School of Engineering and Built Environment

Energy Resources, Generation and Utilisation

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Table of Contents

Section 7: Alternative energy sources II

In this section we will look at the other ways of generating energy sustainably; hydro power; wave power; tidal energy. In each case the energy carrier is water. We will not look in great technical detail at how energy is extracted, but instead focus on the potential of each source and problems extracting the energy. New generation technologies are also considered.

Water

Everyone must have heard at some time how the unique properties of water make life on Earth possible. What is so special about water? The key point is that water is a liquid at the ambient temperature of the planet, when nearly all other substances are liquid or gaseous. Without a neutral liquid medium in which to operate, it would be impossible for the organic molecules that make up living cells to react and interact.

Water is involved everywhere as we look at energy generation and energy issues, be it the operation of a steam turbine for generating electricity, electrolysis to make hydrogen, a central heating system to move heat around the home, the massive contribution of water vapour to the greenhouse effect, or even fusion to produce clean energy in the future.

Nuclear fusion is the process that powers the Sun. Two protons are forced into such close proximity that the nuclear force is engaged and binds them together to form helium, releasing a huge amount of energy. Fusion has already been achieved in the lab but not in a controlled way. Fusion is considered by many scientists to be the most likely way energy will be sustainably generated in one hundred years time. Water, the raw material, is plentiful, but a very high temperature is required to overcome the long-distance repulsive force between protons that normally prevent them coming close together. The temperature must be raised to millions of degrees, but no conventional vessel can be used to contain a material at this temperature. A magnetic bottle must be constructed to confine the **plasma** (of protons and electrons), but it is extremely difficult to produce a magnetic barrier that is completely secure. Further research leading the development of a power plant with net energy output within 50 years is the ambitious objective of the multinational ITER initiative [https://www.euro-fusion.org/2005/07/the-iter-initiative/].

Water is also important in the fundamental reaction that sustains all life - **photosynthesis**. Plants use light energy to combine water with atmospheric carbon dioxide to produce glucose. The reaction is catalysed by a large and complex protein called **chlorophyll**. An important research aspiration is to reproduce the reaction in a controlled fashion in the lab. Chlorophyll is an organic catalyst, and there are efforts made to discover alternative inorganic catalysts that will perform the same function

Task 7.1

How much energy is needed to reduce the temperature of 1 m^3 of water from 10 ^oC to 0 ^oC? When water then freezes, does it absorb or release energy, and how much? The specific heat capacity (SHC) of water is 4.2 kJ $kg^{-1} {}^oC^{-1}$ and the latent heat of fusion is 334 kJ kg^{-1}. This calculation is relevant to ground source heat pumps.

HINT: The energy needed to heat up water by T degrees is mass x SHC x T.

Hydroelectricity

Water will flow from a higher level to a lower level under the influence of gravity. In doing so, the original potential energy is converted to kinetic energy. Fig. 7.1 shows a cube of water of volume V suspended at height h above ground level.

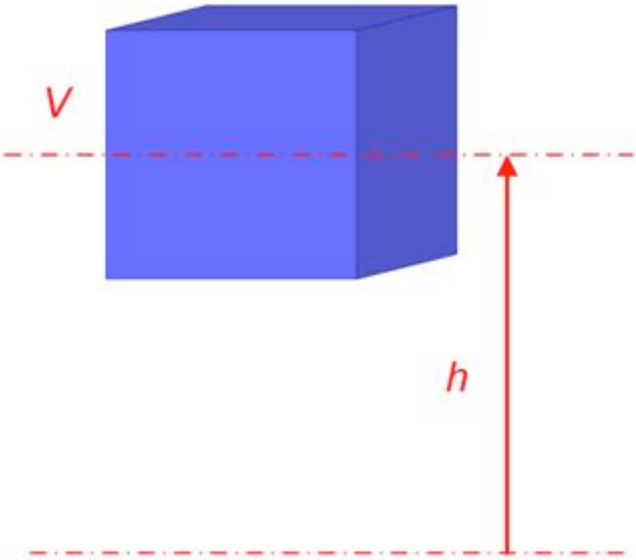

Figure 7.1: The height of the water above the generator should be as great as possible. In the recently completed Glendoe scheme, water from an uphill reservoir is piped down to a turbine 600 m below. 1 m^3 of water will therefore generate 1,000 x 1 x 9.8 x 600 / 3,600,000 x 0.9 = 1.5 units of electricity. Large hydro schemes can be very effective and are completely sustainable.

The total potential energy is:
PE = density x volume x gravitational acceleration x height
= ρVgh

where the density of water is 1,000 kg m^{-3} and the gravitational acceleration is 9.8 m s^{-2}.

If the mean height of a 1 m^3 volume cube of water were 10 m, the stored energy would be 1,000 x 1 x 9.8 x 10 J = 98 kJ.

A hydroelectric scheme converts gravitational potential energy to electrical energy. Water flowing down its natural course is constrained by a barrier causing the water level to rise, causing the stored energy to increase both by virtue of the increasing mass of water and the rising **head of water** (the height of the body of water above the turbine position). When electricity needs to be generated, water is allowed to flow through a turbine. Generation efficiency can approach 90% - more than double that of a thermal power station.

Hydroelectricity takes on a role of energy buffer in an integrated system that includes intermittent renewable energy sources such as wind power, because it can respond very rapidly (less than 30 seconds) and compensate for any sudden drop in wind speed and ensure continuity of supply. Independent Power Projects in Sub-Saharan Africa [https://openknowledge.worldbank.org/bitstream/handle/10986/23970/9781464808005.pdf?sequence=2&isAllowed=y]

The difficulty is that there are very few locations suitable for a hydroelectric scheme, even in a mountainous country with heavy rainfall such as Scotland. The topography must be such that water from a significant catchment area is directed through a narrow channel that can be effectively blocked using a barrier. Alternatively a major river can be dammed, but this will often flood a significant area of fertile land.

The installed capacity in Scotland is 1.39 GW. This is slightly misleading because stations will not always run at full capacity - there is not always sufficient water and as reservoirs are emptied, the head drops and the energy value of the remaining water is reduced. The **load factor** is an indication of what percentage of capacity is really achieved, 0.4 is typical. Scotland has been fully assessed for hydro potential and, in spite of the mountainous terrain, there may be as little as 0.5 GW left to develop.

The British Hydropower Association is the UK industry body, and they strongly promote small or **micro hydro schemes** as there are few remaining locations suitable for larger schemes.

Figure 7.2: Dam on the River Tummel, Scotland (Image: (c)iStockphoto.com/LordRunar).

Worldwide there are many huge hydro schemes under construction, with already 800 GW installed capacity (generating about 20% of the world's electricity). Hydroelectricity is the most significant renewable energy resource in the world today.

On the other end of the scale, micro generation from streams (damming or just exploiting natural flow) is sometimes worthy of consideration.

Task 7.2

The Lochaber hydro scheme has a head of 244 m, a catchment area of 896 km^2, an installed capacity of 85.8 MW, and a load factor of 0.67. How many units of electricity are produced annually and how much water flows (assuming the turbine and generator together are 85% efficient)?

Wave power

Ocean waves build up through the effect of wind on the surface of the water over enormous distances (the **fetch**). Once the water surface is disturbed, the wind gets an increasing 'grip' and large waves can develop. Eventually, the waves equilibrate with the driving force. This is referred to as a **fully developed sea**. Waves can then travel thousands of kilometres before hitting land. There is the illusion that the water flows; in fact water molecules travel in circles relaying energy and momentum to the next molecules along the path of the wave; waves transport energy.

The power P crossing a 1 m line of coast is dependent on the water density (ρ = 1,000 kg m^{-3}), the wave height from trough to peak (H), and the velocity of the waves (v):
P per unit length = $1/8\ \rho g\ H^2 v$

A power density of 50 kW m^{-1} is common and energy densities as high as 400 kW m^{-1} do occur. Waves accumulate and concentrate wind energy and are potentially a huge source of renewable energy, but very few commercial devices have been deployed to date. If we note that a large wind turbine blade will transfer a maximum power of 25 kW m^{-1} it is clear why this is the case. It is technically difficult to design mechanical systems that can withstand the greater forces exerted by waves.

Not that people aren't trying; there are many prototype systems based roughly on five distinct principles (www.europeanvoice.com/archive/article.asp?id=28990).

Overtopping devices capture water from waves and hold it in a reservoir above sea level, before releasing it through low-head turbines which generate power.

Oscillating water columns are hollow structures which enclose a column of air and a column of water. The water level rises and falls as a result of the movement of the waves, compressing and decompressing the air inside the column. When the trapped air is compressed it escapes from the structure via a turbine. As the water level in the structure drops, air is sucked back inside, again causing the turbine to rotate and generating electricity.

Floating devices have components which are hinged together and react to variations in the sea level. Relative motions of different components are resisted by hydraulic pumps which pump high-pressure oil through hydraulic motors.

Underwater buoyant devices (moored to the ocean floor) are pushed up and down by variations in water pressure. The movement is used to pump hydraulic fluid through hydraulic pumps.

Hinged flap devices (moored to the ocean floor) oscillate backwards and forwards according to the movement of the waves. The energy is harnessed by pumping hydraulic fluid through pumps.
There are also difficulties with equipment that has to work in salt water and then transfer the generated energy to shore.
Scotland has a huge marine energy resource and is leading the way in the development of new technology, testing, and deploying prototype devices.

Task 7.3

The average wave power along the north-west of Scotland is 70 kW m^{-1} - see page 4 of this. How does this compare with the wind resource if the wind speed is an average of 7.0 m s^{-1} at ground level? What is the total wave energy incident on Sub-Saharan Africa and how does it compare with total demand?

Tidal energy

Tides arise from the gravitational pull of the Moon and Sun dragging ocean water around their paths. This is a highly predictable process and the energy gained by the water can potentially be extracted as another form of marine renewable energy.

The sea rises by about 1 m in mid-ocean twice per day, much less energy than is associated with ocean waves, but the amplitude increases significantly near land when the water becomes constrained by topological features. Another difference between tidal and wave motion is that the water actually moves, giving rise to surface and underwater tidal currents or flows. The flow can be used to generate energy by installing underwater turbines (in the same way that wind turbines draw energy from air currents). Since the density of water is about 800 times that of air, the blades only have to be 1/30th of the size needed to extract the same energy from wind. This is why the propeller of a large ship that may generate many MW of thrust is relatively small, of the order of 2 m radius. A 3 MW wind turbine has 50 m blades. Underwater turbines would therefore be much smaller.

Another way of exploiting tidal flow is through tidal barrages across estuaries (Fig. 7.3). A barrier across an estuary is closed at high tide and held until low tide when the dammed water is allowed to escape through a turbine to generate electricity. Although not a continuous source of energy, it has the advantage of being predictable. This is effectively a hydroelectric scheme, differing in that no new land is flooded. However, the duration over which the foreshore is under water is changed and this may affect the environment and creatures that feed off the estuary. As with many renewable energy schemes, possibly serious ecological consequences must be balanced against the need to produce clean energy. One important scheme in the UK is the proposed Severn Barrage. This would produce 2 GW average power, about 6% of UK electricity generation. However, the proposal is costly and controversial.

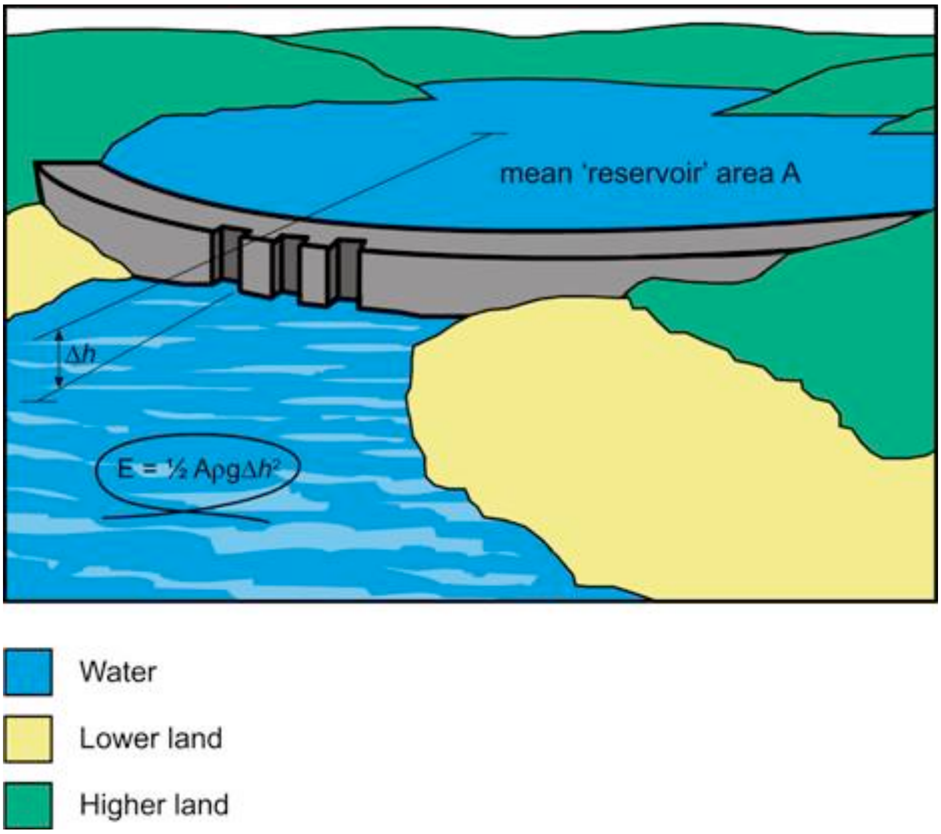

Figure 7.3: Representation of a tidal barrage across an estuary.

There are several sites around Scotland where there is the potential for tidal flow turbines. The Pentland Firth is the channel through which the North Sea is 'emptied' and filled twice daily. The peak flow is 3 million tonnes per second with flow speeds of 5 m s^{-1}. The project is being promoted by the Pentland Firth Tidal Energy group. Another possible site is the Sound of Harris in the Outer Hebrides

The range of devices and techniques is described in Wikipedia's tidal power article. It should be emphasised again how difficult it is to produce effective tidal and wave energy machines - the huge energy resource around our coast that has the power to erode cliffs is still largely out of our grasp.

Energy in Africa [https://en.wikipedia.org/wiki/Energy_in_Africa]

Task 7.4

How much energy could be extracted with a tidal flow speed of 5 m s^{-1}, assuming one hundred 30% efficient turbines with 3 m blades, spaced 10 m apart? Would there be any environmental consequences?

Notes

Types of solar array

The most common type of PV material is crystalline silicon. Monocrystalline silicon is a large crystal of silicon sawn into thin slices, doped and sandwiched to form the junction. Cost can be reduced using polycrystalline silicon - small grains of pure silicon - which is easier to manufacture, but the penalty is slightly lower efficiency.
Gallium Arsenide (GaAs) can be used in place of silicon and will absorb all the incident light with a much thinner junction depth. The band gap also permits a greater portion of the spectrum to be absorbed. In addition, performance is unaffected by temperature. Though GaAs is much more expensive than silicon, it is possible to focus light onto a small junction area to reduce the quantity of material required.

Thin films are cheaper to produce, and amorphous silicon is a thin layer where the crystal structure is imperfect. Normally this means that doping cannot work, but the unconnected parts of the structure are deactivated by bonding hydrogen. PiN devices of this type are cheap, but only have a long-term efficiency of about 8%.

Other materials such as copper indium gallium diselenide (CIGS) and other exotic combinations have a potentially better performance and are being used in new families of thin film devices. Cadmium telluride modules are already in production.
Another approach is to create multi-junction PV cells, by layering absorbers with different optimal absorption bands to extract more of the incident radiation frequencies.

Energy policy of Scotland

The energy policy of Scotland differs from that of the UK government. The target is '50% of electricity generated in Scotland to come from renewable sources by 2020 (interim target of 31% by 2011)'.

Currently, the primary energy demand in Scotland is around 30 GW, and the electricity generated was 6.2 GW in 2006 (multiply by 8760 to get the number of GWh generated annually, 4.9 GW was consumed; the difference is export and transmission losses). Of this, 13% was from renewable sources, mostly hydro with an installed capacity of 1.3 GW and a loading of about 0.3.

The 31% target to be reached by 2010 requires an additional 0.9 GW generation, and if, as is likely, this is from wind turbines with a loading of 30%, an equivalent installed capacity of 3.1 GW is required. To achieve the 50% target, an additional 6.2 GW installed capacity (with a mean output again of about one-third) of wind, wave, tidal, or biomass is needed.

Are these targets achievable? The table below shows the magnitude of the renewable energy resource in Scotland. It could be argued that the target of 50% by 2020 is actually too low if the UK as a whole is to meet its 20% target - because Scotland has the greatest resources and must make a disproportionate contribution to the UK target.

There is clearly a huge potential vastly in excess of what is required. But there is still no economic way of accessing some of these resources. In fact the hydro capacity, which has been there a long time, skews the figures and progress is actually slower than is needed to meet the targets. The planning system is not designed to deal with renewable energy applications, leading to lengthy delays, and there is insufficient investment in marine renewable research and development. To address this last issue, the First Minister Alex Salmond in April 2008 announced the worldwide Saltire Prize of $20 m to stimulate the development of a marine technology that could be effective in Scotland (news.bbc.co.uk/1/hi/scotland/7325870.stm).

Policy is being continuously revised through FREDS, the forum for renewable energy in Scotland. There is some disagreement that a policy that specifically excludes the construction of new nuclear power stations is viable. Brian Wilson, speaking on Newsnight (BBC 2, 2nd April 2008) stated that if the current policy fails, then by 2020 Scotland will become a net importer of energy and will have no control of the energy mix.

The conference of the renewable trade association in March 2008 indicated there are real problems with few of the bodies involved in delivering and achieving targets 'lined up'. A skills shortage is anticipated with a need in particular for staff at a technical level.

The renewable industry in Scotland is aspiring to grow rapidly, and is demanding an easing of constraints and restrictions. However, the environmental impact of renewable energy developments can be enormous and a sensible level of scrutiny must be applied to major planning applications.

Technology	**Capacity in 2006 (GW)**	**Potential capacity (GW)**
Onshore wind	0.94	11.50
Offshore wind	0	25.00
Wave	0.00027	14.00
Tidal stream	0	7.50
Hydro	1.34	1.63
Wood	0.012	0.45
Biomass (non wood)		0.84

Biodiesel		0.14
Landfill gas	0.061	0.07
Geothermal		1.50
Solar		
Total	2.4	62.63

Energy policy of Sub-Saharan Africa

Sub-Saharan Africa, where more than a half billion people live without electricity, trails the world in government policies that promote sustainable energy, according to a new World Bank report

Read more at: [https://phys.org/news/2017-02-sub-saharan-africa-lags-sustainable-energy.html]

Summary

We looked at alternative energy sources and found there are a number of options available. Even now wind power is economically viable, especially on a large scale; but also on a small scale, combined with a heat pump, it is possible to make very significant carbon emission reductions.

Directly exploiting solar radiation is marginal in Scotland, and though lower cost solar hot water systems may be acceptable, passive solar heating is the preferred option.

The hydroelectricity resource has been almost fully developed, but it is disappointing how little progress has been made in the commercial exploitation of wave and tidal power.