Chapter 2
Faraday's Miracle

In this chapter we discuss how electricity generators work. Michael Faraday was the father of electricity generation. Almost 200 years ago, he discovered electromagnetic induction. Induction is the principle behind our modern electricity generators and transformers that are the backbone of our electricity networks. We will discuss, in simple terms, how generators work. We then discuss the different types of engines that can drive generators and the different energy sources used by the different engines. Finally, we compare these different engine types and introduce the term "capacity factor" which is critical to understanding the difference between the engines.

2.1 Faraday's Contribution

Faraday was born to a relatively poor family in London in 1791. He was a largely self-educated chemist and physicist who loved experimenting. His breakthrough experiment involved wrapping two coils of long insulated wire around an iron ring, and discovering that when he passed an electric current through one coil, another current was 'induced' in the other coil. Hence the term 'induction'. This experiment demonstrated the principle of electromagnetic induction and actually produced the first transformer.

He then took the idea further and discovered that a current could also be induced in the coil if it was moved over a stationary magnet. Faraday built the first electric dynamo by rotating a coil of insulated wire in a strong stationary magnetic field, thus converting rotating mechanical energy into electrical energy. This dynamo was the ancestor of modern power generators. We, and the Power Makers, owe Faraday a deep debt of gratitude.

M. Nicholson, *The Power Makers' Challenge*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-2813-7_2,

2.2 Generators Explained

As Faraday discovered, when a coil of insulated copper wire is rotated between two stationary magnets an electric current is induced in the coil. Many of us might have had (or still have) a dynamo on our bicycle wheel that operates the lights. This is how those small dynamos work.

A generator at a power station uses the same principle but generally uses an electromagnet to produce the magnetic field rather than a traditional fixed magnet. An electromagnet is just a magnet produced using electricity in a coil. The rotating part of a generator is called the 'rotor' and the stationary part is called the 'stator'. The electromagnet can be in the stator or the rotor. For a more technical description of how a synchronous generator works see Appendix B.1.

The electric current produced by power generators is normally an alternating current (AC), which means the current constantly changes direction, usually 100 or 120 times a second (50 or 60 cycles per second) depending on the country we live in. This is the form of electricity we receive from the power outlets in our homes and workplaces. The big advantage of AC is that the voltage can be readily changed using a transformer.

2.3 What Drives the Generator?

The generator shaft needs to be rotated by an engine of some kind. Commonly used engines are steam turbines, gas turbines (like jet engines on planes), internal combustion engines (like we use in our cars and trucks), wind turbines or water turbines. These engines convert energy from a fuel into rotary motion and the generator converts that rotary motion into electrical energy.

Most of the world's electricity is generated using steam turbines as the engine—see Fig. 2.1. Steam turbines need a lot of high pressure steam. The high pressure steam can be produced in a steam generator using some kind of heat source to heat the water to a very high temperature and pressure. Steam turbines take several hours to start-up from cold so they cannot be started quickly if needed.

A gas turbine works in a similar way to a steam turbine except it uses pressurised gas to spin the turbine blades rather than high pressure steam. A jet aircraft engine is a form of gas turbine. Most gas turbines produce their own pressurised gas by burning a fuel like propane, natural gas (NG) or jet fuel. The heat that comes from burning the fuel expands air and the high-speed of this hot air spins the turbine. Gas turbines can be started from cold in 10–20 min. Sometimes steam turbines are used in combination with gas turbines by using the waste heat from the gas turbine to generate steam for the steam turbine. These are called 'combined cycle gas turbines' or CCGT for short.

Water turbines used in hydroelectric dams have rotating blades like steam turbines but use fast running water to push the blades round. The blades in a water turbine look quite different to the blades in a steam turbine as water is much denser

Fig. 2.1 750 MW generator with 2 steam turbines. From Campbell G (1993)

than steam and moves much more slowly, but the principle is the same. Like gas turbines, water turbines can be started in a few minutes.

Wind turbines are rotated by the wind. These turbines look nothing like steam, gas, or water turbines. As the wind moves relatively slowly, wind turbines need huge blades—see the photograph Fig. C.1 in Appendix C. Wind turbines work intermittently depending on when the wind is blowing.

The engine we are all most familiar with is the internal combustion petrol or diesel engine we use in our cars and trucks. The same engines can be used to drive a generator. A portable petrol generator is made up of a small petrol engine attached to a generator that can produce mains electricity. Some grid electricity is also produced using large diesel engines driving generators.

Whatever the engine that drives the generators, be it steam, gas, water, wind or diesel the structure of the generator is very similar in all cases. What can be different is the speed of rotation and type of generator used depending on the engine used. See Appendix B.1 and Appendix C.5 for more detailed discussion on generator types.

2.4 What Powers the Engines?

All engines need a primary energy source. These energy sources are even more diverse than engine types. Steam generators can use coal, gas, oil, geothermal heat, sunlight or nuclear reactors to heat the water and produce steam. Some steam turbines use geothermal steam direct from the ground.

Gas turbines can use natural gas or man-made gas such as synthesis gas (syngas) made from coal, oil or biomass. They can also use gas from gas-cooled nuclear reactors (see Appendix G.5).

Other engine types tend to be designed to work with a particular primary energy source. Water turbines use water but it could be freshwater from a dam or a running river or seawater from a tidal flow. Wind turbines rely on wind. Petrol and diesel engines, with their own particular fuels, are also used for driving smaller generators that can be started and stopped quickly.

2.5 Power Generator Types

Power generator types are typically identified by their primary energy source. We talk about 'coal power', meaning power from a steam turbine powered by burning coal. 'Hydropower' is power from a water turbine driven by moving water. 'Wind power' is power from a wind turbine driven by moving air or wind. 'Solar (thermal) power' uses heat from the sun to produce the steam that drives a steam turbine.

The one exception is 'nuclear power' which is power from a turbine driven by heat generated by a fission reaction in a nuclear reactor. The primary energy source is actually uranium or thorium but perhaps this is splitting hairs. We will tend to use the term 'fission' for nuclear in this book.

We also talk about power 'stations'. A power station is a factory devoted to making electricity. It might contain several generators but generally they all use the same primary energy source. So a coal power station might contain two or three coal powered generators. Coal power stations are often located close to coal mines to minimise coal transport costs as coal is a bulky, solid fuel and coal power stations use a lot of coal.

There is another type of electricity generator that does not use electromagnetic induction. This is the solar photovoltaic (PV) cell. PV cells use semiconductor[1] material (typically silicon) to convert solar radiation directly into electricity. Solar PV cells are used in solar panels that we might put on our roof to generate electricity from the sun. We will discuss solar PV in more detail in Part II—Renewable Energy.

2.6 Comparing Generators

All power generators produce exactly the same commodity—electricity. An electron from a wind turbine/generator is identical to an electron from a coal plant. We do not get 'green' electrons from wind and 'black' electrons from coal—they all just move indistinguishably in the same conductor.

What we can compare is how reliably each produce energy and how much electrical energy they each produce over an extended period, say 12 months.

As we learnt in Chap. 1, a megawatt (MW) is a measure of how much instantaneous power a generator can produce. This is important but it does not tell us how

[1] A semiconductor has an electrical conductivity between a conductor and an insulator.

Table 2.1 Capacity factors for electricity generators

Energy source	Capacity factor range (%)	Average annual energy output per rated MW (GWh)
Coal and Gas	80–90	7.4
Nuclear	80–90	7.4
Biomass	50–90	6.1
Geothermal	40–95	5.9
Hydropower	25–75	4.4
Solar thermal	25–50	3.3
Wave	25–45	3.1
Wind	20–40	2.6
Tidal	20–35	2.4
Solar PV	10–25	1.5

much electrical energy we will get. That is determined by the length of time we can get power out of the generator over a given period. We might be able to get power out of a coal power station for 80% of the year because for 20% of the time it is either under maintenance or not required. On average, we will probably only get 30% of the power out of a wind farm because the wind does not always blow and the wind speed varies. This brings us to the term ‘capacity factor’. This might seem a bit technical for some but it is a critical concept when it comes to comparing the effectiveness of various energy sources.

2.7 Capacity Factor

Capacity factor (or ‘load factor’ as it is sometimes called) for a generator is usually defined as the ratio of the actual energy output from the generator over a year to the theoretical maximum output it would produce if it operated non-stop at its full capacity for the whole year. So, in the example above the coal power station would be said to have a capacity factor of 80% and the wind farm would have a capacity factor of 30%. This means that we get 80% of the theoretical maximum energy from the coal plant but only 30% of the theoretical maximum from the wind farm (if the wind blew continuously).

Table 2.1 shows typical capacity factors for various electricity generators. The third column shows the average yearly energy produced in gigawatt-hours (GWh) per MW of generator capacity.[2] It is very clear from the table that a

[2] To calculate the electrical energy Power Makers can get from 1 MW of generator power in a full year we multiply the number of MW by the number of hours in a year. There are $24 \times 365 = 8{,}760$ h in a year so at 100% capacity factor we would get 8,760 MWh of electricity from each MW of generator power. At 80% capacity factor every MW of coal power would produce $8{,}760 \times 0.8 = 7{,}008$ MWh of electricity in the year but every MW of wind power would only produce $8{,}760 \times 0.3 = 2{,}628$ MWh. Each MW of wind power is only worth 37.5% of a MW of coal power.

500 MW solar PV farm is very different to a 500 MW coal plant. The coal plant would produce five times as much electricity as the solar PV farm so when we compare generator plants it is important that we look at electrical energy generated (GWh) not power (MW) installed.

We will discuss renewable energy sources in much greater detail in Part II and explain why their capacity factors are often much lower than for coal, gas and nuclear (fission) energy sources.

Springer

http://www.springer.com/978-1-4471-2812-0

The Power Makers' Challenge
And the Need for Fission Energy
Nicholson, M.
2012, XXIV, 200 p., Hardcover
ISBN: 978-1-4471-2812-0