Chapter 10

Handling variable production

“Nature is an endless combination and repetition of very few laws.
She hums the old well-known air through innumerable variations.”

Ralph Waldo Emerson, author, 1803–1882.

It is important to keep in mind that the maximum capacity of solar PV or wind turbines (expressed in *kW* or *MW*) is seldom achieved. Solar PV can only produce when there is sunlight and wind towers can only deliver power when the wind is blowing. From the user’s point of view, the delivered useful energy (in *kWh* or *MWh*) is the interesting information. This is why the concept of “real” power and energy delivery is essential. Solar PV and wind energy sources have an intermittent production. Solar PV production can change in a few seconds if clouds or precipitation limit the availability of solar radiation for conversion to electric power. Wind speeds can change significantly in only minutes.

Unlike conventional power generating systems like hydropower, renewable production cannot be adjusted to demand. The power delivery from nuclear- or coal-powered thermal plants is predictable and is determined by the system operator. In contrast, renewable energy sources have a production completely independent of the demand. To

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adapt production to consumption some kind of energy storage is needed in order to compensate for short-term or long-term differences between production and consumption.

Often, however, peak production times for solar and wind energy align with peak demand periods for water pumping and treatment. If there is an excess power production the extra energy can always be put to good use, for example to store as a fresh water buffer, as discussed in 10.1. However, electric energy also must be available when the solar PV or wind cannot deliver. Then electric energy storage capacity is needed. Various storage technologies are summarised in 10.2. The most commonly used is battery storage. Some battery technologies are described in 10.3 and characterising parameters are presented in 10.4. Hydrogen storage (10.5) is another possibility with a huge potential for long-term storage. A third possibility is to use excess energy to pump water to a high elevation, like pumped storage hydroelectricity, shown in 10.6. It is always possible to use traditional diesel generators as a last resort if both solar and wind fail to satisfy the load, as shown in 10.7. The cost of energy storage is of primary importance, discussed in 10.8.

One thing should be remembered: production being variable and intermittent does not mean that it is unpredictable. Depending on the economic resources available, the production of both solar PV and wind can often be predicted quite accurately at least for the next 24 hours. Furthermore, it should be kept in mind that most electric energy generation does have some downtime.

10.1 INTERMITTENT PRODUCTION CHARACTERISTICS

There are two key parameters that can characterise variable production from renewable energy sources: capacity factor and load profile. Both have consequences for water supply operations.

10.1.1 Capacity factor

The capacity factor is a measure to quantify the total energy generated from a specific source. The variability of wind and sunshine is the reason that the wind power or solar PV cannot be used at full capacity at all times. The net capacity factor of a power plant is defined as the ratio of its actual output over a period of time to its potential output if it were possible for it to operate at maximum power output continuously. Wind capacity factors range from 20% to around 50% so the power density will be reduced accordingly. For solar PV the capacity factor depends on the latitude and weather pattern. Some typical values are 9% (UK); 13–15% (Massachusetts, US); 18% (Portugal); 19% (Arizona, US).

It ought to be mentioned that the capacity factor is also below 100% for conventional power systems. For hydroelectricity, the global average is 44% (Kumar *et al*., 2011, p. 446) and the range is 10–99% depending on design and local conditions. The averages of the continents vary from 32% (Australia, Oceania) to 54% (Latin America). In the US the downtime for coal-powered thermal plants is around 12% and for nuclear plants 10%.

Of the three approaches for reconciling electricity supply and demand, energy storage gets most of the attention and most of that interest is focused on batteries. The electric vehicle market has led to sharp gains in cost-performance of battery systems – a trend expected to continue. The use of hydrogen for energy storage is getting increasing attention, which should be of major benefit for RE systems. Batteries for energy storage are considered in 10.3–10.4 and hydrogen storage in 10.5.

There's a lot of confusion about how much storage capacity is actually needed, and what cost targets the storage must meet. Energy storage depends on the load profiles for each individual application and on consumer requirements.

10.1.2 Load profile

The most efficient way to use renewable energy, from solar or from wind, is to feed the power directly to the load. Due to the intermittent nature of the production, it does not always fit the load profile. Lighting is the best example of the mismatch between generation and load – the load is turned on when solar PV generation is not available. On the contrary, cooling is an apparent example of a load that follows the availability of the solar resource: the more sun, the hotter the weather and the higher the demand for cooling. Commercial and domestic loads usually follow quite strict timings, for example work hours and times of meal preparation.

It is obvious that some energy storage is required to compensate for the mismatch between production and consumption. To deliver the power via storage will always reduce the efficiency of the system. Naturally storage adds cost to the system as well.

Energy storage is required to compensate for the mismatch between production and consumption.

The simplest load profile is a constant load over time. However, most load profiles follow the daily living pattern. To estimate the load profile several factors ought to be considered:

- The day of the week,
- The hour of the day,
- The outside temperature,
- The season,
- The service demands.

Considering the load profile on a household or village level in a rural area in Africa or developing Asia will emphasise special needs. Figure 10.1 illustrates a typical daily load profile for households in rural areas. Similar load profiles from Zimbabwe and Uganda are published by Prinsloo *et al.* (2016, Figure 3). Note that the high load peak in the morning is just around sunrise and the evening peak is after sunset.

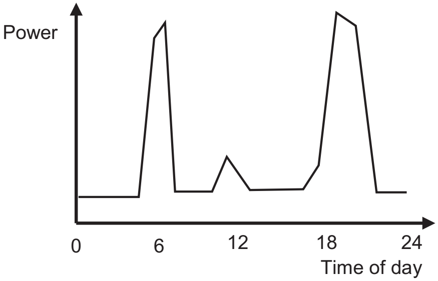

Figure 10.1 Typical household electric load profile in rural areas. Adopted from IEA (2013) and Prinsloo *et al.* (2016).

Institutions such as schools, health centres or community centres have a different load profile, since most of their activities take place during typical working hours, usually in the daytime. Since the highest power demand occurs during sunshine hours, a significant share of the PV-generated electricity can be used immediately when generated. The peak load and daily energy demand can vary significantly, depending on the specific user of the system. It may, for example, include running refrigerators for cooling medicines at a health centre or charging batteries and mobile phones for villagers at a community centre.

A number of load profiles from various customers of a mini-grid in Tanzania are presented by Hartvigson and Ahlgren (2018). The authors had first estimated load profiles based on interviews, but later measurements of the load profiles showed quite different behaviour. The lesson learnt is that simplified load profiles may lead to inappropriate sizing of the power production. Predicted and measured load profiles for a household and for three small workshops with machine operation loads during the day are presented. The authors also emphasise the need for more data on load profiles in rural areas.

Knowing the load profile is essential to find out the need for energy storage.

The renewable electric energy will not primarily be used for heating since the regions considered are relatively warm countries. However, in rural areas in Asia there is a need for heating for substantial periods of the year

The load profiles of water pumping and water cleaning can adapt to available electric power. Pumping water can be used as a balancing activity. When there is insufficient power supply pumping can be switched off and when power capacity exceeds the need pumping can be used to store energy in elevated water tanks.

Water supply treatment via desalination and disinfection can also run intermittently. This of course requires water storage capacity for untreated as well as for treated water.

10.1.3 Intermittent desalination

Intermittent use of a desalination plant to meet baseload water demand requires oversizing the plant relative to what would be needed under steady operation. Another difficulty is that the long-term reliability and the operational life of membranes are affected by intermittent operation and variable pressure (Lienhard *et al*., 2016).

Intermittent power supply for desalination causes damage to the equipment. The membranes in a reverse osmosis plant are the most sensitive parts of the system. They are designed to have a constant pressure so they will last a long time, but with variable pressure their usual operational life of eight years (with a well operated plant) may reduce to two years. Research is needed to study and further understand the phenomena taking place within RO membranes operating under variable pressure and intermittent conditions.

Another important problem observed in transient operation of desalination systems is the increased risk of membrane scaling, bio, organic and mineral fouling, collectively known as fouling. Increased fouling also necessitates greater cleaning activities and the membranes may need to be replaced earlier (Lienhard *et al*., 2016, Chapter 2).

Intermittent power supply for desalination is shortening the operating life of the equipment.

A desalination plant that requires a certain production around the clock will need power for 24 hours, but the solar PV is available for only around eight hours/day. Thus, the power of the solar PV system must be at least three times the size of a power plant that operates around the clock.

To produce a certain amount of energy, a solar PV system operating eight hours per day will require a power rating three times higher than a system operating around the clock.

10.2 STORAGE OF ENERGY

A solar PV system is limited to working only in daylight unless it is integrated with an energy storage system. A solar thermal system with a medium for thermal storage can operate through the day. Heat can be stored during the day and excess daytime heat can potentially be stored, as shown in Chapter 6.

Often solar PV and wind can complement each other to provide a more reliable power source (Weiner *et al.*, 2001). Meteorological data will decide whether the accumulated wind and solar energy production can satisfy the power demand.

> In any intermittent production the need for storage capacity must be well thought out.

The combination of solar, wind and battery storage is often too costly for poor areas that may be satisfied, at least primarily, with less ambitious energy supply.

10.2.1 Storage requirements in low-income versus high-income countries

The priorities concerning variable energy sources appear to be quite different in high-income and in low-income regions. In the former case power availability around the clock is emphasised, even if it means a higher cost for control and storage. For the user in a low-income country there is a higher acceptance that power is not available around the clock, particularly for those people who previously had no electric power.

10.2.2 Storage technologies

There is no “one-size-fits-all” solution to storage need. There are several different technologies available and the type of need as well as economy will determine the kind of technology to be used.

Different technologies are suitable depending on the timescale:

- *Timescale of minutes to less than an hour*: The purpose of the storage is to keep the power delivery from solar and wind smooth. Also, short variations in the consumption can be compensated for.

- *Diurnal variations*: The solar power has a diurnal variation, so the cycle time is one day. To fully compensate for variations in this timescale the buffer storage capacity needs to be several *kWh* per *kW* of renewable energy capacity.
- *Bridging periods of bad weather*: This is a period where the skies are overcast and there is hardly any wind. To store capacity during such a period is naturally much more challenging than with diurnal variations. To afford this storage capacity may be unrealistic in a low-income region.
- *Seasonal variations*: In a cold climate there is a large temperature difference between cold and warm seasons. Thus, the need for energy storage for the winter is high. On the other hand, the difference between the coldest and warmest month in a tropical or subtropical country is much less. Therefore, the need to store energy for the coldest month is not as great.

The most important storage technologies are listed here. They are suitable for different time and energy scales and not all of them are appropriate for a low budget.

- *Batteries*: For short variations it is common to use batteries. Car lead-acid batteries have been used for decades and are a viable alternative in low-income countries. However, the requirements for the battery for a renewable energy system are different than for a car. Battery storage is described in 10.3–10.4. The discharge time is several hours.
- *Flywheels*: The electric power can be stored in a flywheel storage. In other words, the electric energy is converted into kinetic energy, coming from a motion of a spinning mass, or a rotor. Most modern high-speed flywheel energy storage systems consist of a rotating cylinder, supported by magnetic bearings. The flywheel operates in a vacuum to reduce drag. A motor-generator unit will convert the electric energy to rotation; and to utilise the stored kinetic energy the motor-generator unit is used in the opposite direction to generate electric power. Flywheel storages are common in aerospace and telecommunications. Typical timescales for discharge are in the range of seconds to minutes.
- *Compressed air*: A compressed air system uses excess electric energy to compress ambient air and store it under pressure in a

pressure container or an underground cavern. When electricity is needed the pressurised air is heated and drives a turbine that is connected to a generator for power production. The discharge time can be several hours, but the efficiency is quite low.

- *Pumped storage*: Using excess power to store water in a tank at an elevated level. Pumped storage can be used at any scale, from household level to large-scale utility level. The discharge time is typically from several hours to a day.
- *Hydrogen*: Electric energy can be converted to hydrogen by electrolysis. The stored hydrogen can be converted back to electricity, but the overall efficiency is quite low, around 30–50%. Hydrogen storage may have an increasingly important role to play, since the energy density of hydrogen is higher than in most other storage technologies. However, hydrogen technology is probably not relevant for low-cost installations.
- *Diesel-powered generators*: To manage longer-term storage there is still a possibility in some areas of using traditional diesel-powered generators.

The storage technologies are at different development stages. Some of them are mature and proven over a long time, like pumped hydropower. Flywheels are getting more common in certain applications. Battery technology has been developed over many decades and lead-acid batteries are used everywhere. More advanced battery technology is being developed at a high rate, driven by the growth in development of electric vehicles.

For lighting and clean water operations we are considering the following alternative storage technologies:

- Batteries,
- Hydrogen,
- Pumped storage, and
- Traditional diesel generators.

10.3 BATTERY STORAGE

Globally, battery storage for large-scale as well as small-scale applications has grown rapidly over the last few years. Grid-connected stationary battery storage capacity has grown from 345 *MW* in 2010 to

620 *MW* in 2013 and 1,719 *MW* in 2016. In the year 2016 global battery capacity grew by 50% (REN21, 2017a).

This rapid battery development, together with low-cost solar PV systems, is seen by many experts as a potential disruptive technology that could dramatically change future energy markets.

The number of electric vehicles is increasing and as a result automotive companies are expanding into energy storage research and development. Tesla has released the Powerwall battery and companies like Mercedes-Benz and BMW are now marketing stand-alone batteries. This development will hopefully have a positive influence on the solar energy market.

Not all batteries are created equal, even batteries with the same chemistry. Batteries can be designed either to be high-power or high-energy and are often classified as one or other of these categories. We concentrate on three categories of batteries: lead-acid, lithium and saltwater. Lithium batteries have the longest lifetime, saltwater shorter and the lead-acid batteries the shortest lifetime.

Batteries are often evaluated according to their energy density (*kWh*/litre of battery) or total weight. This is important in transportation and in many consumer products like mobile telephones. By this measure lithium batteries have so far been the most successful. However, their cost is relatively high. A stationary battery can be assessed in a different way: even if its energy density is less the battery may still be successful; the total weight is not critical, so other properties can be considered. Consequently, a lot of attention is directed towards flow batteries and saltwater batteries.

Stationary batteries should be evaluated differently from batteries for transportation.

10.3.1 Lead-acid batteries

The cheapest and most common battery is a standard car battery of the lead-acid type. These batteries are a proven technology that has been used in off-grid energy systems for decades. This is probably the least expensive alternative available for households. A drawback of deep-cycle lead-acid batteries is their expected short lifetime. Even if they are carefully managed their lifetime may be only three years, which is much shorter than other components in the energy system. If the capacity of discharge is limited to 20% then the batteries may last five years.

There are three main types of lead-acid batteries: flooded, AGM (absorbent glass mat) and gel. In a flooded battery the electrolyte is in liquid form (sulphuric acid diluted in water) while in the AGM and gel the electrolyte cannot flow. The liquid in the flooded battery must be maintained, while the latter two do not need maintenance. They can also be used in any orientation.

Traditional car lead-acid batteries are usually not the best option for solar energy storage. Unfortunately, they are the type of batteries most commonly used in the developing world as they are cheap and easily available. A car battery is designed to produce a high current over a short time in order to provide power to start an engine. Typical loads powered by solar energy, on the contrary, usually require low currents over an extended period. The problem is not the battery chemistry; it is the design of the batteries. A traditional car battery will not survive for long if it is discharged more than 50%. Deep-cycle batteries are better for solar energy uses as they have larger electrodes than car batteries.

Traditional car lead-acid batteries are usually not the best option for solar energy storage.

All three lead-acid battery types are available for deep cycle. A flooded battery has a price of around 70–80 USD/*kWh* while AGM and gel batteries are more expensive, around 260–330 USD/*kWh*.

At first glance the use of a car battery for the storage of solar-generated power may look more attractive than other options. However, in the long run this choice will almost certainly turn out to be wrong.

10.3.2 Lithium batteries

We use lithium batteries in our mobile telephones. Such batteries use some form of lithium chemical composition. They are lighter and more compact than lead-acid batteries. They can be discharged more, are robust and have a longer lifespan. They are more expensive; but the price of lithium batteries has dropped by nearly 20% per year since 2010. Lithium represents the key limiting resource for most batteries. The largest reserves of lithium by far are found in Chile, ahead of China, Argentina and Australia.

> Lithium batteries are lighter, more robust and more compact compared to lead-acid batteries. They can be discharged more and have a longer lifespan, but are more expensive.

The two main types of lithium batteries used in solar applications are lithium cobalt oxide and lithium iron phosphate. Today the cheapest lithium battery is the Tesla Powerwall, with a cost of around 500 USD/kWh. Kittner *et al.* (2017) explain that R&D investments in energy storage projects have been remarkably effective in bringing the cost per kWh of a lithium- battery down from 10,000 USD/kWh in the early 1990s to a trajectory that could reach 100 USD/kWh in 2019. This means that storage prices are falling faster than solar PV or wind technologies.

10.3.3 Saltwater batteries

There are interesting new types of batteries still in a development phase. Saltwater or sodium-ion batteries have attractive properties. They do not contain heavy metals but instead use saltwater electrolytes, consisting of sodium sulphate in an aqueous solution. This means that a saltwater battery can be easily recycled, in contrast to a lead-acid or a lithium battery. Today there are battery stacks available for 48 V or 24 V with a current rating of 82 Ah (see below) and above 2 kWh energy capacity. An interesting feature is that these battery stacks can be connected in parallel even if the discharges and voltages of the individual battery stacks are not the same. This cannot be done with lead-acid batteries.

Saltwater batteries are interesting not only from a performance point of view but also due to their price. This kind of battery is maintenance-free; even discharging deeply does not have a large impact on its performance. The price is of the order 400–500 USD/kWh. A saltwater battery can have up to 3,500 cycles with a 90% discharge. This corresponds to an operational life of almost ten years.

One drawback of the saltwater battery is that it is slightly heavier than a lead-acid battery. The other disadvantage is that it has to be charged and discharged at lower rates than the other battery types. A typical charge time is ten hours and discharge time 20 hours, because the current should not exceed around 14 *A*. The saltwater battery temperature should not exceed 40°C, which can be a problem in tropical regions. There are still very few manufacturers of saltwater batteries, so as competition increases and with economy of scale these batteries may become much more economically attractive.

10.3.4 Flow batteries

A flow battery, also called a redox flow battery is an electrochemical cell. Two chemical components dissolved in liquids are contained in the system and separated by a membrane, Figure 10.2. The chemicals provide chemical energy that is converted to electrical energy via the membrane. There is ion exchange through the membrane, while both liquids circulate in their own respective volumes. The ion exchange is followed by an electric current. The cell voltage typically reaches 1–2.2 *V*.

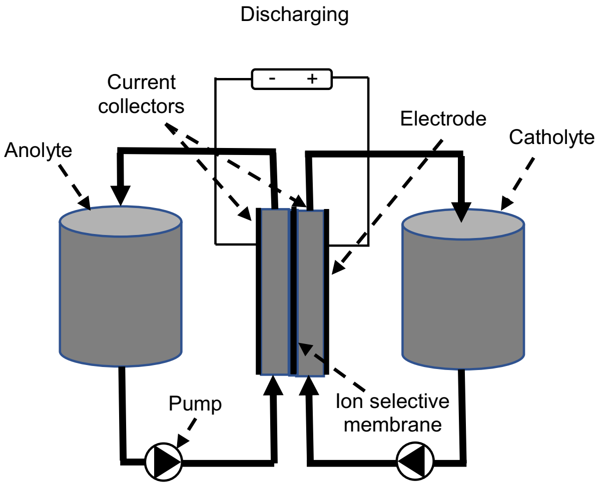

Figure 10.2 Principle of a redox flow battery. Modified from Akhil *et al.* (2013).

The battery can serve as a rechargeable battery, where an electric power source drives regeneration of the fuel. One of the biggest advantages of flow batteries is that they can be almost instantly recharged by replacing the electrolyte liquid. The energy capacity is a function of the amount of liquid electrolyte and the power a function of the surface area of the electrodes.

The fundamental difference between conventional batteries and flow batteries is that energy is stored as the electrode material in conventional batteries but as the electrolyte in flow batteries. A wide range of chemistries and electrolytes have been tried for flow batteries. Vanadium is increasingly being embraced by battery manufacturers as a core material in the production of batteries to be used in both small-scale and large-scale applications. The electrolyte is composed of vanadium salts in sulphuric acid. Vanadium redox-flow batteries (VFBs) have started to grow in influence as energy companies look to improve energy storage.

During a VFB battery charge, V^{3+} ions are converted to V^{2+} ions at the negative electrode through the acceptance of electrons. Meanwhile, at the positive electrode, V^{4+} ions are converted to V^{5+} ions through the release of electrons. Both of these reactions absorb the electrical energy put into the system and store it chemically. During discharge, the reactions run in the opposite direction, resulting in the release of the chemical energy as electrical energy.

Due to their superior performance and gradual price reduction lithium batteries have until now been the preferred technology. However, the demand for flow batteries has increased rapidly over the last couple of years. The flow batteries have low variable costs (USD/*kWh*) and use a wide state of charge (SoC) range. On the other hand, efficiency is lower than for the lithium batteries and fixed costs (USD/*kW*) are higher.

Activities in flow batteries in China illustrates the growing interest in using flow batteries for energy storage. Two recently announced projects in Hubei and Dalian are sized at 100 *MW*/500 *MWh* and 200 *MW*/800 *MWh* respectively. The Chinese government is aiming for a long-term strategy to push energy storage to integrate renewable energy.

10.4 BATTERY PARAMETERS

A battery can be characterised not only by its energy capacity but also by its discharge rate. Both these parameters are crucial for a storage battery used in renewable energy systems.

10.4.1 Battery capacity

A battery's capacity is the total amount of energy (*kWh*) that it can store. Capacity is often expressed in ampere-hours (*Ah*). The voltage is assumed to be given, so the capacity in *kWh* can be calculated. This is the discharge current a battery can deliver over time. By stacking several batteries, the total capacity can be increased. It should be noted that capacity does not indicate how much power a battery can deliver at a given moment; therefore, its power rating (measured in *kW*) should be declared. Consequently, a battery with a high capacity and a low power rating would deliver a low amount of electricity for a long time. A battery with a low capacity and a high power rating could run a high load but only for a relatively short time.

The electrochemical battery has the advantage over other energy storage devices in that the delivered power stays high during most of the discharge and then drops rapidly as the charge depletes.

Usually it is not possible (or advisable) to use all the capacity of a battery. Most batteries need to retain some charge at all times due to their chemical composition. The depth of discharge (DoD) of a battery refers to the amount of a battery's capacity that has been used. Most batteries have a recommended maximum DoD for best performance. For example, if a 10-*kWh* battery has a DoD of 90% then only 9 *kWh* can be used before recharging it.

The rating of a battery is usually expressed in amp-hours (*Ah*). The standard rating is a discharge current taken for 20 hours. Thus, a 100 *Ah* battery can discharge 5 *A* for 20 hours, from 100% state-of-charge to the cut-off voltage. It is important to know that this is not a linear relationship. If instead the discharge current is 100 *A* then the discharge time is less than one hour.

Battery capacity can also be expressed in terms of "energy capacity". This is the total energy (in *kWh* or *Wh*), expressed as the discharge power times the discharge time. The time is defined as the time for 100% state-of-charge to the cut-off voltage, which is the voltage that generally defines the "empty" state of the battery. Like capacity, energy decreases with increasing discharge current.

Temperature will significantly influence the battery. Since a lead-acid battery is an electrochemical device, an increasing temperature will accelerate the chemical activity while a colder temperature will slow it down. For a lead-acid battery an increasing temperature has several consequences:

- Increases performance,
- Increases internal losses,
- Decreases cell voltage for a given charge current,
- Shortens the battery life,
- Increases maintenance requirement.

10.4.2 Battery sizing

Assume that the power requirement is 300 *W* for 16 hours. This corresponds to an energy requirement of 4,800 *Wh* or 4.8 *kWh*. Assuming a battery with 12 *V*, this means that the required rating of *Ah* is 4,800/12 = 400 *Ah*. However, the battery's losses should be taken into consideration. Assuming 15% losses (85% battery efficiency), this means that 400 *Ah* will be divided by 0.85 to find the necessary rating. Then the battery cannot be discharged 100%. Assuming an allowable discharge of 60% means that the capacity will be further divided by 0.6 to obtain the required capacity. The final battery rating then has to be 400/(0.85 · 0.6) = 784 *Ah* or around 800 *Ah*. Typical rating of a lead-acid battery is of the order 100–600 *Ah*.

In summary, the required battery rating is calculated as

$$\text{Battery rating } (Ah) = \frac{\text{Total battery energy capacity } (Wh)}{\text{Battery efficiency} \cdot \text{Depth of discharge} \cdot \text{Battery voltage } (V)}$$

10.4.3 Battery classification

Batteries are classified in C- or E-rates, which is a way of showing the discharge current. It its normalised against battery capacity. A C-rate is a measure of the rate at which a battery is discharged compared to its maximum capacity. The rate 1C means that the discharge current will discharge the battery in one hour. For a battery with a capacity of 100 *Ah* it means that the discharge current will be 100 *A*. A C/2 rate would be 50 *A*. Applying a smaller charge/discharge rate will prolong the life of a chemical battery, so a discharge rate of for instance <0.1C is quite favourable for the battery's life. Similarly, using a battery discharge rate >1C is called a “high current” use. Usually a manufacturer specifies the maximum rating.

An E-rate defines the discharge power, so a 1E rate is the discharge power to discharge the whole battery in one hour.

Generally, the useful lifespan of a battery is 5–15 years, which is much shorter than the typical guarantee time of 25 years for solar cells. However, there is a lot of effort currently being devoted to battery development. Two particular demands are causing this: the rapid expansion of renewable energy and the increasing interest in electric vehicles.

10.4.4 Battery charge controller

A solar charge controller must match the voltage of the solar PV array and the batteries. It is usually defined by the current (ampere) and voltage (V) capacities. The charge controller need to have sufficient capacity to handle the current from the PV array. A standard practice is to design the solar PV charge controller 30% larger than the short circuit current (I_{SC}) of the PV array (see Chapter 8.2).

The charging voltage must be higher than the battery voltage for current to flow into the battery. There are two basic ways to charge a lead-acid battery:

- *A constant voltage* is applied across the battery terminals. As the voltage of the battery increases the charging current tapers off. This method requires only simple equipment, but is usually not recommended.
- *Constant current charge*: an adjustable voltage source maintains a constant current flow into the battery. This requires a more sophisticated charge controller but is the more commonly recommended technique.

10.5 HYDROGEN ENERGY STORAGE

Hydrogen as an energy storage system is receiving increasing attention and some systems are already in use. The systems are probably still too expensive for low-income countries but there is a huge research effort into hydrogen energy storage technology, so it should be mentioned here as a realistic possibility for energy storage in renewable energy systems.

To use hydrogen for energy storage is not new. Dr Allan Hoffman has been one of the key scientists working in Washington DC to influence the development of renewable energy and the awareness of the water-energy nexus. In 1995 he served as Associate Deputy Assistant Secretary and then Acting Deputy Assistant Secretary for DOE's (Department of Energy) Office of Utility Technologies (OUT) in the Bill Clinton administration. This Office had responsibility for developing the full range of renewable electric technologies as well as hydrogen and energy storage technologies. In 1995 he wrote an OUT report: "I also believe that over this time period, hydrogen will emerge as an important energy carrier to complement electricity, given its ability to be used in all end use sectors and its benign environmental characteristics."

The main attraction of hydrogen is that excess energy can be stored for a long time, not only from day to night, but also between seasons. For example, at northern latitudes excess renewable energy can be produced during the summer. Battery power cannot supply energy for any longer than a few days. If the excess energy is stored as hydrogen, it can be reused as electricity during the cold winter. Prototype systems using this facility are already in use. Hydrogen is one of the most promising ways of dealing with longer-term energy storage.

The main attraction of hydrogen is that excess energy can be stored for a long time and then reused as electricity.

Simply explained, excess electricity is used to electrolyse water into hydrogen and oxygen. The hydrogen is stored and later used in fuel cells that generate electricity.

10.5.1 Electrolysis of water

In electrolysis, water is split into hydrogen and oxygen using electricity. Using excess electric power from solar PV or wind does not create any greenhouse gas to produce the hydrogen. At the same time the cost for extra energy is practically zero. The electrolysis takes place in a device called an electrolyser. There are a lot of different configurations, but the principle and the key reactions are shown in Figure 10.3. Different electrolysers function in slightly different ways, mainly due to the different type of electrolyte material involved.

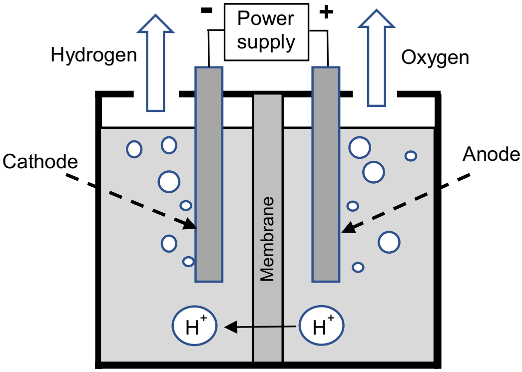

Figure 10.3 Principal electrolysis of water. Modified from Larminie and Dicks (2003).

When an electric current is passing through the water, electrons from the electric current cause an oxidation-reduction reaction. The electrons flow through an external circuit and the hydrogen ions selectively move across the membrane to the cathode. At one electrode, the cathode, electrons pass into the solution and cause a reduction. At the other electrode, the anode, electrons leave the solution completing the circuit, and cause an oxidation.

To carry out electrolysis the solution must conduct electric current. Pure water is a very poor conductor, so an electrolyte is added to enhance the water's conductivity. In most places, however, there are enough minerals in the water that the ionic strength or conductivity of the water is great enough for electrolysis. One problem with adding electrolytes is that they can electrolyse more easily than water.

At the cathode (the negative electrode), water dissociates into H^+ ions and OH^- ions. The H^+ ions are attracted to the cathode and are converted (reduced) to a hydrogen atom:

$$H^+ + e^- \rightarrow H$$

This is a highly unstable configuration, and therefore immediately reacts with another hydrogen atom to produce H_2, molecular hydrogen gas.

At the other electrode (the anode), oxidation occurs. The OH^- ions are attracted to the positive electrode, where they are oxidised to form oxygen gas (O_2) and hydrogen ions (H^+). The anode reaction is

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

Combining the cathode and anode reactions, we get the overall reaction:

$$2H_2O \rightarrow 2H_2\text{ (gas)} + O_2\text{ (gas)}$$

Producing hydrogen from solar PV is probably the cheapest method available today. However, it must be recognised that electrolysis, plus the associated equipment to compress and store hydrogen, is capital-intensive. The cost of equipment will probably come down, but the cost is currently still an obstacle.

Hydrogen does not need to be stored as a gas in pressure tanks. A new technology makes it possible to store the hydrogen in liquid form, a technology called Liquid Organic Hydrogen Carrier (LOHC). The technology is based on two separate processes: the loading (hydrogenation) and the unloading (dehydrogenation) of a liquid energy carrier. This liquid is composed of an organic molecule having similar physico-chemical properties to diesel. The LOHC-module consists of a hydration and dehydration unit and two tanks. One of the tanks contains the LOHC liquid carrier in its initial state. The hydration unit inserts hydrogen into the fluid in a chemical reaction. The loaded LOHC is then stored inside the second tank. Hydrogen can be discharged from the dehydration unit by an endothermic reaction (a chemical reaction that absorbs energy from its surroundings). The fluid returns to the initial tank.

A big advantage of hydrogen being chemically bonded to the liquid carrier is that it can be stored under ambient conditions (normal pressure and temperature) without suffering any self-discharge or the loss of hydrogen. One litre of the energy carrier can store an equivalent of 2 *kWh* thermal energy or, after reconversion, 1 *kWh* electrical energy.

10.5.2 Fuel cells

Hydrogen that is stored will sooner or later be converted to electricity. This is done in a fuel cell, a device that converts the chemical energy from a fuel into electricity. Here the fuel is hydrogen that will react with oxygen or another oxidising agent. In a battery the chemical energy comes from chemicals present in the battery. In a fuel cell there must be a continuous supply of fuel (hydrogen) and oxygen (usually from the air) to sustain the chemical reaction. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. They are not new inventions; the first was invented in 1838.

All fuel cells contain an anode, a cathode and an electrolyte: see Figure 10.4. There are many types, classified by the type of electrolyte and different start-up times.

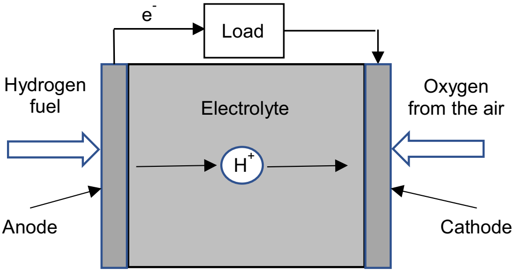

Figure 10.4 Electrode reactions and electric circuit flow for an electrolyte fuel cell. Note that the negative electrons move from anode to cathode, while the "conventional current" flows from cathode to anode. Modified from Larminie and Dicks (2003).

At the anode a catalyst breaks down the fuel (hydrogen gas) into electrons and ions. The catalyst speeds the reactions at the electrodes. The anode catalyst often consists of fine platinum powder:

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

The hydrogen ions travel through the electrolyte from the anode to the cathode. The electrons from the anode are led to the cathode via an external electrical circuit, thus producing a DC current. Oxygen from the air enters the cell at the cathode.

At the cathode another catalyst (often nickel) causes hydrogen ions, electrons and oxygen to react:

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

where the water is considered to be a by-product. In other words, the summary reaction is very simple:

$$2H_2 + O_2 \rightarrow 2H_2O$$

A single cell will typically produce quite small voltages: 0.6–0.7 V. Therefore, several cells must be connected in series to create a sufficient voltage to meet the requirement for the specific load. If cells are connected in parallel a higher current can be supplied. Connection of cells is called a fuel cell stack.

The fuel cell will also produce water and heat as well as small amounts of emission, for example nitrogen dioxide (NO_2). The energy efficiency is not high; between 40% and 60%. This means that storage of energy as hydrogen causes significant energy losses, even though in many cases the waste heat can be utilised.

It should be emphasised that fuel cells have no moving parts. This makes them reliable sources of electrical energy.

10.6 PUMPED AND CLEANED WATER AS STORAGE

Storing energy as water in elevated places has been known about and practised for centuries. In hydropower water can be stored in reservoirs as potential energy that can be converted to electricity.

In many places pumped water storage is used to make use of excess energy. Then the potential energy of the water can be used to generate electricity when needed. This principle can also be used in stand-alone systems at the household level. Excess energy from solar PV or wind can be used to pump water to an elevated storage. Then the water can be used in two ways:

- If the elevation is sufficiently high, then the water may drive a turbine and generator to generate electricity;
- Otherwise the water can be used directly either for drinking (if the quality is adequate) or for irrigation, using only gravity.

The stored water can also be led into a desalination unit to be upgraded. Excess electric energy can also be used for pumping, desalination and disinfection.

10.7 DIESEL GENERATORS AS BACKUP

In many cases an existing diesel generator will be replaced by renewable energy. The old generator can be used as a backup for the intermittent generation, even if this will cost fuel and add to the carbon footprint. However, the advantage of using this backup is that even long-term lack of power can be rectified.

10.8 COST OF ENERGY STORAGE

To compare various technologies of energy storage, the concept of levelised cost of storage (LCOS) has been defined. This is usually expressed as a cost of energy storage capacity per *kWh*. Thus, the LCOS expresses the average cost over the life of the storage, including both capital and operational costs.

The huge solar PV and wind energy cost reduction has been achieved through an increasing mass production of PV panels and wind turbines. A similar revolution is apparently coming to energy storage. Worldwide there are massive investments in battery facilities. Energy storage cost has decreased from more than 500 USD/*kWh* in 2013 to around 200 USD/*kWh* in 2017 (Lazard, 2016). According to Boston Consulting Group (www.bcg.com) the cost is expected to drop below 100 USD/*kWh* in the next five to ten years.

10.9 FURTHER READING

There is a huge ongoing effort to develop batteries with larger capacity, smaller size and lower prices. To get acquainted with current storage research we refer to the Joint Center for Energy Storage Research (JCESR) in Argonne, supported by the US Department of Energy, and their webpage http://www.jcesr.org.

Sandia Laboratories has issued a handbook on electricity storage with a lot of technical information (Akhil *et al.*, 2013). IEC has published a white paper on electric storage systems (IEC, 2011); a major contribution comes from the Fraunhofer Institut für Solare Energiesysteme.

Delucchi and Jacobson (2011) discuss methods of addressing the variability of wind, water and solar energy to ensure that power supply reliably matches demand.

A comparison between lithium-based and flow batteries is presented by Uhrig *et al.* (2016).

Fundamental principles of fuel cells are explained in detail in Larminie and Dicks (2003). A very personal account of the development of renewable energy in the US is told by Hoffman (2016). He also regularly writes on energy issues on his blog (Lapsed Physicist, 2018).

For the reader particularly interested in renewable energy the book Jones (2017) is a deep well of information. The book concentrates on renewable power production and its integration into grids. Challenges related to variable production and energy storage as well as island power systems are analysed.

There is a lot of practical information on YouTube concerning battery choice, design, charging and discharging. Look for "solar batteries".