN HYBRID ENERGY SYSTEMS

Hybrid energy systems are still an emerging technology. It is expected that technology will continue to evolve in the future, so that it will have wider applicability and lower costs. There will be more standardized designs, and it will be easier to select a system suited to particular applications. There will be increased communication between components. This will facilitate control, monitoring, and diagnosis. Finally, there will be increased use of power electronic converters. Power electronic devices are already used in many hybrid systems, and as costs go down and reliability improves, they are expected to be used more and more.

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Further Reading

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