4

HARNESSING ENERGY FLOWS: TECHNOLOGIES FOR RENEWABLE POWER PRODUCTION

Ola Carlson
Linus Hammar
Zack Norwood
Emil Nyholm
Department of Energy and Environment, Chalmers University of Technology*

* Division of Energy Technology (Z. Norwood, E. Nyholm), Division of Electrical Power Engineering (O. Carlson), Division of Environmental Systems Analysis (L. Hammar)
Chapter reviewers: Björn Sandén, Environmental Systems Analysis, Fredrik Hedenus, Physical Resource Theory, Energy and Environment, Chalmers

Systems Perspectives on Renewable Power 2014, ISBN 978-91-980974-0-5

INTRODUCTION

In this chapter, the technologies for renewable power production of today and in the near future will be described and explained. Renewable power production is electric power production without using a fuel that will end some day in the future. In this chapter, as in this book, power production based on renewable fuels (biomass) is excluded[1].

Some of the technologies such as wind or solar has reached industry mass production in recent years, hydro power has been in operation more than 100 years and others like wave or ocean current power have still some development to do before robust power production units are available.

SOLAR POWER

Solar energy is harnessed today by two main types of technology. Thermal-electric systems, often called concentrating solar power (CSP), collect the light from the sun and convert that thermal energy to electricity through a heat engine, whereas

---

[1] For more details on this topic, see *Systems Perspectives on Biorefineries*. (2014) 3rd edition. Chalmers Univeristy of Technology, Göteborg, Sweden.

photovoltaic (PV) systems convert the photons from sunlight directly into electricity in a semiconductor device. Although the photovoltaic process is more direct, the overall efficiency (percent of sunlight incident that is converted to electricity) of commercial solar thermal-electric and photovoltaic systems fall in similar ranges (10-30%), with the high end of this range reached for both high concentration PV systems and some CSP systems.

All solar power technologies use electromagnetic radiation from the sun to generate electricity, but if a system optically concentrates the light it collects primarily the direct portion of the radiation, whereas non-concentrating systems (e.g. flat plate PV) can collect both the direct and diffuse components of sunlight (see Chapter 3).

Additionally, since only direct light can be optically concentrated, concentration requires the ability to track the sun so that the collector is always pointing directly at the sun as it moves across the sky, further complicating the system. However, since solar thermal-electric efficiency benefits greatly from generating higher temperatures to drive the heat engines that convert the thermal energy to electricity, concentrating systems are the standard in this arena.

In the case of photovoltaics, there is also a potential, due to the properties of the PV cell material, to increase efficiency and substantially decrease the needed amount of the sometimes expensive photovoltaic material by using concentration, typically with exotic multi-junction high-efficiency solar cells. The economics of concentrating PV (CPV) are not as favourable as in the CSP case, because CPV increases the need for cooling, in addition to the tracking and more complex optics required, and there is typically not as strong an increase in efficiency with concentration as in thermal systems.

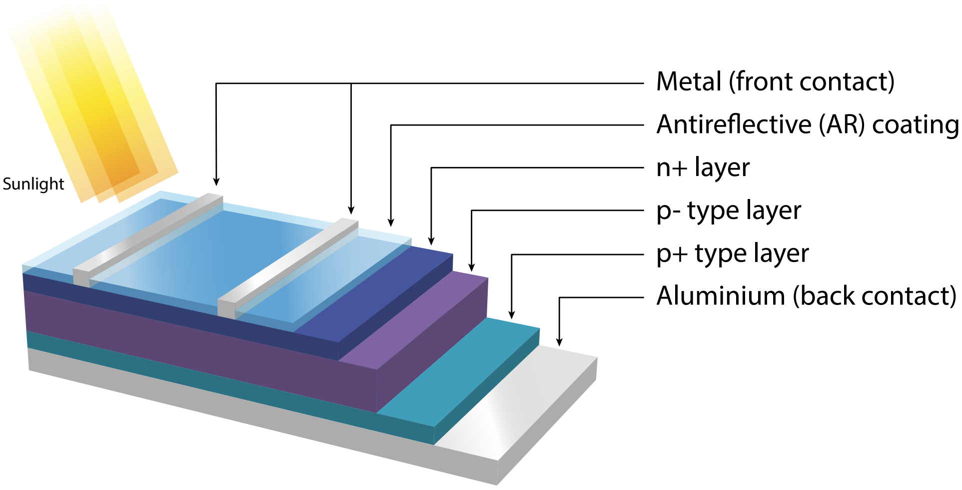

Figure 4.1 A crystalline silicon solar cell.

At the core of photovoltaic technology is the solar cell, or the material that converts the sunlight to electricity. A solar cell is formed at the junction between two semiconductor materials (of which there exists many varieties). Multiple such junctions can be arranged in series (or parallel) that have different abilities to absorb different wavelengths of light (corresponding to different electron band gaps). All of these variations, in the end, affect how much of the sunlight can be converted to electricity, with the goal to develop low-cost materials reaching the theoretical limit of efficiency. For a single junction cell, as shown in Figure 4.1, this efficiency limit is approximately 30%, but increases to 42% for two-junctions, and 48% for three-junctions, with a theoretical limit of 68% achievable with infinite junctions. Under high concentration the corresponding limits are 40% for a single-junction cell, 55% for two-junctions, 63% for three-junctions, and an 86% theoretical limit with infinite junctions.[2]

The PV industry is dominated by silicon cells. Silicon technologies are broadly divided into crystalline cells (single or polycrystalline), which make up over 80% of the world market,[3] and non-crystalline cells (amorphous). Amorphous cells are generally thin-films, meaning a thin layer (about one micrometer) of the semiconductor material is deposited on a base layer. This process reduces cost by reducing the amount of material used in the process, but also decreases the efficiency of the cell compared to crystalline silicon cells. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) cells are other examples of commercial thin film technology. At the top end of the spectrum, in terms of efficiency, are multi-junction cells, the most advanced of which are generally made up of layers of compounds of group III and V elements of the periodic table. A range of other types of cells are under development including dye-sensitised, organic, and quantum dot solar cells.

When talking about systems that convert sunlight to thermal energy and then to electricity, we often use the term “concentrating solar power” (CSP) although, as mentioned above, these systems could also focus the sunlight on PV cells instead of a thermal fluid. The scale of CSP systems is usually very large (i.e. power plant), but smaller systems can also be designed, for example, in remote villages for rural electrification. Solar thermal-electric systems offer the advantages of being suitable for operation on other fuels when the sun is not shining, and can store energy as thermal energy to later be converted to electricity. This method of storing energy thermally is generally less expensive than storing the generated electricity at a later stage (see also Chapter 5 and 12).

The general principle behind solar thermal-electric systems is that a working fluid (usually a molten salt, mineral oil, or water) is heated to high temperatures at the focus of a concentrating solar collector, and the energy from that hot fluid is then used to run a heat engine. The heat engine is usually based on either a Rankine cycle (the same cycle used in most fossil-fuel power plants) or a Stirling cycle.

To get the high temperatures needed to operate heat engines efficiently, solar thermal-electric systems usually use concentrating solar collectors which can produce fluid temperatures from a couple hundred to over a thousand degrees Celsius. These collector systems can generally be categorised as one of four types: Parabolic trough, linear Fresnel, dish engines, or central receivers, as shown in Figure 4.2.

---

[2] De Vos, A. (1980) Detailed balance limit of the efficiency of tandem solar cells. *Journal of Physics D: Applied Physics* 13(5):839.

[3] Masson, G, M et al. (2013) *Global market outlook for photovoltaics 2013-2017*. Brussels, Belgium: European Photovoltaic Industry Association (EPIA).

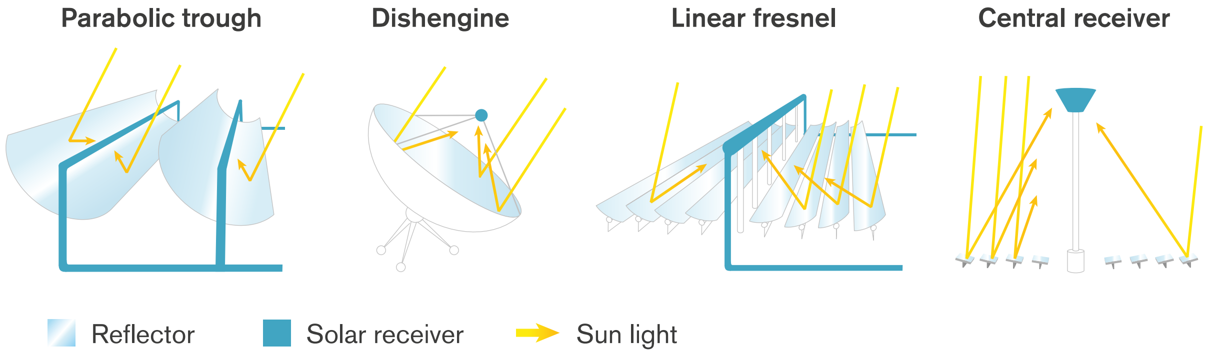

Figure 4.2 Types of CSP (Concentrating Solar Power).

An area of expanding research in the field of solar power is so called hybrid PV-thermal (PVT) systems. These systems combine a thermodynamic heat engine cycle, like in CSP, with a photovoltaic material to boost the overall conversion efficiency of sunlight to electricity. For example, one such system would use an optically selective fluid (e.g. with suspended nanoparticles) running over a photovoltaic material at the focus of a concentrating solar collector. The fluid would mainly absorb those wavelengths of light that were not useful to the PV, thereby allowing the useful wavelengths to hit the PV, while the other wavelengths heat the thermal fluid to high enough temperatures to run an additional heat engine cycle to produce electricity. The overall solar-electric efficiency from such a system could be higher than either a CSP or PV system alone.

The output of all solar power systems varies directly with the amount of sunlight, so is highest during the summer (on the northern hemisphere), tapers off in the winter, and varies depending on seasonal weather patterns. Regions nearer to the equator see less variation and more total production.

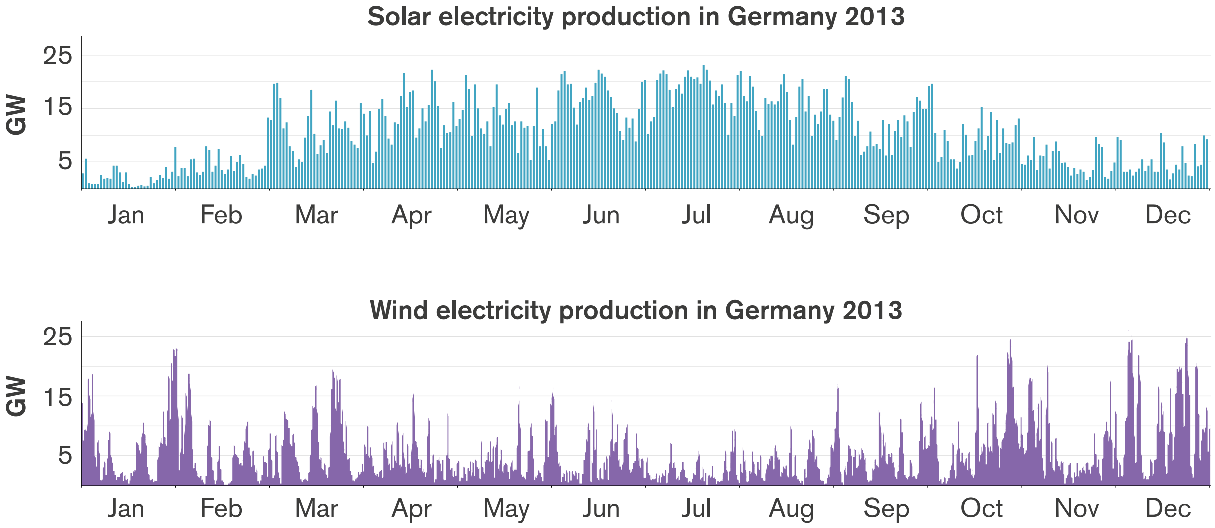

Figure 4.3 Solar electricity production in Germany, 2013 (top) compared to wind electricity production in the same year (bottom). Source: Fraunhofer ISE (2013).

Figure 4.3 shows the total production of solar electricity in Germany in 2013 compared to the corresponding production from wind turbines in that year. Note that the seasonal variation of these technologies makes them good complements for each other, as wind is often stronger in the winter months and solar in the summer months.

As of 2013 PV make up the lion's share of existing solar-electric capacity, with global PV capacity estimated at 140 GW, and thermal-electric at less than 3 GW. The solar electricity production the same year can be estimated at 130-150 TWh.[4] In the last decade, the installed PV capacity has grown, on average, by more than 50% annually.

WIND POWER

Wind power turbines create electrical energy from the kinetic energy in the wind. A wind power plant operates according to following principle: 1) The motion of the wind puts the turbine in motion; 2) a torque is created on the axis connected to the generator; and 3) the generator transforms mechanical energy into electrical energy.

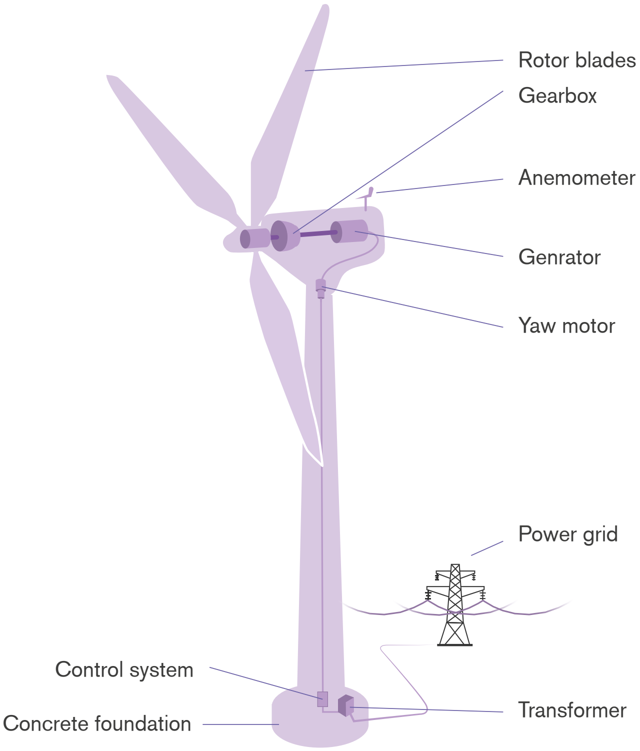

Figure 4.4 Components of a wind power plant.

A wind power plant consists of a number of components, shown in Figure 4.4. The main components are foundation, tower, wind turbine and nacelle. The foundation gives stability to the plant construction. The tower is often created by steel and has the shape of a cone. Some fabricates has concrete as an alternative material for the tower. The nacelle contains gearbox, generator and electrical equipment, and it turns towards the wind direction. There are several ways to design a wind power plant. Size of tower, rotor blades and the electrical system varies between different models.[5]

---

[4] The rapid growth in many different countries with varying insolation makes the estimate uncertain. The estimate is based on BP (2013) *BP statistical review of world energy 2013*. London, UK: BP plc.

[5] Wizelius, T. (2002) *Vindkraft i teori och praktik*. Lund, Sweden: Studentlitteratur.

The kinetic power of the wind is proportional to the density of the air mass and the third power of the wind speed (see Box 4.1). The implication of this is that when the wind speed doubles, the power increases by a factor of eight. Hence, the wind energy resource varies a lot between windy and less windy locations (see Chapter 5).

Box 4.1 Power and tip speed ratio.

The power from a turbine, P(W), is calculated from:

$$P = c_p \, P_w = \frac{1}{2} \, c_p \, \rho \, A \, v_w^{\,3}$$

where P_w = kinetic power of the fluid (wind or water current), ρ = density of the fluid (kg/m^3), A = wrapped rotor area (m^2), v_w = undisturbed wind speed (m/s), c_p = efficiency coefficient = 16/27 η, where 16/27 is the theoretical maximum efficiency (the Betz limit) and η = the efficiency of the turbine, c_p is usually 0.4 – 0.5 for wind turbines.

The tip speed ratio λ, measures of how fast the blades rotate compared to the speed of the fluid (wind or water)

$$\lambda = \frac{v_\mathrm{b}}{v_\mathrm{w}} = \frac{\omega r}{v_\mathrm{w}}$$

where v_b = tip speed of the blades (m/s), r = radius of the rotor (m), and ω = angular velocity (rad/s).

When a wind turbine is designed, the tip speed ratio is an important parameter. It is a measure of how fast the blades rotate compared to the wind speed (Box 4.1). If the wind turbine rotates too slowly, most of the wind will pass the rotor without hitting the blades. On the other hand, if the rotor speed is too fast, the wind will have a hard time passing the rotor, since the rotating blades will act like a wall against the wind. Because of this, the wind turbine is designed according to an optimal value of the tip speed ratio, to extract a maximum amount of energy. The theoretical maximum efficiency of a turbine, the Betz limit, is about 59% (or exactly 16/27).

For technical reasons, each power plant has maximum power output, i.e. it cannot make use of the all the energy of wind speeds above a rated speed. Figure 4.5 shows the theoretical wind power curve and a curve measured from a wind power plant owned by Chalmers University of Technology and situated on the island of Hönö, outside Göteborg, Sweden. The measured values initially follow the theoretical curve, but as the rated wind speed is approached, the measured power output stabilises at a constant value. At this point, the turbine, not the available wind energy, limits the power output.

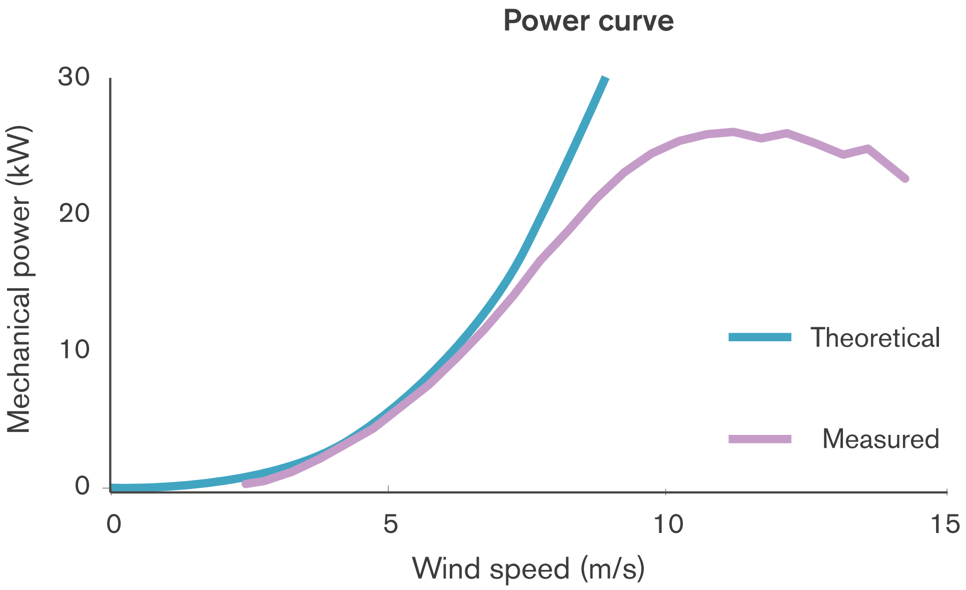

Figure 4.5 Theoretical and measured power curve from Chalmers wind power plant on the island of Hönö, Sweden.

There are mainly two types of wind power plants, vertical axis wind turbines, VAWT, and horizontal axis wind turbines, HAWT. In the VAWT, the axis between the generator and turbine is vertical to the ground, and in the HAWT it is horizontal to the ground. The HAWT dominates the wind power market today. Figure 4.6 shows one traditional (A) and two modern (B and D) HAWTs, and one VAWT (C), and their performance profiles.

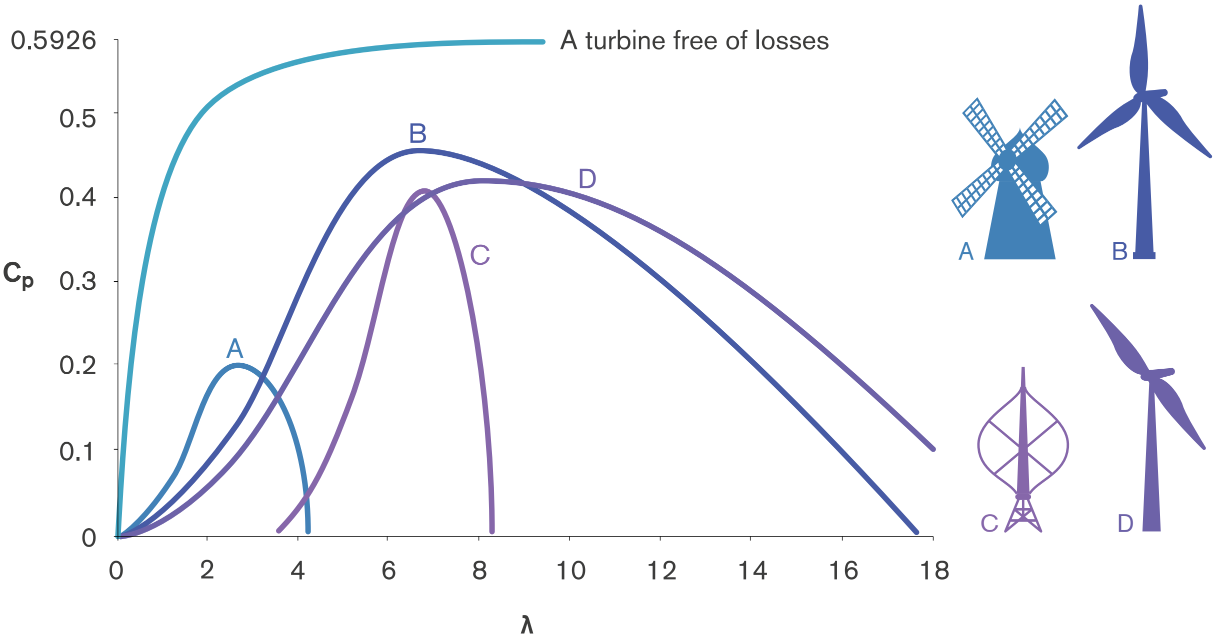

Figure 4.6 Different types of wind turbines.

At the end of 2013, the accumulated wind power installation worldwide was 310 GW and the electricity production in 2012 was about 500 TWh.[6] The installed

---

[6] GWEC (2014) *Global installed wind power capacity in 2013 - Regional Distribution*. Global Wind Energy Council; BP (2013) *BP statistical review of world energy 2013*. London, UK: BP plc.

capacity has on average grown by about 25% annually over the last three decades. In the last decade, the European offshore market has grown rapidly, from a few MWs to an installed capacity of more than 6 GW in 2013.[7]

HYDRO POWER

Hydro power, originating from the early civilizations millennia ago, exploits the potential energy of water precipitated on land at altitudes higher than sea level by forcing water from rivers or reservoirs through turbines. The available amount of energy is dependent on water flow (m^3/s) and the head (m) (water level difference). Historically, the mechanical energy was used directly for milling and other machinery. Today, generators convert the energy into electricity.

Several different turbine designs are used. Two common turbines are the Francis turbine and the Kaplan turbine where the former is the most common for high-head systems and the latter is typically used in low-head systems. Hydropower schemes can be of different types: *Run-of-river schemes* have turbines installed directly in a river, or have pipes leading water from a river through an adjacent turbine installation thus harvesting energy from the natural flow without options for energy storage. *Storage schemes* have a dam which impounds water and turbines installed in the dam wall, hereby partly controlling the temporal availability of the energy resource. *Pumped-storage schemes* have several interconnected reservoirs so that water can be pumped from lower to higher reservoirs when electricity demand is low, hereby allowing for a high control of the temporal availability of the energy resource.

The different schemes vary in their ability of storing energy and thereby optimising the selling price. Storage- and pumped storage schemes can be useful base supply in electric grids where power is saved for peak load periods (see Chapter 11), while run-off-river schemes, which are smaller, have the advantages of simple installation, lower environmental impacts and higher geographical availability. Although large-scale hydropower contributes with the vast majority of generated power, small-scale hydropower is regarded increasingly important for remote area power supply in many countries.[8]

Hydropower production has grown almost linearly over four decades, from 1000 TWh per year in the 1960s to 3700 TWh in 2012. Since 2000, its share of world electricity production has remained at about 16%.[9]

TIDAL POWER

Tidal power comprises both tidal barrages and tidal current turbines. Barrages capture the tidal wave inside large enclosures that are open when the tide rises and closes at high tide. With tidal withdrawal, at ebb, a head is created between the water trapped inside the barrage and the natural sea level outside the barrage. Electricity is generated when the water levels are allowed to even out through low-head turbines.

---

[7] EWEA (2014) *The European offshore wind industry - key trends and statistics 2013*. Brussels, Belgium: European Wind Energy Association. See also Chapter 15.

[8] Kumar, A. et al. (2011) Hydropower. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds O. Edenhofer, et al.):437-496. Cambridge, UK and New York, USA: Cambridge University Press

[9] BP (2013).

Tidal barrages can operate through *one-way mode*, where electricity is only produced during ebb, or *two-way mode*, where electricity is generated during both flood and ebb.[10] Tidal barrages are normally constructed across natural bays or river inlets in order to minimise the length and cost of the barrage. Modern tidal barrages may also come to be constructed on offshore banks (called tidal lagoons). Tidal barrages are based on conventional hydropower technology and can be used both for supplying local needs through small tidal ponds and for large scale power production.[11]

Tidal barrage technology is proven since more than 50 years but only a handful of large barrages have been installed. The most well-known being La Rance power station (240 MW) in France but the technology is used also in e.g. South Korea, China, Canada and Russia. A very large tidal barrage is now under appraisal in the Severn Estuary, UK.[12] A mean tidal range of 5 m is often thought to be required for tidal barrages to be economically feasible, but with modern low-head turbines also lower tides may be of interest.[13] Tidal barrages imply modification of the natural tidal regime, inevitably affecting the local environment. The environmental impact of tidal barrages has long been considered a major constraint to expansion of the technology (Chapter 8).

Tidal current turbines utilises energy from the fast-flowing currents that develop where the tidal wave passes through narrow straits or bends around peninsulas. A large number of technical solutions for tidal current power are currently under development. Electricity is generated through submerged turbines typically driven by large *horizontal-axis rotors*, much looking like underwater wind power plants, or small *vertical-axis rotors* mounted in grid-like constructions. Some designs are also based on *oscillating hydrofoils.*[14] On smaller turbines the water flow over rotors can be enhanced by ducting shrouds.

As with wind power and wave power, tidal current power is based on relatively small units (<2 MW) and meant for deployment in arrays. Most of these modern devices are open-flow tidal current turbines targeting tidal currents with water speeds around 2-4 m/s. The energetic currents also imply harsh conditions and rise high demand on marine engineering. Nevertheless, several full-scale devices have recently been installed and the technology is often believed to stand a good chance of becoming locally important in the near future.[15]

The tidal resource is dependent on the tidal range (m) which varies among locations due to landmass positioning and local bathymetry. Fast-flowing currents are rare and tidal current power is therefore particularly site specific (see Chapter

---

[10] Charlier, R.H. (2003) Sustainable co-generation from the tides: A review. *Renewable and Sustainable Energy Reviews*, 7(3):187-213.

[11] Charlier, R. H. and Justus, J. R. (1993) *Ocean energies.* Amsterdam, The Netherlands: Elsevier Science Publishers.

[12] Xia, J. et al. (2010) Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK. *Ocean Modelling*, 32(1-2):86-104.

[13] Liu, L. et al. (2011) The development and application practice of neglected tidal energy in China. *Renewable and Sustainable Energy Reviews*, 15(2):1089-1097.

[14] Khan, J. and Bhuyan, G. (2009). *Ocean Energy: Global Technology Development Status.* (T0104) IEA-OES. [Online],

[15] Bahaj, A.S. (2011) Generating electricity from the oceans. *Renewable and Sustainable Energy Reviews*, 15(7):3399-3416; Esteban, M. and Leary, D. (2012) Current developments and future prospects of offshore wind and ocean energy. *Applied Energy*, 90(1). pp. 128-136.

3). The tidal period is 24 h 50 min and the tide rises and falls one (diurnal tides) or two (semi-diurnal tides) times per day. In addition, the magnitude of tides increases two times per month (spring tides) as the gravitational force of the sun complements the force of the moon. The tidal power output is therefore variable over both hours and weeks, unlike the phase of human demand which typically has a diurnal period of 24 h, sometimes in addition to an annual period. By tidal barrages this can partly be solved by dividing the barrage into different basins so that the outflow is regulated and at least the diurnal variation is reduced. The output of tidal current turbines cannot be regulated and power remains variable but highly predictable.

OCEAN CURRENT POWER

Ocean current power, or ocean current energy conversion, basically works under similar principles as tidal current power, with turbines capturing the energy of the flow. However, due to the low energy density of ocean currents the power devices either have to be very large or particularly ingenious in the design (the power in stream is proportional to the third power of the water speed, see Box 4.1 and Figure 3.2). As an example of the former, it has previously been suggested to extract power from the Florida Current by installing arrays of turbines with rotor diameters exceeding 100 m.[16] A modern example of the latter is the Deep Green prototype, currently being developed by the Swedish firm Minesto[17]. The Deep Green consists of an underwater kite equipped by a smaller rotor and turbine. As the kite is swept in circles by the current the rotor experience an increased water flow, enhancing the energy density by a factor of ten. Ocean current power devices are still in early development and it is not known whether marine fauna will be able to avoid collision with its moving components. Thus, both costs and environmental feasibility of this power source remain very uncertain (Chapter 8).

WAVE POWER

Wave power uses wind-driven surface waves to generate electricity. The many currently developing technical solutions can be classified as *oscillating water column systems* where waves pressurise air chambers and spin turbines, *absorber systems* where a buoy attached to the seabed is dragged up and down by the waves in order to spin turbines or drag pistons through linear generators, *overtopping systems* where waves force water into an elevated reservoir which is emptied through low-head turbines, *inverted pendulum systems* where waves force an oscillator to move back and forth and pressurise fluids to drive generators, or *elongated attenuators* (interconnected elongated floaters) where the wave motions pressurise hydraulics connected to internal generators.[18]

Wave power devices can be shore-based, installed in shallow water, or anchored in deeper water. Floating wave power units are small (<1 MW) but intended for array deployment. As a general indicator wave power devices harvest about a fifth of the incoming wave energy and some devices are more generalist than other in

---

[16] Charlier, R. H. and Justus, J. R. (1993) *Ocean energies.* Amsterdam, The Netherlands: Elsevier Science Publishers.

[17] The Deep Green turbine is developed by Minesto. See Minesto (2014).

[18] Thomas, G. (2008). The Theory Behind the Conversion of Ocean Wave Energy: a Review. In *Ocean Wave Energy - Current Status and Future Perspectives* (ed. J. Cruz):41-91. Heidelberg, Germany: Springer (Green Energy and Technology); Khan, J. and Bhuyan, G. (2009). *Ocean Energy: Global Technology Development Status.* (T0104) IEA-OES. [Online]

the capturing of variable frequencies of waves. The power output is variable and undergoes both seasonal and daily changes, but is typically less variable and more predictable than wind power.[19] Long-distance waves (swell), which characterise tropical oceans, even out much of the short-term variation and thus, wave power around tropical islands can be particularly suitable. A common problem for wave power systems, and particularly for offshore devices, is to be sensitive enough to efficiently utilise common waves and at the same time be robust enough to withstand the rare but powerful extreme waves. Environmental impacts of wave power can be expected to be limited unless a high proportion of the incoming wave energy is absorbed by the power plants (Chapter 8).

OCEAN THERMAL ENERGY CONVERSION

Ocean thermal energy conversion (OTEC) utilises the temperature difference between warm surface water and cold deep sea water using heat engine technology.[20] Surface water and deep sea water are collected from the ocean via large diameter pipes and then released back to the ocean or partly utilised as freshwater. Electricity can be generated using *open-cycle*, *closed-cycle* or *hybrid* designs.

In an open-cycle OTEC warm surface water is vaporised in low pressure chambers and used to drive turbines before it is re-condensed by the cold deep sea water. In a closed-cycle OTEC warm surface water heats up a working fluid that vaporises and drives turbines before it is re-condensed by the cold deep sea water and recycled in the process. In the hybrid design warm surface water is vaporised like in the open-cycle design and is then used to vaporise a working fluid which in turn drives turbines. In the open-cycle and hybrid cycle designs, freshwater is produced as a by-product. This can be an important additional value where water for consumption or irrigation is scarce. For instance, a small OTEC plant has been installed in India with the sole purpose of producing freshwater[21] and a full scale 100 MW OTEC could produce freshwater enough for a larger city.

OTEC power plants can be installed on land or offshore as ship-like constructions. Due to the requirement of massive amounts of seawater, only large scale plants can become economically viable. By adding solar heaters to warm up the surface water the efficiency of the process can be improved.[22] The OTEC resource is determined by water temperature differences (Figure 3.3 and 3.4) and its availability, which in the case of land-based OTEC is determined by the distance between shore and deep sea water (1000 m depth is often assumed to be enough). As the heating and currents are relatively constant, OTEC power production is predictable although it may vary slightly over seasons.[23] The OTEC principles where explored with several pilot plants already in the mid-20th century, so the technical

---

[19] Charlier, R. H. and Justus, J. R. (1993) *Ocean energies*. Amsterdam, The Netherlands: Elsevier Science Publishers.

[20] Krock, H. (2010). Ocean Thermal Energy Conversion. In *2010 Survey of Energy Resources* (ed. P. Gadonneix):588-602. London, UK: World Energy Council; Magesh, R. (2010). OTEC Technology - A World of Clean Energy and Water. *Proceedings of the World Congress on Engineering*, 2. WCE 2010, London, U.K., Jun. 30 - Jul. 2.

[21] Bhuyan, G.S. (2008). Harnessing the Power of the Oceans. *IEA OPEN Energy Technology Bulletin*, 52:1-6.

[22] Straatman, P.J.T. and van Sark, W.G.J.H.M. (2008). A new hybrid ocean thermal energy conversion-Offshore solar pond (OTEC-OSP) design: A cost optimization approach. *Solar Energy*, 82:520-527.

[23] Vega, L.A. (2011) Hawaii National Marine Renewable Energy Center (HINMREC). *OCEANS 2011* :1-4, Waikoloa, HI, USA, Sep. 19-22

principles are not new. Its implementation has been haltered due to high capital costs of construction, however, a small OTEC plant is now under construction off the coast in the French island of Martinique. The environmental impact could be considerable (Chapter 3 and 8).

GEOTHERMAL POWER

Geothermal power utilises the heat produced within the earth in order to generate power, in contrast to most other forms of renewable power for which the primary energy source is the sun (see Chapter 3 and Table 3.1).

There are several geothermal resources that could be utilised as heat sources. However, today hydrothermal sources in the form of vapour and hot water at depths up to a few kilometres are the only commercially used sources. In these, water is used as an energy carrier, moving energy from the Earth's interior to the surface. Such resources are primarily created by rain water which percolates down to areas of permeable heated rock, there the water is heated acting as an energy reservoir. On top of the reservoir there needs to be a cap rock, i.e. an impermeable rock that prevent vapour from rising to the surface. In order to utilise the energy, wells are drilled to the reservoirs and through these the hot water or vapour rises to the surface.

At the surface, the heat energy is used to generate electricity and the water, now at a lower temperature, is then injected back into the reservoir. Depending on water temperature of the field three different methods are used to generate electricity: flash-steam, dry-steam and binary cycles. All of these have capacity factors of up to 0.9 (new plants) with an average of 0.75 and are thus able to act as base load plants.[24] The size of a power plant can vary between 0.1 MW and 120 MW.[25]

The most common type is the flash steam. For such cycles the fluid from the well is used as working fluid in a steam cycle. In the process pressurised water rises from the well and as the pressure drops the water eventually flashes into steam. The steam and hot water are then separated and the steam is used to drive a steam turbine. Due to the prevalence of corrosive gases in the steam the relatively low temperature, resulting in water droplets being formed, the turbine needs to be both corrosion and erosion resistant, and therefore more costly than ordinary turbines.

Dry-steam plants are used in areas which can produce dry superheated steam as a source. This removes the need for a flash process in order to separate liquid and vapour, resulting in a less complex and thereby cheaper plant. Steam is instead fed to a particulate remover and then directly to the turbine

---

[24] Goldstien, B. et al. (2011) Geothermal Energy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge, UK and New York, USA: Cambridge University Press; IEA-GIA (2012) *Trends in geothermal applications, Survey Report on Geothermal Utilization and Development in IEA-GIA Member Countries in 2010*. Taupo, New Zealand: IEA Geothermal Implementing Agreement

[25] DiPippo, R. (2012) *Geothermal Power Plants - Principles, Applications, Case Studies and Environmental Impact* 3rd Edition. OXFORD, UK: Butterworth-Heinemann.

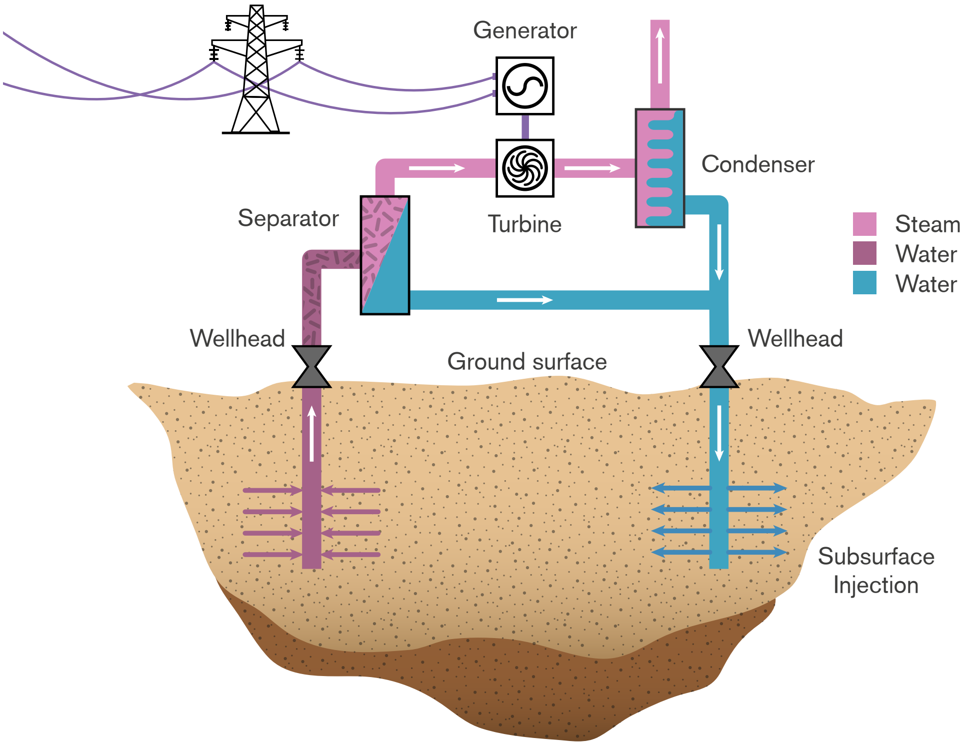

Figure 4.8. Principal schematic of a flash steam plant

For temperatures below 150°C it becomes economically difficult to use a flash process to convert the heat to electricity. Instead a binary cycle, typically an organic Rankine cycle, is used in which a separate working fluid is heat exchanged with the fluid from the well and cycled in the power plant. In such a plant a pump is used to bring the water to the surface and to keep it pressurised enough to remain a liquid. The water is then heat exchanged with the working fluid with a low boiling point. The vapour is then fed to a turbine, condensed and recirculated to the heat exchanger. The water from the well is injected back into the reservoir after the heat exchanger. There are also more complex forms of binary plants as well as combined binary and flash steam plants.

The installed capacity of geothermal power plants has increased linearly since the 1970s and reached 12 GW in 2013 with an expected annual production of 70-80 TWh.[26]

CONCLUDING REMARKS

The electric power production of the world of today is dominated by coal and gas. As described in Chapter 2, there is an urgent need to transition to renewable power. Renewable power plants are different and come in many forms, rely on a range of resources and use a variety of conversion technologies. Some rely on knowledge fields already mainstream in the energy sector, such as the thermodynamic cycles in solar thermal electric and geothermal power plants, others draw on similar physical principles while applied in different environments, such as turbines rotating in air or water, while yet others, such as solar cells, bring in

---

[26] GEA (2013). *2013 Geothermal power: International market overview,* Washington DC, USA: Geothermal Energy Association.

the domains of semiconductor electronics and nanotechnology. There are vast opportunities to capture the energy flows that every second pass by, but it will require combination of knowledge fields, engineering ingenuity, entrepreneurial experimentation and continuous investment.

The maturity of the technologies differs widely. While some, like many ocean energy technologies remain to be extensively tested, hydro power has grown steadily over more than a century. In the last two decades, wind and solar PV has grown exponentially, initially from low levels, but now reaching several percent of the electricity supply in many countries. However, as shown in Chapter 3, all renewable power technologies are far from their ultimate potentials, and as shown in the rest of this book, there are many obstacles yet to overcome, related to compatibility with existing technical systems, environmental concerns, economic competitiveness and political power.