School of Engineering and Built Environment

Energy Resources, Generation and Utilisation

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Task Exercise No: 5

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We have seen there are environmental problems associated with fossil fuels, and to a lesser extent with alternative energy. While renewable energy is an attractive prospect, it must still compete economically with fossil fuel, and we will now consider if this is the case, but it is not just cost - a way of dealing with the intermittency of renewable sources might also be needed.

Energy calculations

As far as the end-user is concerned, the key unit of energy measurement is the **kilowatt-hour (kWh)** or **unit of electricity**. It represents the consumption of 1,000 J of energy every second (1 kW) for an entire hour, because there are 3,600 seconds in one hour, **1 kWh is equivalent to 3.6 MJ of energy**.

For an energy producer, this is too small a unit to use. If the primary source of energy is oil, then **1 tonne of oil(toe) contains potentially 42GJ of chemical energy**. Dividing by 3.6 MJ, this is equivalent to 11,666 electricity units. Thermal power generation is approximately 38% efficient overall, hence 4,400 units of electricity can actually be generated from 1 toe. A barrel of oil (boe) is equivalent to 0.146 toe, and will generate 647 units of electricity. There are many other units in use, but we will keep with J, W, kWh, toe, and multiples of these.

Example 1

A car battery is rated at 12 V and has an energy content of 75 amp-hours. This means the battery will supply 75 amperes for 1 hour. The energy delivered each second is the voltage times the current, hence the total energy stored in the battery (in joules) is found by multiplying the voltage by the current by the number of seconds in one hour:
E = 12 x 75 x 3600 J = 3.24 MJ.

This is equivalent to 0.9 kWh. A lead-acid car battery is about 80% efficient, (in contrast, lithium-ion batteries used in mobile phones are 99.9% efficient) which means that the energy put in during charging will be:
0.9 / 0.8 kWh = 1.125 kWh if the full battery capacity is to be extracted.
The cost to charge a car battery is therefore about that of 1 unit of electricity.

Example 2

It has been estimated that a typical home has an average of 4 devices left on standby - each consuming about 3 W. There may also be a PC which, if left on all the time, will use 35 W typically when idle and the display on standby. This is a total of 0.047 kWh of energy consumption. Multiplying by the number of hours in one year, the devices will use 412 units of electricity, equivalent at current prices to £50.00 or about £12 per quarter.

Example 3

If a room is illuminated by 8 conventional 40 W spot lamps and the lights are on for an average of 4 hours per day over the whole year, the number of units consumed in the year is 8 x 0.04 x 4 x 365 = 467.2, or a cost of £61 for that room.

If all the lamps were replaced with one 22W compact fluorescent lamp (CFL) or tube (CFT) in the centre of the room, the calculation would become 0.022 x 4 x 365 = 32.1, a cost of £4.00 for the entire year. This is a significant reduction.

Example 4

A fridge freezer will have an energy rating that indicates how much power is being consumed for each litre of storage. This depends on where the freezer is located, how often it is opened and so on. You can check this. If a freezer has a 0.5 kW pump and is on for 3 minutes in every hour, then the total energy used is 0.5 x 3 x 24 x 365/60 = 219 kWh.
A modern very efficient 100 litre freezer will consume 200 kWh per year; an older freezer will consume three times this much or more (and should be replaced for economic reasons alone).

Task 5.1

A home oil-fired central heating system uses 2000 litres of fuel a year (energy 40 MJ l^{-1}, cost £0.48 l^{-1}). What would be the comparative cost of heating with off-peak electricity (£0.065 kWh^{-1})?

Generation methods and costs

We will now look at the cost of generating one unit of electricity by different methods and how economics is likely to change as the cost of fossil fuels rise.

All traditional power plants works on the same basic principle. A working fluid is used to move the blades of a turbine, or push the piston of a reciprocating engine such as found in small diesel power stations. The working fluid gains its thermal and kinetic energy by a variety of means: the combustion of fossil fuel; a nuclear reactor; natural energy in the environment (wind, wave, tides, geothermal); water pressure (hydro).

In thermal power stations, the working fluid is heated in a controlled manner. The vast majority of thermal power plants use pressurised steam as the working fluid, with the energy in the steam producing rotational motion (mechanical work) in the turbine. The turbine will then drive a generator to produce electricity.

In a gas turbine, hot gas from the combustion of natural gas is used to directly turn the turbine blades - steam is not used. A gas turbine will respond faster than a steam turbine and is suited to **balancing**, i.e. adapting to quick changes on the **load** (the end-user electricity demand), but the electricity produced is more costly because of the lower efficiency of the process.

A steam engine is much more efficient than a reciprocating engine. The different generation methods are categorised in Table 5.1. Thermal power stations can only turn a fraction (between 35-50%) of the energy available in the primary fuel into work because of the limitations imposed by the laws of thermodynamics and losses at each step in the process (friction etc). However, the waste heat may be recovered and used for purposes other than electricity generation to improve the plant overall energy economy.

Table 5.1: Different methods of power generation.

Working fluid	**Turbine**	**Piston**
Water	Hydro Tidal Wave	
Steam	Nuclear Coal Geothermal (oil, gas)	
Hot gas	Gas turbine	Diesel engine Petrol engine
Cold gas	Wind	

We are concerned here only with large scale generation. The comparative costs of generating a unit of electricity by fossil fuels, nuclear power, and renewable energy are shown in Fig. 5.1. This is taken from an independent report conducted in 2004 and shows that wind power was very much more expensive at the time. Since then the figures have changed and will continue to change. Clearly wind turbine costs are driven up by the effort and time required to obtain planning permission and increasing manufacturing costs, but mass production and standardised manufacture will drive the price down. On the other hand, fossil fuel and, to a lesser extent, nuclear power costs are being driven inexorably upwards. The (retail) price to the consumer will be 2-3 times the generation (wholesale) cost once all the other costs are factored in.

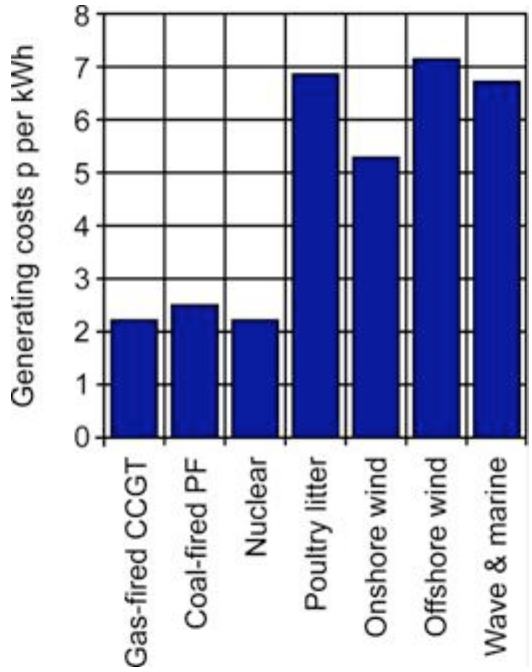

Figure 5.1: The cost of electricity generation in 2004. CCGT is combined cycle gas turbine and PF is pulverised fuel

Although renewable energy is *possibly* not currently economical, it must eventually become so. The primary energy is free - it is not subject to the rising fuel prices associated with traditional generation methods. There is no clear answer to the question of exactly when renewable energy will become competitive, but you can try to explore this in the tasks below. Bear in mind that a mix of energy sources, including renewables, is desirable and reduces dependence. Renewables do have the additional problem of intermittence or variability of supply, and this also must be addressed - it is not just the relative cost with respect to conventional energy generation that is important.

Task 5.2

Investigate how the costs of electricity generated by conventional and alternative means have changed since 2004. How do you think things will develop in the future? Why does renewable energy cost anything at all after initial installation?

Conventional power distribution and energy storage

Power stations tend to be located away from the main sources of population and in the UK the energy is distributed on a shared network called the National Grid that runs down the backbone of the country. Note that the links stop far short of areas to the north and north-west of Scotland (and the Isles) that have been identified as prime locations for marine and wind energy, and the grid would have to be extended to make large-scale renewable projects viable.

Extending the grid is hard because the infrastructure is so invasive on the landscape, making the planning process very difficult. Power is distributed at voltages of 132, 275 or 400 kV in order to keep power losses due to cable resistance to a minimum. Air is used for insulation; consequently the cables hang far above the ground on tall pylons. The distribution system is effective and only 850 MW is lost in the wire, about 1% of the energy carried. Energy is also lost through coronal discharge, and at the substations connecting into the grid that eventually drop the voltage to the 240V that reaches the home, with the result that the mean accumulated losses associated with distribution is 7% - still relatively low. The National Grid has a cable capacity of 77 GW, well above the peak demand of 63 GW - more on this later!

Keeping the load balanced is important. The generation capacity should match the demand. This can be achieved using hydroelectricity and gas turbines to manage rapid fluctuations, and assigning larger stations that have a slower response to match the very predictable overall daily demand curve. Any excess generation can be 'mopped up' using **pumped-storage**, ie running a hydro plant in reverse, to 'soak up' the difference.

Another problem is that if an intermittent source such as a large wind farm is connected into the grid, it is very hard to compensate for variation, and rapid changes over a few seconds can cause instability. And it is not just keeping the supply stable - if we are heavily reliant on renewable energy as a nation, what happens if there is no wind for several days. Where would excess produced on windy days be stored for use when there is no wind? Pump storage has insufficient capacity. Do we just keep all the existing power stations on line ready for times of no wind? The argument has been made that over the entire UK there will never be a time when there is no energy available from renewable sources, but this remains to be demonstrated. Extensive deployment of renewable energy with no conventional generation backup should really be accompanied by a high-capacity storage system to smooth out variation.

This works on a small scale. The Isle of Eigg has recently switched to a local grid system driven by renewable energy [http://www.bbc.com/future/story/20170329-the-extraordinary-electricity-of-the-scottish-island-of-eigg] and buffered by hydro. Unfortunately this model is not scaleable, and on Eigg the huge cost of £1.6 million to power 71 buildings highlights the other drawback of renewable energy: high initial cost and long payback time

Task 5.3

How can different stations add power to the same line and how do they keep track of whose power is being used? How can renewable energy be put on the Sub-Saharan African grid?

The hydrogen economy

The existing electricity distribution system is very efficient, but it is not the only way of transporting energy. Fossil fuels are effectively moved around the country in solid, liquid, and gaseous states, though the distribution costs are more significant, particularly for remote communities. Could excess energy generated by renewable means not be converted into some tangible form and stored for use in times of energy drought? Yes - it is relatively easy to produce hydroge**n** using electricity by **electrolysing** water. The hydrogen is then collected and stored. The process is not subject to the restrictions of a thermodynamic cycle and is *potentially* close to 100% efficient. The hydrogen can later be burnt when all the energy is recovered, or a **fuel cell** can be used to reverse the **electrolysis** process and produce electricity from hydrogen. In this context, hydrogen is an **energy carrier**, not a source of energy. A sustainable future world where cars and buildings run off piped hydrogen produced using clean energy is the idea of a **hydrogen economy** emerging from the ashes of the present oil age. This is the ultimate in clean technologies; the only 'waste' product from the combustion of hydrogen is pure water.
Jeremy Rifkin wrote in 2003 of the development of a hydrogen economy as a way of weaning the world off oil and avoiding growing international tension as oil supplies become scarce.

The hydrogen economy is theoretically feasible, but a number of technical difficulties will have be resolved first: such as significantly raising the efficiencies of electrolysers and fuel cells, finding ways to store huge quantities of hydrogen - hydrogen is very hard to compress to liquid form - and designing a car that will run a reasonable distance, say 400 miles, on a 'tank full' of hydrogen. There is also a public perception that hydrogen is unsafe (because of the hydrogen bomb and airship disasters, perhaps), though it was a significant component of the 'town gas' and 'coal gas' formerly used for cooking and for heating homes. Of course the fear can be alleviated by educating people (even at school age) in the production, handling and use of hydrogen with a sensible regard for safety - it is after all an inflammable gas (Fig. 2).

Figure 5.2: The Hydrogen Lab at Lews Castle College, UHI. It is used for training in the production, handling, and use of hydrogen. The facility is linked to an electrolyser and a range of renewable energy generation devices (March 2008).

Another difficulty shared with renewable energy generation is the huge cost of building up an infrastructure for production, storage, and distribution - all from scratch. All the basic components: fuel cells, electrolysers, and electronics to manage the load and for grid connectivity, are very, very expensive and beyond any sensible payback calculations. Nevertheless, pilot projects have been proposed and implemented. Of note is the PURE project on Unst in the Shetlands (Fig. 3) and the Hydrogen Park proposed by Comhairle nan Eilean Siar, the Western Isles Council. In Phase 2 of the project, the objective is to use energy from recycling to produce hydrogen to power vehicles.

Scotland is at the forefront in many of the developments in renewable energy and there are many opportunities in this field for individual employment and business development. The relevant trade organisation to contact or join is Scottish Renewables
http://www.scottishrenewables.com/]

The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers. https://www.oxfamamerica.org/static/media/files/oxfam-RAEL-energySSA-pt1.pdf

Figure 5.3: The PURE project converts the output from two 15 kW turbines to hydrogen, which is used to run a nearby business facility (https://pureenergycentre.com/).

Task 5.4

Electrolysers and fuel cells are only 60% efficient in practice. How does this compare with the use of fossil fuels (38% electricity generation efficiency)? Is this a fair comparison?

Notes

Combined cycle power generation

A **combined cycle power plant** uses a gas turbine to generate electricity with a conventional thermal generation in the first phase to produce electricity with an efficiency of about 38%. The waste heat is recovered and in the second part of the cycle is used to make steam and generate more energy using a steam turbine. This is not a 'loophole' in the laws of thermodynamics, rather the difference between the input and output temperature of the working fluid is made as large as possible to get close to the maximum efficiency allowed by the laws of thermodynamics.

The combined cycle can realise efficiencies of 59%, a substantial improvement. The remaining waste heat cannot be used to generate electricity but can be piped around and used for domestic and industrial space heating. By combining heat and power, 89% of the primary energy content of the fuel can be put to use.

Summary

In this section, we started looking at the economics of energy production and consumption. This activity will be taken further in the final section of the Unit. Energy produced from fossil fuels is likely to rise in price as the supply diminishes. Renewable energy has no continuous fuel cost but the initial set-up costs are high. The notion of payback time was introduced to be able to compare an upfront investment with the conventional way of paying for energy as it is used. It is found that wind energy is becoming competitive, particularly if used to power a heat pump for space heating. A heat pump moves heat from a cold region to a warmer region at a significantly lesser energy cost than generating the heat directly. The intermittency of renewable sources is still a big problem.