Rahman, Saifur "Electric Power Generation: Non-Conventional Methods"
The Electric Power Engineering Handbook
Ed. L.L. Grigsby
Boca Raton: CRC Press LLC, 2001

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Electric Power Generation: Non-Conventional Methods

Saifur Rahman
Virginia Tech

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Gary L. Johnson
Kansas State University

Saifur Rahman
Virginia Tech

Roger A. Messenger
Florida Atlantic University

1.1 Wind Power

Gary L. Johnson

The wind is a free, clean, and inexhaustible energy source. It has served humankind well for many centuries by propelling ships and driving wind turbines to grind grain and pump water. Denmark was the first country to use wind for generation of electricity. The Danes were using a 23-m diameter wind turbine in 1890 to generate electricity. By 1910, several hundred units with capacities of 5 to 25 kW were in operation in Denmark (Johnson, 1985). By about 1925, commercial wind-electric plants using two- and three-bladed propellers appeared on the American market. The most common brands were Wincharger (200 to 1200 W) and Jacobs (1.5 to 3 kW). These were used on farms to charge storage batteries which were then used to operate radios, lights, and small appliances with voltage ratings of 12, 32, or 110 volts. A good selection of 32-VDC appliances was developed by the industry to meet this demand.

In addition to home wind-electric generation, a number of utilities around the world have built larger wind turbines to supply power to their customers. The largest wind turbine built before the late 1970s was a 1250-kW machine built on Grandpa's Knob, near Rutland, Vermont, in 1941. This turbine, called the Smith-Putnam machine, had a tower that was 34 m high and a rotor 53 m in diameter. The rotor turned an ac synchronous generator that produced 1250 kW of electrical power at wind speeds above 13 m/s.

After World War II, we entered the era of cheap oil imported from the Middle East. Interest in wind energy died and companies making small turbines folded. The oil embargo of 1973 served as a wakeup call, and oil-importing nations around the world started looking at wind again. The two most important countries in wind power development since then have been the U.S. and Denmark (Brower et al., 1993).

The U.S. immediately started to develop utility-scale turbines. It was understood that large turbines had the potential for producing cheaper electricity than smaller turbines, so that was a reasonable decision. The strategy of getting large turbines in place was poorly chosen, however. The Department of

TABLE 1.1 Wind Power Installed Capacity

Canada	83
China	224
Denmark	1450
India	968
Ireland	63
Italy	180
Germany	2874
Netherlands	363
Portugal	60
Spain	834
Sweden	150
U.K.	334
U.S.	1952
Other	304
Total	9839

Energy decided that only large aerospace companies had the manufacturing and engineering capability to build utility-scale turbines. This meant that small companies with good ideas would not have the revenue stream necessary for survival. The problem with the aerospace firms was that they had no desire to manufacture utility-scale wind turbines. They gladly took the government's money to build test turbines, but when the money ran out, they were looking for other research projects. The government funded a number of test turbines, from the 100 kW MOD-0 to the 2500 kW MOD-2. These ran for brief periods of time, a few years at most. Once it was obvious that a particular design would never be cost competitive, the turbine was quickly salvaged.

Denmark, on the other hand, established a plan whereby a landowner could buy a turbine and sell the electricity to the local utility at a price where there was at least some hope of making money. The early turbines were larger than what a farmer would need for himself, but not what we would consider utility scale. This provided a revenue stream for small companies. They could try new ideas and learn from their mistakes. Many people jumped into this new market. In 1986, there were 25 wind turbine manufacturers in Denmark. The Danish market gave them a base from which they could also sell to other countries. It was said that Denmark led the world in exports of two products: wind turbines and butter cookies! There has been consolidation in the Danish industry since 1986, but some of the companies have grown large. Vestas, for example, has more installed wind turbine capacity worldwide than any other manufacturer.

Prices have dropped substantially since 1973, as performance has improved. It is now commonplace for wind power plants (collections of utility-scale turbines) to be able to sell electricity for under four cents per kilowatt hour.

Total installed worldwide capacity at the start of 1999 was almost 10,000 MW, according to the trade magazine *Wind Power Monthly* (1999). The countries with over 50 MW of installed capacity at that time are shown in Table 1.1.

Applications

There are perhaps four distinct categories of wind power which should be discussed. These are

1. small, non-grid connected
2. small, grid connected
3. large, non-grid connected
4. large, grid connected

By small, we mean a size appropriate for an individual to own, up to a few tens of kilowatts. Large refers to utility scale.

Small, Non-Grid Connected

If one wants electricity in a location not serviced by a utility, one of the options is a wind turbine, with batteries to level out supply and demand. This might be a vacation home, a remote antenna and transmitter site, or a Third-World village. The costs will be high, on the order of $0.50/kWh, but if the total energy usage is small, this might be acceptable. The alternatives, photovoltaics, microhydro, and diesel generators, are not cheap either, so a careful economic study needs to be done for each situation.

Small, Grid Connected

The small, grid connected turbine is usually not economically feasible. The cost of wind-generated electricity is less because the utility is used for storage rather than a battery bank, but is still not competitive.

In order for the small, grid connected turbine to have any hope of financial breakeven, the turbine owner needs to get something close to the retail price for the wind-generated electricity. One way this is done is for the owner to have an arrangement with the utility called net metering. With this system, the meter runs backward when the turbine is generating more than the owner is consuming at the moment. The owner pays a monthly charge for the wires to his home, but it is conceivable that the utility will sometimes write a check to the owner at the end of the month, rather than the other way around. The utilities do not like this arrangement. They want to buy at wholesale and sell at retail. They feel it is unfair to be used as a storage system without remuneration.

For most of the twentieth century, utilities simply refused to connect the grid to wind turbines. The utility had the right to generate electricity in a given service territory, and they would not tolerate competition. Then a law was passed that utilities had to hook up wind turbines and pay them the avoided cost for energy. Unless the state mandated net metering, the utility typically required the installation of a second meter, one measuring energy consumption by the home and the other energy production by the turbine. The owner would pay the regular retail rate, and the utility would pay their estimate of avoided cost, usually the fuel cost of some base load generator. The owner might pay $0.08 to $0.15 per kWh, and receive $0.02 per kWh for the wind-generated electricity. This was far from enough to economically justify a wind turbine, and had the effect of killing the small wind turbine business.

Large, Non-Grid Connected

These machines would be installed on islands or in native villages in the far north where it is virtually impossible to connect to a large grid. Such places are typically supplied by diesel generators, and have a substantial cost just for the imported fuel. One or more wind turbines would be installed in parallel with the diesel generators, and act as fuel savers when the wind was blowing.

This concept has been studied carefully and appears to be quite feasible technically. One would expect the market to develop after a few turbines have been shown to work for an extended period in hostile environments. It would be helpful if the diesel maintenance companies would also carry a line of wind turbines so the people in remote locations would not need to teach another group of maintenance people about the realities of life at places far away from the nearest hardware store.

Large, Grid Connected

We might ask if the utilities should be forced to buy wind-generated electricity from these small machines at a premium price which reflects their environmental value. Many have argued this over the years. A better question might be whether the small or the large turbines will result in a lower net cost to society. Given that we want the environmental benefits of wind generation, should we get the electricity from the wind with many thousands of individually owned small turbines, or should we use a much smaller number of utility-scale machines?

If we could make the argument that a dollar spent on wind turbines is a dollar not spent on hospitals, schools, and the like, then it follows that wind turbines should be as efficient as possible. Economies of scale and costs of operation and maintenance are such that the small, grid connected turbine will always need to receive substantially more per kilowatt hour than the utility-scale turbines in order to break even. There is obviously a niche market for turbines that are not connected to the grid, but small, grid connected turbines will probably not develop a thriving market. Most of the action will be from the utility-scale machines.

Sizes of these turbines have been increasing rapidly. Turbines with ratings near 1 MW are now common, with prototypes of 2 MW and more being tested. This is still small compared to the needs of a utility, so clusters of turbines are placed together to form wind power plants with total ratings of 10 to 100 MW.

Wind Variability

One of the most critical features of wind generation is the variability of wind. Wind speeds vary with time of day, time of year, height above ground, and location on the earth's surface. This makes wind generators into what might be called energy producers rather than power producers. That is, it is easier to estimate the energy production for the next month or year than it is to estimate the power that will be produced at 4:00 PM next Tuesday. Wind power is not dispatchable in the same manner as a gas turbine. A gas turbine can be scheduled to come on at a given time and to be turned off at a later time, with full power production in between. A wind turbine produces only when the wind is available. At a good site, the power output will be zero (or very small) for perhaps 10% of the time, rated for perhaps another 10% of the time, and at some intermediate value the remaining 80% of the time.

This variability means that some sort of storage is necessary for a utility to meet the demands of its customers, when wind turbines are supplying part of the energy. This is not a problem for penetrations of wind turbines less than a few percent of the utility peak demand. In small concentrations, wind turbines act like negative load. That is, an increase in wind speed is no different in its effect than a customer turning off load. The control systems on the other utility generation sense that generation is greater than load, and decrease the fuel supply to bring generation into equilibrium with load. In this case, storage is in the form of coal in the pile or natural gas in the well.

An excellent form of storage is water in a hydroelectric lake. Most hydroelectric plants are sized large enough to not be able to operate full-time at peak power. They therefore must cut back part of the time because of the lack of water. A combination hydro and wind plant can conserve water when the wind is blowing, and use the water later, when the wind is not blowing.

When high-temperature superconductors become a little less expensive, energy storage in a magnetic field will be an exciting possibility. Each wind turbine can have its own superconducting coil storage unit. This immediately converts the wind generator from an energy producer to a peak power producer, fully dispatchable. Dispatchable peak power is always worth more than the fuel cost savings of an energy producer. Utilities with adequate base load generation (at low fuel costs) would become more interested in wind power if it were a dispatchable peak power generator.

The variation of wind speed with time of day is called the diurnal cycle. Near the earth's surface, winds are usually greater during the middle of the day and decrease at night. This is due to solar heating, which causes "bubbles" of warm air to rise. The rising air is replaced by cooler air from above. This thermal mixing causes wind speeds to have only a slight increase with height for the first hundred meters or so above the earth. At night, however, the mixing stops, the air near the earth slows to a stop, and the winds above some height (usually 30 to 100 m) actually increase over the daytime value. A turbine on a short tower will produce a greater proportion of its energy during daylight hours, while a turbine on a very tall tower will produce a greater proportion at night.

As tower height is increased, a given generator will produce substantially more energy. However, most of the extra energy will be produced at night, when it is not worth very much. Standard heights have been increasing in recent years, from 50 to 65 m or even more. A taller tower gets the blades into less turbulent air, a definite advantage. The disadvantages are extra cost and more danger from overturning in high winds. A very careful look should be given the economics before buying a tower that is significantly taller than whatever is sold as a standard height for a given turbine.

Wind speeds also vary strongly with time of year. In the southern Great Plains (Kansas, Oklahoma, and Texas), the winds are strongest in the spring (March and April) and weakest in the summer (July and August). Utilities here are summer peaking, and hence need the most power when winds are the lowest and the least power when winds are highest. The diurnal variation of wind power is thus a fairly good match to utility needs, while the yearly variation is not.

TABLE 1.2 Monthly Average Wind Speed in MPH and Projected Energy Production at 65 m, at a Good Site in Southern Kansas

Month	10 m Speed	60 m Speed	Energy (MWh)	Month	10 m Speed	60 m Speed	Energy (MWh)
1/96	14.9	20.3	256	1/97	15.8	21.2	269
2/96	16.2	22.4	290	2/97	14.7	19.0	207
3/96	17.6	22.3	281	3/97	17.4	22.8	291
4/96	19.8	25.2	322	4/97	15.9	20.4	242
5/96	18.4	23.1	297	5/97	15.2	19.8	236
6/96	13.5	18.2	203	6/97	11.9	16.3	167
7/96	12.5	16.5	169	7/97	13.3	18.5	212
8/96	11.6	16.0	156	8/97	11.7	16.9	176
9/96	12.4	17.2	182	9/97	13.6	19.0	211
10/96	17.1	23.3	320	10/97	15.0	21.1	265
11/96	15.3	20.0	235	11/97	14.3	19.7	239
12/96	15.1	20.1	247	12/97	13.6	19.5	235

The variability of wind with month of year and height above ground is illustrated in Table 1.2. These are actual wind speed data for a good site in Kansas, and projected electrical generation of a Vestas turbine (V47-660) at that site. Anemometers were located at 10, 40, and 60 m above ground. Wind speeds at 40 and 60 m were used to estimate the wind speed at 65 m (the nominal tower height of the V47-660) and to calculate the expected energy production from this turbine at this height. Data have been normalized for a 30-day month.

There can be a factor of two between a poor month and an excellent month (156 MWh in 8/96 to 322 MWh in 4/96). There will not be as much variation from one year to the next, perhaps 10 to 20%. A wind power plant developer would like to have as long a data set as possible, with an absolute minimum of one year. If the one year of data happens to be for the best year in the decade, followed by several below average years, a developer could easily get into financial trouble. The risk gets smaller if the data set is at least two years long.

One would think that long-term airport data could be used to predict whether a given data set was collected in a high or low wind period for a given part of the country, but this is not always true. One study showed that the correlation between average annual wind speeds at Russell, Kansas, and Dodge City, Kansas, was 0.596 while the correlation between Russell and Wichita was 0.115. The terrain around Russell is very similar to that around Wichita, and there is no obvious reason why wind speeds should be high at one site and low at the other for one year, and then swap roles the next year.

There is also concern about long-term variation in wind speeds. There appears to be an increase in global temperatures over the past decade or so, which would probably have an impact on wind speeds. It also appears that wind speeds have been somewhat lower as temperatures have risen, at least in Kansas. It appears that wind speeds can vary significantly over relatively short distances. A good data set at one location may underpredict or overpredict the winds at a site a few miles away by as much as 10 to 20%. Airport data collected on a 7-m tower in a flat river valley may underestimate the true surrounding hilltop winds by a factor of two. If economics are critical, a wind power plant developer needs to acquire rights to a site and collect wind speed data for at least one or two years before committing to actually constructing turbines there.

Land Rights

Spacing of turbines can vary widely with the type of wind resource. In a tradewind or a mountain pass environment where there are only one or two prevailing wind directions, the turbines can be located "shoulder to shoulder" crossways to the wind direction. A downwind spacing of ten times the rotor diameter is usually assumed to be adequate to give the wind space to recover its speed. In open areas, a crosswind spacing of four rotor diameters is usually considered a minimum. In the Great Plains, the prevailing winds are from the south (Kansas, Oklahoma, and Texas) or north (the Dakotas). The energy in the winds from east and west may not be more than 10% of the total energy. In this situation, a spacing of ten rotor diameters north–south and four rotor diameters east–west would be minimal. Adjustments would be made to avoid roads, pipelines, power lines, houses, ponds, and creeks.

The results of a detailed site layout will probably not predict much more than 20 MW of installed capacity per square mile (640 acres). This figure can be used for initial estimates without great error. That is, if a developer is considering installing a 100-MW wind plant, rights to at least five square miles should be acquired.

One issue that has not received much attention in the wind power community is that of a fair compensation to the land owner for the privilege of installing wind turbines. The developer could buy the land, hopefully with a small premium. The original deal could be an option to buy at some agreed upon price, if two years of wind data were satisfactory. The developer might lease the land back to the original landowner, since the agricultural production capability is only slightly affected by the presence of wind turbines. Outright purchase between a willing and knowledgeable buyer and seller would be as fair an arrangement as could be made.

But what about the case where the landowner does not want to sell? Rights have been acquired by a large variety of mechanisms, including a large one-time payment for lease signing, a fixed yearly fee, a royalty payment based on energy produced, and combinations of the above. The one-time payment has been standard utility practice for right-of-way acquisitions, and hence will be preferred by at least some utilities. A key difference is that wind turbines require more attention than a transmission line. Roads are not usually built to transmission line towers, while they are built to wind turbines. Roads and maintenance operations around wind turbines provide considerably more hassle to the landowner. The original owner got the lease payment, and 20 years later the new owner gets the nuisance. There is no incentive for the new landowner to be cooperative or to lobby county or state officials on behalf of the developer.

A one-time payment also increases the risk to the developer. If the project does not get developed, there has been a significant outlay of cash which will have no return on it. These disadvantages mean that the one-time payment with no yearly fees or royalties will probably not be the long-term norm in the industry.

To discuss what might be a fair price for a lease, it will be helpful to use an example. We will assume the following:

- 20 MW per square mile
- Land fair-market value $500/acre
- Plant factor 0.4
- Developer desired internal rate of return 0.2
- Electricity value $0.04/kWh
- Installed cost of wind turbine $1000/kW

A developer that purchased the land at $500/acre would therefore want a return of $(500)(0.2) = $100/acre. America's cheap food policy means that production agriculture typically gets a much smaller return on investment than the developer wants. Actual cash rent on grassland might be $15/acre, or a return of 0.03 on investment. We see an immediate opportunity for disagreement, even hypocrisy. The developer might offer the landowner $15/acre when the developer would want $100/acre if he bought the land. This hardly seems equitable.

The gross income per acre is

$$I = \frac{(20{,}000\ \text{kW})(0.4)(8760\ \text{hours/year})(\$0.04)}{640\ \text{acres}} = \$4380/\text{acre}/\text{year} \tag{1.1}$$

The cost of wind turbines per acre is

$$CT_a = \frac{(20{,}000\ \text{kW})(\$1000/\text{kW})}{640\ \text{acres}} = \$31{,}250/\text{acre} \tag{1.2}$$

We see that the present fair-market value for the land is tiny compared with the installed cost of the wind turbines. A lease payment of $100/acre/year is slightly over 2% of the gross income. It is hard to imagine financial arrangements so tight that they would collapse if the landowner (either rancher or developer) were paid this yearly fee. That is, it seems entirely reasonable for a figure like 2% of gross income to be a starting point for negotiations.

There is another factor that might result in an even higher percentage. Landowners throughout the Great Plains are accustomed to royalty payments of 12.5% of wholesale price for oil and gas leases. This is determined independently of any agricultural value for the land. The most worthless mesquite in Texas gets the same terms as the best irrigated corn ground in Kansas. We might ask if this rate is too high. A royalty of 12.5% of wholesale amounts to perhaps 6% of retail. Cutting the royalty in half would have the potential of reducing the price of gasoline about 3%. In a market where gasoline prices swing by 20%, this reduction is lost in the noise. If a law were passed which cut royalty payments in half, it is hard to argue that it would have much impact on our gasoline buying habits, the size of vehicles we buy, or the general welfare of the nation.

One feature of the 12.5% royalty is that it is high enough to get most oil and gas producing land under lease. Would 6.25% have been enough to get the same amount of land leased? If we assumed that some people would sign a lease for 12.5% that would not sign if the offer were 6.25%, then we have the interesting possibility that the supply would be less. If we assume the law of supply and demand to apply, the price of gasoline and natural gas would increase. The possible increase is shear speculation, but could easily be more than the 6.25% that was "saved" by cutting the royalty payment in half.

The point is that the royalty needs to be high enough to get the very best sites under lease. If the best site produces 10% more energy than the next best, it makes no economic sense to pay a 2% royalty for the second best when a 6% royalty would get the best site. In this example, the developer would get 10% more energy for 4% more royalty. The developer could either pocket the difference or reduce the price of electricity a proportionate amount.

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1.2 Advanced Energy Technologies

Saifur Rahman

Storage Systems

Energy storage technologies are of great interest to electric utilities, energy service companies, and automobile manufacturers (for electric vehicle application). The ability to store large amounts of energy would allow electric utilities to have greater flexibility in their operation because with this option the supply and demand do not have to be matched instantaneously. The availability of the proper battery at the right price will make the electric vehicle a reality, a goal that has eluded the automotive industry thus far. Four types of storage technologies (listed below) are discussed in this section, but most emphasis is placed on storage batteries because it is now closest to being commercially viable. The other storage technology widely used by the electric power industry, pumped-storage power plants, is not discussed as this has been in commercial operation for more than 60 years in various countries around the world.

- Flywheel storage
- Compressed air energy storage
- Superconducting magnetic energy storage
- Battery storage

Flywheel Storage

Flywheels store their energy in their rotating mass, which rotates at very high speeds (approaching 75,000 rotations per minute), and are made of composite materials instead of steel because of the composite's ability to withstand the rotating forces exerted on the flywheel. In order to store enegy the flywheel is placed in a sealed container which is then placed in a vacuum to reduce air resistance. Magnets embedded in the flywheel pass near pickup coils. The magnet induces a current in the coil changing the rotational energy into electrical energy. Flywheels are still in research and development, and commercial products are several years away.

Compressed Air Energy Storage

As the name implies, the compressed air energy storage (CAES) plant uses electricity to compress air which is stored in underground reservoirs. When electricity is needed, this compressed air is withdrawn, heated with gas or oil, and run through an expansion turbine to drive a generator. The compressed air can be stored in several types of underground structures, including caverns in salt or rock formations, aquifers, and depleted natural gas fields. Typically the compressed air in a CAES plant uses about one third of the premium fuel needed to produce the same amount of electricity as in a conventional plant. A 290-MW CAES plant has been in operation in Germany since the early 1980s with 90% availability and 99% starting reliability. In the U.S., the Alabama Electric Cooperative runs a CAES plant that stores compressed air in a 19-million cubic foot cavern mined from a salt dome. This 110-MW plant has a storage capacity of 26 h. The fixed-price turnkey cost for this first-of-a-kind plant is about $400/kW in constant 1988 dollars.

The turbomachinery of the CAES plant is like a combustion turbine, but the compressor and the expander operate independently. In a combustion turbine, the air that is used to drive the turbine is compressed just prior to combustion and expansion and, as a result, the compressor and the expander must operate at the same time and must have the same air mass flow rate. In the case of a CAES plant, the compressor and the expander can be sized independently to provide the utility-selected "optimal" MW charge and discharge rate which determines the ratio of hours of compression required for each hour of turbine-generator operation. The MW ratings and time ratio are influenced by the utility's load curve, and the price of off-peak power. For example, the CAES plant in Germany requires 4 h of compression per hour of generation. On the other hand, the Alabama plant requires 1.7 h of compression for each hour of generation. At 110-MW net output, the power ratio is 0.818 kW output for each kilowatt input. The heat rate (LHV) is 4122 BTU/kWh with natural gas fuel and 4089 BTU/kWh with fuel oil. Due to the storage option, a partial-load operation of the CAES plant is also very flexible. For example, the heat rate of the expander increases only by 5%, and the airflow decreases nearly linearly when the plant output is turned down to 45% of full load. However, CAES plants have not reached commercial viability beyond some prototypes.

Superconducting Magnetic Energy Storage

A third type of advanced energy storage technology is superconducting magnetic energy storage (SMES), which may someday allow electric utilities to store electricity with unparalled efficiency (90% or more). A simple description of SMES operation follows.

The electricity storage medium is a doughnut-shaped electromagnetic coil of superconducting wire. This coil could be about 1000 m in diameter, installed in a trench, and kept at superconducting temperature by a refrigeration system. Off-peak electricity, converted to direct current (DC), would be fed into this coil and stored for retrieval at any moment. The coil would be kept at a low-temperature superconducting state using liquid helium. The time between charging and discharging could be as little as 20 ms with a round-trip AC–AC efficiency of over 90%.

Developing a commercial-scale SMES plant presents both economic and technical challenges. Due to the high cost of liqiuid helium, only plants with 1000-MW, 5-h capacity are economically attractive. Even then the plant capital cost can exceed several thousand dollars per kilowatt. As ceramic superconductors, which become superconducting at higher temperatures (maintained by less expensive liquid nitrogen), become more widely available, it may be possible to develop smaller scale SMES plants at a lower price.

Battery Storage

Even though battery storage is the oldest and most familiar energy storage device, significant advances have been made in this technology in recent years to deserve more attention. There has been renewed interest in this technology due to its potential application in non-polluting electric vehicles. Battery systems are quiet and non-polluting, and can be installed near load centers and existing suburban substations. These have round-trip AC–AC efficiencies in the range of 85%, and can respond to load changes within 20 ms. Several U.S., European, and Japanese utilities have demonstrated the application of lead–acid batteries for load-following applications. Some of them have been as large as 10 MW with 4 h of storage.

The other player in battery development is the automotive industry for electric vehicle application. In 1991, General Motors, Ford, Chrysler, Electric Power Research Institute (EPRI), several utilities, and the U.S. Department of Energy (DOE) formed the U.S. Advanced Battery Consortium (USABC) to develop better batteries for electric vehicle (EV) applications. A brief introduction to some of the available battery technologies as well some that are under study is presented in the following (Source:http://www.eren.doe.gov/consumerinfo/refbriefs/fa1/html).

Battery Types

Chemical batteries are individual cells filled with a conducting medium-electrolyte that, when connected together, form a battery. Multiple batteries connected together form a battery bank. At present, there are two main types of batteries: primary batteries (non-rechargeable) and secondary batteries (rechargeable). Secondary batteries are further divided into two categories based on the operating temperature of the electrolyte. Ambient operating temperature batteries have either aqueous (flooded) or nonaqueous electrolytes. High operating temperature batteries (molten electrodes) have either solid or molten electrolytes. Batteries in EVs are the secondary-rechargeable-type and are in either of the two sub-categories. A battery for an EV must meet certain performance goals. These goals include quick discharge and recharge capability, long cycle life (the number of discharges before becoming unserviceable), low cost, recyclability, high specific energy (amount of usable energy, measured in watt-hours per pound [lb] or kilogram [kg]), high energy density (amount of energy stored per unit volume), specific power (determines the potential for acceleration), and the ability to work in extreme heat or cold. No battery currently available meets all these criteria.

Lead–Acid Batteries

Lead–acid starting batteries (shallow-cycle lead–acid secondary batteries) are the most common battery used in vehicles today. This battery is an ambient temperature, aqueous electrolyte battery. A cousin to this battery is the deep-cycle lead–acid battery, now widely used in golf carts and forklifts. The first electric cars built also used this technology. Although the lead–acid battery is relatively inexpensive, it is very heavy, with a limited usable energy by weight (specific energy). The battery's low specific energy and poor energy density make for a very large and heavy battery pack, which cannot power a vehicle as far as an equivalent gas-powered vehicle. Lead–acid batteries should not be discharged by more than 80% of their rated capacity or depth of discharge (DOD). Exceeding the 80% DOD shortens the life of the battery. Lead–acid batteries are inexpensive, readily available, and are highly recyclable, using the elaborate recycling system already in place. Research continues to try to improve these batteries.

A lead–acid nonaqueous (gelled lead acid) battery uses an electrolyte paste instead of a liquid. These batteries do not have to be mounted in an upright position. There is no electrolyte to spill in an accident. Nonaqueous lead–acid batteries typically do not have as high a life cycle and are more expensive than flooded deep-cycle lead–acid batteries.

Nickel Iron and Nickel Cadmium Batteries

Nickel iron (Edison cells) and nickel cadmium (nicad) pocket and sintered plate batteries have been in use for many years. Both of these batteries have a specific energy of around 25 Wh/lb (55 Wh/kg), which is higher than advanced lead–acid batteries. These batteries also have a long cycle life. Both of these batteries are recyclable. Nickel iron batteries are non-toxic, while nicads are toxic. They can also be discharged to 100% DOD without damage. The biggest drawback to these batteries is their cost. Depending on the size of battery bank in the vehicle, it may cost between $20,000 and $60,000 for the batteries. The batteries should last at least 100,000 mi (160,900 km) in normal service.

Nickel Metal Hydride Batteries

Nickel metal hydride batteries are offered as the best of the next generation of batteries. They have a high specific energy: around 40.8 Wh/lb (90 Wh/kg). According to a U.S. DOE report, the batteries are benign to the environment and are recyclable. They also are reported to have a very long cycle life. Nickel metal hydride batteries have a high self-discharge rate: they lose their charge when stored for long periods of time. They are already commercially available as "AA" and "C" cell batteries, for small consumer appliances and toys. Manufacturing of larger batteries for EV applications is only available to EV manufacturers. Honda is using these batteries in the EV Plus, which is available for lease in California.

Sodium Sulfur Batteries

This battery is a high-temperature battery, with the electrolyte operating at temperatures of 572°F (300°C). The sodium component of this battery explodes on contact with water, which raises certain safety concerns. The materials of the battery must be capable of withstanding the high internal temperatures they create, as well as freezing and thawing cycles. This battery has a very high specific energy: 50 Wh/lb (110 Wh/kg). The Ford Motor Company uses sodium sulfur batteries in their Ecostar, a converted delivery minivan that is currently sold in Europe. Sodium sulfur batteries are only available to EV manufacturers.

Lithium Iron and Lithium Polymer Batteries

The USABC considers lithium iron batteries to be the long-term battery solution for EVs. The batteries have a very high specific energy: 68 Wh/lb (150 Wh/kg). They have a molten-salt electrolyte and share many features of a sealed bipolar battery. Lithium iron batteries are also reported to have a very long cycle life. These are widely used in laptop computers. These batteries will allow a vehicle to travel distances and accelerate at a rate comparable to conventional gasoline-powered vehicles. Lithium polymer batteries eliminate liquid electrolytes. They are thin and flexible, and can be molded into a variety of shapes and sizes. Neither type will be ready for EV commercial applications until early in the 21st century.

Zinc and Aluminum Air Batteries

Zinc air batteries are currently being tested in postal trucks in Germany. These batteries use either aluminum or zinc as a sacrificial anode. As the battery produces electricity, the anode dissolves into the electrolyte. When the anode is completely dissolved, a new anode is placed in the vehicle. The aluminum or zinc and the electrolyte are removed and sent to a recycling facility. These batteries have a specific energy of over 97 Wh/lb (200 Wh/kg). The German postal vans currently carry 80 kWh of energy in their battery, giving them about the same range as 13 gallons (49.2 liters) of gasoline. In their tests, the vans have achieved a range of 615 mi (990 km) at 25 miles per hour (40 km/h).

Fuel Cells

In 1839, a British Jurist and an amateur physicist named William Grove first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electricity and water which was then used to split water in a different container to produce hydrogen and oxygen. However, it took another 120 years until NASA demonstrated its use to provide electricity and water for some early space flights. Today the fuel cell is the primary source of electricity on the space shuttle. As a result of these successes, industry slowly began to appreciate the commercial value of fuel cells. In addition to stationary power generation applications, there is now a strong push to develop fuel cells for automotive use. Even though fuel cells provide high performance characterisitics, reliability, durability, and environmental benefits, a very high investment cost is still the major barrier against large-scale deployments.

Basic Principles

The fuel cell works by processing a hydrogen-rich fuel — usually natural gas or methanol — into hydrogen, which, when combined with oxygen, produces electricity and water. This is the reverse electrolysis process. Rather than burning the fuel, however, the fuel cell converts the fuel to electricity using a highly efficient electrochemical process. A fuel cell has few moving parts, and produces very little waste heat or gas.

A fuel cell power plant is basically made up of three subsystems or sections. In the fuel-processing section, the natural gas or other hydrocarbon fuel is converted to a hydrogen-rich fuel. This is normally accomplished through what is called a steam catalytic reforming process. The fuel is then fed to the power section, where it reacts with oxygen from the air in a large number of individual fuel cells to produce direct current (DC) electricity, and by-product heat in the form of usable steam or hot water. For a power plant, the number of fuel cells can vary from several hundred (for a 40-kW plant) to several thousand (for a multi-megawatt plant). In the final, or third stage, the DC electricity is converted in the power conditioning subsystem to electric utility-grade alternating current (AC).

In the power section of the fuel cell, which contains the electrodes and the electrolyte, two separate electrochemical reactions take place: an oxidation half-reaction occurring at the anode and a reduction half-reaction occurring at the cathode. The anode and the cathode are separated from each other by the electrolyte. In the oxidation half-reaction at the anode, gaseous hydrogen produces hydrogen ions, which travel through the ionically conducting membrane to the cathode. At the same time, electrons travel through an external circuit to the cathode. In the reduction half-reaction at the cathode, oxygen supplied from air combines with the hydrogen ions and electrons to form water and excess heat. Thus, the final products of the overall reaction are electricity, water, and excess heat.

Types of Fuel Cells

The electrolyte defines the key properties, particularly the operating temperature, of the fuel cell. Consequently, fuel cells are classified based on the types of electrolyte used as described below.

1. Polymer Electrolyte Membrane (PEM)
2. Alkaline Fuel Cell (AFC)
3. Phosphoric Acid Fuel Cell (PAFC)
4. Molten Carbonate Fuel Cell (MCFC)
5. Solid Oxide Fuel Cell (SOFC)

These fuel cells operate at different temperatures and each is best suited to particular applications. The main features of the five types of fuel cells are summarized in Table 1.3.

Fuel Cell Operation

Basic operational characteristics of the four most common types of fuel cells are discussed in the following.

Polymer Electrolyte Membrane (PEM)

The PEM cell is one in a family of fuel cells that are in various stages of development. It is being considered as an alternative power source for automotive application for electric vehicles. The electrolyte in a PEM cell is a type of polymer and is usually referred to as a membrane, hence the name. Polymer electrolyte membranes are somewhat unusual electrolytes in that, in the presence of water, which the membrane readily absorbs, the negative ions are rigidly held within their structure. Only the positive (H) ions contained within the membrane are mobile and are free to carry positive charges through the membrane in one direction only, from anode to cathode. At the same time, the organic nature of the polymer electrolyte membrane structure makes it an electron insulator, forcing it to travel through the outside circuit providing electric power to the load. Each of the two electrodes consists of porous carbon to which very small platinum (Pt) particles are bonded. The electrodes are somewhat porous so that the gases can diffuse through them to reach the catalyst. Moreover, as both platinum and carbon conduct

TABLE 1.3 Comparison of Five Fuel Cell Technologies

Type	Electrolyte	Operating Temperature (°C)	Applications	Advantages
Polymer Electrolyte Membrane (PEM)	Solid organic polymer poly-perflouro-sulfonic acid	60–100	Electric utility, transportation, portable power	Solid electrolyte reduces corrosion, low temperature, quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90–100	Military, space	Cathode reaction faster in alkaline electrolyte; therefore high performance
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175–200	Electric utility, transportation, and heat	Up to 85% efficiency in co-generation of electricity
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates soaked in a matrix	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts. Solid electrolyte advantages like PEM

electrons well, they are able to move freely through the electrodes. Chemical reactions that take place inside a PEM fuel cell are presented in the following.

Anode

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Cathode

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$\text{Net reaction: } 2H_2 + O_2 = 2H_2O$$

Hydrogen gas diffuses through the polymer electrolyte until it encounters a Pt particle in the anode. The Pt catalyzes the dissociation of the hydrogen molecule into two hydrogen atoms (H) bonded to two neighboring Pt atoms. Only then can each H atom release an electron to form a hydrogen ion (H^+) which travels to the cathode through the electrolyte. At the same time, the free electron travels from the anode to the cathode through the outer circuit. At the cathode the oxygen molecule interacts with the hydrogen ion and the electron from the outside circuit to form water. The performance of the PEM fuel cell is limited primarily by the slow rate of the oxygen reduction half-reaction at the cathode, which is 100 times slower than the hydrogen oxidation half-reaction at the anode.

Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid technology has moved from the laboratory research and development to the first stages of commercial application. Turnkey 200-kW plants are now available and have been installed at more than 70 sites in the U.S., Japan, and Europe. Operating at about 200°C, the PAFC plant also produces heat for domestic hot water and space heating, and its electrical efficiency approaches 40%. The principal obstacle against widespread commercial acceptance is cost. Capital costs of about $2500 to $4000/kW must be reduced to $1000 to $1500/kW if the technology is to be accepted in the electric power markets.

The chemical reactions occurring at two electrodes are written as follows:

At anode: $2H_2 \rightarrow 4H^+ + 4e^-$

At cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Molten Carbonate Fuel Cell (MCFC)

Molten carbonate technology is attractive because it offers several potential advantages over PAFC. Carbon monoxide, which poisons the PAFC, is indirectly used as a fuel in the MCFC. The higher operating temperature of approximately 650°C makes the MCFC a better candidate for combined cycle applications whereby the fuel cell exhaust can be used as input to the intake of a gas turbine or the boiler of a steam turbine. The total thermal efficiency can approach 85%. This technology is at the stage of prototype commercial demonstrations and is estimated to enter the commercial market by 2003 using natural gas, and by 2010 with gas made from coal. Capital costs are expected to be lower than PAFC. MCFCs are now being tested in full-scale demonstration plants. The following equations illustrate the chemical reactions that take place inside the cell.

At anode: $2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$

and $2CO + 2CO_3^{2-} \rightarrow 4CO_2 + 4e^-$

At cathode: $O_2 + 2CO_2 + 4e^- \rightarrow 2O_3^{2-}$

Solid Oxide Fuel Cell (SOFC)

A solid oxide fuel cell is currently being demonstrated at a 100-kW plant. Solid oxide technology requires very significant changes in the structure of the cell. As the name implies, the SOFC uses a solid electrolyte, a ceramic material, so the electrolyte does not need to be replenished during the operational life of the cell. This simplifies design, operation, and maintenance, as well as having the potential to reduce costs. This offers the stability and reliability of all solid-state construction and allows higher temperature operation. The ceramic make-up of the cell lends itself to cost-effective fabrication techniques. The tolerance to impure fuel streams make SOFC systems especially attractive for utilizing H_2 and CO from natural gas steam-reforming and coal gasification plants. The chemical reactions inside the cell may be written as follows:

At anode: $2H_2 + 2O^{2-} + 2H_2O + 4e^-$

and $2CO + 2O^{2-} \rightarrow 2CO_2 + 4e^-$

At cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

Summary

Fuel cells can convert a remarkably high proportion of the chemical energy in a fuel to electricity. With the efficiencies approaching 60%, even without co-generation, fuel cell power plants are nearly twice as efficient as conventional power plants. Unlike large steam plants, the efficiency is not a function of the plant size for fuel cell power plants. Small-scale fuel cell plants are just as efficient as the large ones, whether they operate at full load or not. Fuel cells contribute significantly to the cleaner environment; they produce dramtically fewer emissions, and their by-products are primarily hot water and carbon dioxide in small amounts. Because of their modular nature, fuel cells can be placed at or near load centers, resulting in savings of transmission network expansion.

1.3 Photovoltaics

Roger A. Messenger

Types of PV Cells

Silicon Cells

Silicon PV cells come in several varieties. The most common cell is the single-crystal silicon cell. Other variations include multicrystalline (polycrystalline), thin silicon (buried contact) cells, and amorphous silicon cells.

Single-Crystal Silicon Cells

While single crystal silicon cells are still the most common cells, the fabrication process of these cells is relatively energy intensive, resulting in limits to cost reduction for these cells. Since single-crystal silicon is an indirect bandgap semiconductor ($E_g = 1.1$ eV), its absorption constant is smaller than that of direct bandgap materials. This means that single-crystal silicon cells need to be thicker than other cells in order to absorb a sufficient percentage of incident radiation. This results in the need for more material and correspondingly more energy involved in cell processing, especially since the cells are still produced mostly by sawing of single-crystal silicon ingots into wafers that are about 200 μm thick. To achieve maximum fill of the module, round ingots are first sawed to achieve closer to a square cross-section prior to wafering.

After chemical etching to repair surface damage from sawing, the junction is diffused into the wafers. Improved cell efficiency can then be achieved by using a preferential etch on the cell surfaces to produce textured surfaces. The textured surfaces reflect photons back toward the junction at an angle, thus increasing the path length and increasing the probability of the photon being absorbed within a minority carrier diffusion length of the junction. Following the chemical etch, contacts, usually aluminum, are evaporated and annealed and the front surface is covered with an antireflective coating.

The cells are then assembled into modules, consisting of approximately 33 to 36 individual cells connected in series. Since the open-circuit output voltage of an individual silicon cell typically ranges from 0.5 to 0.6 V, depending upon irradiance level and cell temperature, this results in a module open-circuit voltage between 18 and 21.6 V. The cell current is directly proportional to the irradiance and the cell area. A 4-ft^2 (0.372-m^2) module (active cell area) under full sun will typically produce a maximum power close to 55 W at approximately 17 V and 3.2 A.

Multicrystalline Silicon Cells

By pouring molten silicon into a crucible and controlling the cooling rate, it is possible to grow multicrystalline silicon with a rectangular cross-section. This eliminates the "squaring-up" process and the associated loss of material. The ingot must still be sawed into wafers, but the resulting wafers completely fill the module. The remaining processing follows the steps of single-crystal silicon, and cell efficiencies in excess of 15% have been achieved for relatively large area cells. Multicrystalline material still maintains the basic properties of single-crystal silicon, including the indirect bandgap. Hence, relatively thick cells with textured surfaces have the highest conversion efficiencies. Multicrystalline silicon modules are commercially available and are recognized by their "speckled" surface appearance.

Thin Silicon (Buried Contact) Cells

The current flow direction in most PV cells is between the front surface and the back surface. In the thin silicon cell, a dielectric layer is deposited on an insulating substrate, followed by alternating layers of n-type and p-type silicon, forming multiple pn junctions. Channels are then cut with lasers and contacts are buried in the channels, so the current flow is parallel to the cell surfaces in multiple parallel conduction paths. These cells minimize resistance from junction to contact with the multiple parallel conduction paths and minimize blocking of incident radiation by the front contact. Although the material is not single crystal, grain boundaries cause minimal degradation of cell efficiency. The collection efficiency is very high, since essentially all photon-generated carriers are generated within a diffusion length of a pn junction. This technology is relatively new, but has already been licensed to a number of firms worldwide (Green and Wenham, 1994).

Amorphous Silicon Cells

Amorphous silicon has no predictable crystal structure. As a result, the uniform covalent bond structure of single-crystal silicon is replaced with a random bonding pattern with many open covalent bonds. These bonds significantly degrade the performance of amorphous silicon by reducing carrier mobilities and the corresponding diffusion lengths. However, if hydrogen is introduced into the material, its electron will pair up with the dangling bonds of the silicon, thus passivating the material. The result is a direct bandgap material with a relatively high absorption constant. A film with a thickness of a few micrometers will absorb nearly all incident photons with energies higher than the 1.75 eV bandgap energy.

Maximum collection efficiency for a-Si:H is achieved by fabricating the cell with a pin junction. Early work on the cells revealed, however, that if the intrinsic region is too thick, cell performance will degrade over time. This problem has now been overcome by the manufacture of multi-layer cells with thinner pin junctions. In fact, it is possible to further increase cell efficiency by stacking cells of a-SiC:H on top, a-Si:H in the center, and a-SiGe:H on the bottom. Each successive layer from the top has a smaller bandgap, so the high-energy photons can be captured soon after entering the material, followed by middle-energy photons and then lower energy photons.

While the theoretical maximum efficiency of a-Si:H is 27% (Zweibel, 1990), small-area lab cells have been fabricated with efficiencies of 14% and large-scale devices have efficiencies in the 10% range (Yang et al., 1997).

Amorphous silicon cells have been adapted to the building integrated PV (BIPV) market by fabricating the cells on stainless steel (Guha et al., 1997) and polymide substrates (Huang et al., 1997). The "solar shingle" is now commercially available, and amorphous silicon cells are commonly used in solar calculators and solar watches.

Gallium Arsenide Cells

Gallium arsenide (GaAs), with its 1.43 eV direct bandgap, is a nearly optimal PV cell material. The only problem is that it is very costly to fabricate cells. GaAs cells have been fabricated with conversion efficiencies above 30% and with their relative insensitivity to severe temperature cycling and radiation exposure, they are the preferred material for extraterrestrial applications, where performance and weight are the dominating factors.

Gallium and arsenic react exothermically when combined, so formation of the host material is more complicated than formation of pure, single-crystal silicon. Modern GaAs cells are generally fabricated by growth of a GaAs film on a suitable substrate, such as Ge. A typical GaAs cell has a Ge substrate with a layer of n-GaAs followed by a layer of p-GaAs and then a thin layer of p-GaAlAs between the p-GaAs and the top contacts. The p-GaAlAs has a wider bandgap (1.8 eV) than the GaAs, so the higher energy photons are not absorbed at the surface, but are transmitted through to the GaAs pn junction, where they are then absorbed.

Recent advances in III-V technology have produced tandem cells similar to the a-Si:H tandem cell. One cell consists of two tandem GaAs cells, separated by thin tunnel junctions of GaInP, followed by a third tandem GaInP cell, separated by AlInP tunnel junctions (Lammasniemi et al., 1997). The tunnel junctions mitigate voltage drop of the otherwise forward-biased pn junction that would appear between any two tandem pn junctions in opposition to the photon-induced cell voltage. Cells have also been fabricated of InP (Hoffman et al., 1997).

Copper Indium (Gallium) Diselenide Cells

Another promising thin film material is copper indium (gallium) diselenide (CIGS). While the basic copper indium diselenide cell has a bandgap of 1.0 eV, the addition of gallium increases the bandgap to closer to 1.4 eV, resulting in more efficient collection of photons near the peak of the solar spectrum. CIGS has a high absorption constant and essentially all incident photons are absorbed within a distance of 2 μm, as in a-Si:H. Indium is the most difficult component to obtain, but the quantity needed for a module is relatively minimal.

The CIGS cell is fabricated on a soda glass substrate by first applying a thin layer of molybdenum as the back contact, since the CIGS will form an ohmic contact with Mo. The next layer is p-type CIGS, followed by a layer of n-type CdS, rather than n-type CIGS, because the pn homojunction in CIGS is neither stable nor efficient. While the cells discussed thus far have required metals to obtain ohmic front contacts, it is possible to obtain an ohmic contact on CdS with a transparent conducting oxide (TCO) such as ZnO. The top surface is first passivated with a thin layer (50 nm) of intrinsic ZnO to prevent minority carrier surface recombination. Then a thicker layer (350 nm) of n^+ ZnO is added, followed by an MgF_2 antireflective coating.

Efficiencies of laboratory cells are now near 18% (Tuttle et al., 1996), with a module efficiency of 11.1% reported in 1998 (Tarrant and Gay, 1998). Although at the time of this writing, CIGS modules were not commercially available, the technology has been under field tests for nearly 10 years. It has been projected that the cells may be manufactured on a large scale for $1/W or less. At this cost level, area-related costs become significant, so that it becomes important to increase cell efficiency to maximize power output for a given cell area.

Cadmium Telluride Cells

Of the II-VI semiconductor materials, CdTe has a theoretical maximum efficiency of near 25%. The material has a favorable direct bandgap (1.44 eV) and a large absorption constant. As in the other thin film materials, a 2-μm thickness is adequate for the absorption of most of the incident photons. Small laboratory cells have been fabricated with efficiencies near 15% and module efficiencies close to 10% have been achieved (Ullal et al., 1997). Some concern has been expressed about the Cd content of the cells, particularly in the event of fire dispersing the Cd. It has been determined that anyone endangered by Cd in a fire would be far more endangered by the fire itself, due to the small quantity of Cd in the cells. Decommissioning of the module has also been analyzed and it has been concluded that the cost to recycle module components is pennies per watt (Fthenakis and Moskowitz, 1997).

The CdTe cell is fabricated on a glass superstrate covered with a thin TCO (1 μm). The next layer is n-type CdS with a thickness of approximately 100 nm, followed by a 2-μm thick CdTe layer and a back contact of an appropriate metal for ohmic contact, such as Au, Cu/Au, Ni, Ni/Al, ZnTe:Cu or (Cu, HgTe). The back contact is then covered with a layer of ethylene vinyl acetate (EVA) or other suitable encapsulant and another layer of glass. The front glass is coated with an antireflective coating.

Experimental CdTe arrays up to 25 kW have been under test for several years with no reports of degradation. It has been estimated that the cost for large-scale production can be reduced to below $1/W. Once again, as in the CIGS case, module efficiency needs to be increased to reduce the area-related costs.

Emerging Technologies

The PV field is moving so quickly that by the time information appears in print, it is generally outdated. Reliability of cells, modules, and system components continues to improve. Efficiencies of cells and modules continue to increase, and new materials and cell fabrication techniques continue to evolve.

One might think that Si cells will soon become historical artifacts. This may not be the case. Efforts are underway to produce Si cells that have good charge carrier transport properties while improving photon absorption and reducing the energy for cell production. Ceramic and graphite substrates have been used with thinner layers of Si. Processing steps have been doubled up. Metal insulator semiconductor inversion layer (MIS-IL) cells have been produced in which the diffused junction is replaced with a Schottky junction. By use of clever geometry of the back electrode to reduce the rear surface recombination velocity along with front surface passivation, an efficiency of 18.5% has been achieved for a laboratory MIS-IL cell. Research continues on ribbon growth in an effort to eliminate wafering, and combining crystalline and amorphous Si in a tandem cell to take advantage of the two different bandgaps for increasing photon collection efficiency has been investigated.

At least eight different CIS-based materials have been proposed for cells. The materials have direct bandgaps ranging from 1.05 to 2.56 eV. A number of III-V materials have also emerged that have favorable photon absorption properties. In addition, quantum well cells have been proposed that have theoretical efficiencies in excess of 40% under concentrating conditions.

The PV market seems to have taken a strong foothold, with the likelihood that annual PV module shipments will exceed 200 MW before the end of the century and continue to increase by approximately 15% annually as new markets open as cost continues to decline and reliability continues to improve.

PV Applications

PV cells were first used to power satellites. Through the middle of the 1990s the most common terrestrial PV applications were stand-alone systems located where connection to the utility grid was impractical. By the end of the 1990s, PV electrical generation was cost-competitive with the marginal cost of central station power when it replaced gas turbine peaking in areas with high afternoon irradiance levels. Encouraged by consumer approval, a number of utilities have introduced utility-interactive PV systems to supply a portion of their total customer demand. Some of these systems have been residential and commercial rooftop systems and other systems have been larger ground-mounted systems. PV systems are generally classified as utility interactive (grid connected) or stand-alone.

Orientation of the PV modules for optimal energy collection is an important design consideration, whether for a utility interactive system or for a stand-alone system. Best overall energy collection on an annual basis is generally obtained with a south-facing collector having a tilt at an angle with the horizontal approximately 90% of the latitude of the site. For optimal winter performance, a tilt of latitude +15° is best and for optimal summer performance a tilt of latitude –15° is best. In some cases, when it is desired to have the PV output track utility peaking requirements, a west-facing array may be preferred, since its maximum output will occur during summer afternoon utility peaking hours. Monthly peak sun tables for many geographical locations are available from the National Renewable Energy Laboratory (Sandia National Laboratories, 1996; Florida Solar Energy Center).

Utility-Interactive PV systems

Utility-interactive PV systems are classified by IEEE Standard 929 as small, medium, or large (ANSI/IEEE, 1999). Small systems are less than 10 kW, medium systems range from 10 to 500 kW, and large systems are larger than 500 kW. Each size range requires different consideration for the utility interconnect. In addition to being able to offset utility peak power, the distributed nature of PV systems also results in the reduction of load on transmission and distribution lines. Normally, utility-interactive systems do not incorporate any form of energy storage — they simply supply power to the grid when they are operating. In some instances, however, where grid power may not be as reliable as the user may desire, battery back-up is incorporated to ensure uninterrupted power.

Since the output of PV modules is DC, it is necessary to convert the module output to AC before connecting it to the grid. This is done with an inverter, also known as a power conditioning unit (PCU). Modern PCUs must meet the standards set by IEEE 929. If the PCU is connected on the customer side of the revenue meter, the PV system must meet the requirements of the *National Electrical Code®* (*NEC®*) (National Fire Protection Association, 1998). For a system to meet *NEC* requirements, it must consist of UL listed components. In particular, the PCU must be tested under UL 1741 (Underwriters Laboratories, 1997). But UL 1741 has been set up to test for compliance with IEEE 929, so any PCU that passes the UL 1741 test is automatically qualified under the requirements of the *NEC*.

Utility-interactive PCUs are generally pulse code modulated (PCM) units with nearly all *NEC*-required components, such as fusing of PV output circuits, DC and AC disconnects, and automatic utility disconnect in the event of loss of utility voltage. They also often contain surge protectors on input and output, ground fault protection circuitry, and maximum power tracking circuitry to ensure that the PV array is loaded at its maximum power point. The PCUs act as current sources, synchronized by the utility voltage. Since the PCUs are electronic, they can sample the line voltage at a high rate and readily shut down under conditions of utility voltage or frequency as specified by IEEE 929.

The typical small utility-interactive system of a few kilowatts consists of an array of modules selected by either a total cost criterion or, perhaps, by an available roof area criterion. The modules are connected to produce an output voltage ranging from 48 V to 300 V, depending upon the DC input requirements of the PCU. One or two PCUs are used to interface the PV output to the utility at 120 V or, perhaps, 120/240 V. The point of utility connection is typically the load side of a circuit breaker in the distribution panel of the occupancy if the PV system is connected on the customer side of the revenue meter. Connections on the utility side of the meter will normally be with double lugs on the line side of the meter. Section 690 of the *NEC* provides the connection and installation requirements for systems connected on the customer side of the revenue meter. Utility-side interconnects are regulated by the local utility.

Since the cost of PCUs is essentially proportional to their power handling capability, to date there has been no particular economy of scale for PV system size. As a result, systems are often modular. One form of modularity is the AC module. The AC module incorporates a small PCU (≈300 W) mounted on the module itself so the output of the module is 120 V AC. This simplifies the hook-up of the PV system, since *NEC* requirements for PV output circuits are avoided and only the requirements for PCU output circuits need to be met.

Medium- and large-scale utility-interactive systems differ from small-scale systems only in the possibility that the utility may require different interfacing conditions relating to power quality and/or conditions for disconnect. Since medium- and large-scale systems require more area than is typically available on the rooftop of a residential occupancy, they are more typically found either on commercial or industrial rooftops or, in the case of large systems, are typically ground-mounted. Rooftop mounts are attractive since they require no additional space other than what is already available on the rooftop. The disadvantage is when roof repair is needed, the PV system may need to be temporarily removed and then reinstalled. Canopies for parking lots present attractive possibilities for large utility-interactive PV systems.

Stand-Alone PV Systems

Stand-alone PV systems are used when it is impractical to connect to the utility grid. Common stand-alone systems include PV-powered fans, water pumping systems, portable highway signs, and power systems for remote installations, such as cabins, communications repeater stations, and marker buoys. The design criteria for stand-alone systems is generally more complex than the design criteria for utility-interactive systems, where most of the critical system components are incorporated in the PCU. The PV modules must supply all the energy required unless another form of backup power, such as a gasoline generator, is also incorporated into the system. Stand-alone systems also often incorporate battery storage to run the system under low sun or no sun conditions.

PV-Powered Fans

Perhaps the simplest of all PV systems is the connection of the output of a PV module directly to a DC fan. When the module output is adequate, the fan operates. When the sun goes down, the fan stops. Such an installation is reasonable for use in remote bathrooms or other locations where it is desirable to have air circulation while the sun is shining, but not necessarily when the sun goes down. The advantage of such a system is its simplicity. The disadvantage is that it does not run when the sun is down, and under low sun conditions, the system operates very inefficiently due to a mismatch between the fan I-V characteristic and the module I-V characteristic that results in operation far from the module maximum power point.

If the fan is to run continuously, or beyond normal sunlight hours, then battery storage will be needed. The PV array must then be sized to provide the daily ampere-hour (Ah) load of the fan, plus any system losses. A battery system must be selected to store sufficient energy to last for several days of low sun, depending upon whether the need for the fan is critical, and an electronic controller is normally provided to prevent overcharge or overdischarge of the batteries.

PV-Powered Water Pumping System

If the water reservoir is adequate to provide a supply of water at the desired rate of pumping, then a water pumping system may not require battery storage. Instead, the water pumped can be stored in a storage tank for availability during low sun times. If this is the case, then the PV array needs to be sized to meet the power requirements of the water pump plus any system losses. If the reservoir provides water at a limited rate, the pumping rate may be limited by the reservoir replenishment rate, and battery storage may be required to extend the pumping time.

While it is possible to connect the PV array output directly to the pump, it is generally better to employ the use of an electronic maximum power tracker (MPT) to better match the pump to the PV array output. The MPT is a DC–DC converter that either increases or decreases pump voltage as needed to maximize pump power. This generally results in pumping approximately 20% more water in a day. Alternatively, it allows for the use of a smaller pump with a smaller array to pump the same amount of water, since the system is being used more efficiently.

PV-Powered Highway Information Sign

The PV-powered highway information sign is now a familiar sight to most motorists. The simpler signs simply employ bidirectional arrows to direct traffic to change lanes. The more complex signs display a message. The array size for a PV-powered highway information sign is limited by how it can be mounted without becoming a target for vandalism. Generally this means the modules must be mounted on the top of the sign itself to get them sufficiently above grade level to reduce temptation. This limits the array dimensions to the width of the trailer (about 8 ft) and the length of the modules (about 4 ft). At full sun, such a 32-ft^2 array, if 15% efficient, can produce approximately 450 W. Depending on location and time of year, about 5 h of full sun is typically available on an average day. This means the production of approximately 2250 Wh of energy on the typical day. Taking into account system losses in the batteries, the control circuitry, and degraded module performance due to dirty surfaces, about 70 to 75% of this energy can be delivered to the display, or about 1600 Wh/d. Hence, the average power available to the display over a 24-h period is 67 W. While this may not seem to be very much power, it is adequate for efficient display technology to deliver a respectable message.

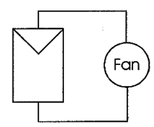
If the system is a 12 V DC system, a set of deep discharge batteries will need to have a capacity of 185 Ah for each day of battery back-up (day of autonomy). For 3 d of autonomy, a total of 555 Ah of storage will be needed, which equates to eight batteries rated at 70 Ah each.

Hybrid PV-Powered Single Family Dwelling

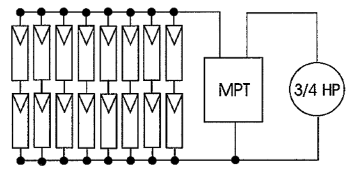
In areas where winter sunlight is significantly less than summer sunlight, and/or where winter electrical loads are higher than summer electrical loads, if sufficient PV is deployed to meet winter needs, then the system produces excess power for many months of the year. If this power is not used, then the additional capacity of the system is wasted. Thus, for such cases, it often makes sense to size the PV system to completely meet the system needs during the month(s) with the most sunlight, and then provide backup generation of another type, such as a gasoline generator, to provide the difference in energy during the remaining months.

Such a system poses an interesting challenge for the system controller. It needs to be designed to make maximum use of PV power before starting the generator. Since generators operate most efficiently at about 90% of full load, the controller must provide for battery charging by the generator at the appropriate rate to maximize generator efficiency. Typically the generator will be sized to charge the batteries from 20 to 70% charge in about 5 h. When the batteries have reached 70% charge, the generator shuts down to allow available sunlight to complete the charging cycle. If the sunlight is not available, the batteries discharge to 20% and the cycle is repeated.

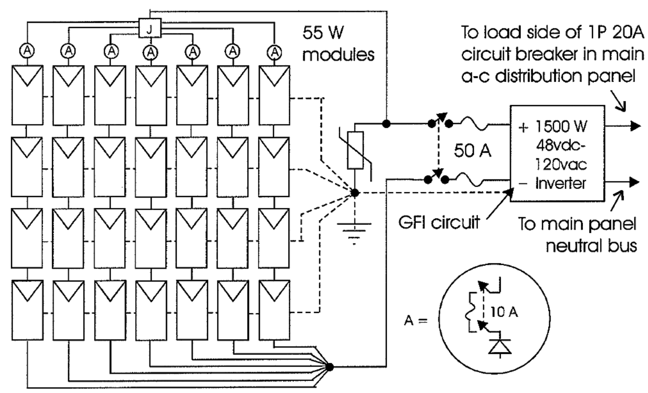
Figure 1.1 shows schematic diagrams of a few typical PV applications.



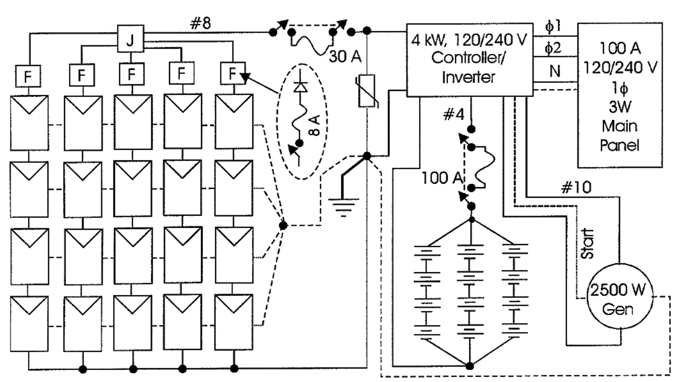
a. Simple PV-powered fan



b. Water pump with maximum power tracking.



c. A 1.5 kW residential rooftop utility interactive system connected on customer side of revenue meter.



d. A hybrid residential installation.

FIGURE 1.1 Examples of PV systems.

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