School of Engineering and Built Environment

Energy Resources, Generation and Utilisation

Module Code: M2H823551

Task Exercise No: 6

Tutor: Zeno Gaburro

Email: zgaburro@alueducation.com

Test Exercise No: 6

Table of Contents

Section 6: Alternative energy sources I

We have seen there are advantages in producing energy by renewable means, but what sort of renewable source is best (or what combination)? We will give a description of each category of energy source beginning in this section with wind, geothermal, biomass, and solar to get an idea of the energy potential of each source and future prospects.

Wind power

Though air is rather insubstantial - a cubic metre only weighs about 1.2 kg - air has a significant passive effect because there is so much of it. Whilst we are generally unaware of the fact, the entire weight of the atmosphere above us exerts the same pressure at ground level as would 10 m of water. Air is also capable of carrying energy by virtue of its motion, or kinetic energy. The wind speed in the UK will generally vary from 0-30 ms^{-1} (Table 6.1) and if one were to point a hoop of area 1 m^2 into the wind, the energy passing through the hoop each second varies with the cube of the wind speed, reaching 16.2 kJ when the wind speed is 30 ms^{-1}, equivalent to 16.2 kWh of energy each hour (Table 6.1). This is a significant quantity of 'free' energy that could potentially be harvested. A wind turbine is a device for extracting energy from the wind and will typically consist of blades that rotate with the wind. The motion produces electricity by driving a conventional electrical generator.

Table 6.1: The energy in wind. The first column is the Beaufort number. The entries shaded pink and blue are the wind speeds over which a typical wind turbine will operate.

	Wind	**Wind Speed (mph)**	**Wind Speed (ms^{-1})**	**Power in $1m^2$ (kW)**
0	calm	less than 1	less than 0.5	less than 0.00007
1	light air	1-3	0.5-1.4	0.00007-0.0016
2	slight breeze	4-7	1.5-3.2	0.002-0.019
3	gentle breeze	8-12	3.3-5.4	0.021-0.094
4	moderate breeze	13-18	5.5-8.0	0.1-0.3
5	fresh breeze	19-24	8.1-11.7	0.31-0.96
6	strong breeze	25-31	11.8-13.8	0.98-1.5
7	moderate gale	32-38	13.9-17.0	1.6-2.9
8	fresh gale	39-46	17.1-20.6	3.0-5.2
9	strong gale	47-54	20.7-24.1	5.3-8.4
10	whole gale	55-63	24.2-28.2	8.5-13.4
11	storm	64-75	28.3-33.5	13.6-22.5
12	hurricane	more than 75	more than 33.5	more than 22.5

A generator will typically extract 30-40% of the wind energy streaming through the area swept out by the blades. It is not possible to remove all the energy from the wind because it would then cease to flow. A turbine actually works by moving a tube of air into a larger cone as shown in Fig. 6.1, and the process has a maximum efficiency of 59%, the Betz limit.

There are many different designs of turbine: horizontal axis, vertical axis, single blade, 2-blade, 3-blade and so on. The most common type is a 3-blade horizontal axis device (which will chase the wind by changing orientation). The blades act as aerofoils (and are not simply pushed by the wind) to allow the blade tip to move faster than the wind speed and extract more energy.

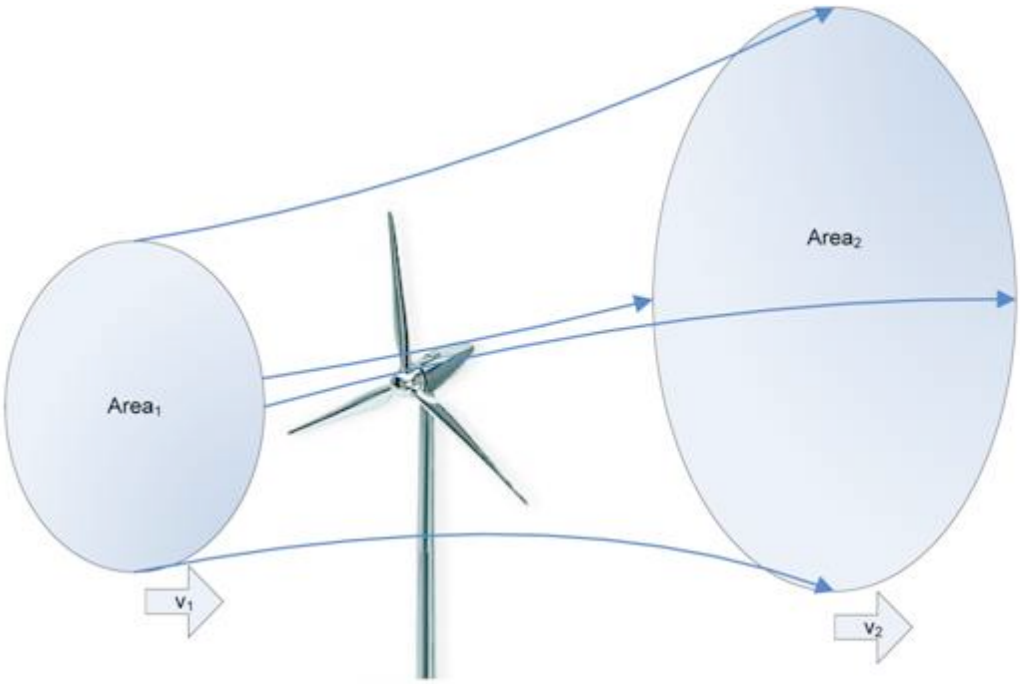

Figure 6.1: A turbine moves an area of incident air A_1 at velocity V_1 to a larger area. Conservation of mass requires that $V_1A_1 = V_2A_2$.

Wind is unpredictable and there is not much energy when the wind speed is low. Large turbines are generally economically viable, but small devices tend to be very costly (£5 k per kWh) and perform less well.

There is an estimated commercially viable 72 TW of wind power in the world - 4 times the energy demand.

Choosing a site either onshore or offshore is a major difficulty because of impact and potential environmental damage and this is a major barrier to the widespread deployment of wind turbines. It is also necessary to develop grid links to transfer energy from the often remote points of generation to market. Finally there is the issue of who 'owns' the wind energy and if there should be any payment for it.

Task 6.1

If the mean wind speed over a region is 8.0 ms^{-1}, how much power would a 3.6 MW Siemens wind turbine generate in a year?

Sketch the typical power curve of the turbine. Why is this calculation not absolutely precise?

What are ROCs?

If the turbine costs £3.0 m to manufacture and install, what is the payback time at the current wholesale price of electricity (£55 per MWh), ROCs and tax incentives?

Geothermal energy

Geothermal energy refers to energy stored in the ground. This can either be energy that was absorbed from the Sun, or energy produced deep within the Earth arising from natural radioactive decay.

The core of the Earth is very hot, about 4,000 ^{o}C, and the mantle is 3,000 ^{o}C in some places. Some of this heat conducts to the surface through the crust, and because heat will only travel along a temperature gradient, we find that the temperature of the crust gradually increases with depth by 25-30 ^{o}C per kilometre.

One way of extracting this energy is by drilling two holes side by side, injecting water down one well and recovering the heated water from the second well. This process can capture a great deal of heat because drilling depths exceeding 10 km are routinely achieved during oil exploration.

Drilling is not always necessary. At points within the Earth, the temperature is high enough for rock to melt. The top layer of the mantle is pressurised molten magma that can find its way to the surface, or reach near to the surface, through weaknesses in the crust. Faults occur where the continental plates meet (major plate boundaries where earthquakes and volcanoes are concentrated) and the energy seeping to the surface in these places can be significant. Iceland for example produces 26% of its electricity from geothermal energy

Other countries far from geological fault lines, such as the UK, do have regions below ground where the crust is significantly hotter, but there are no visible clues from surface observation where these energy reservoirs might be. These energy pools are called **aquifers** if underground water is present. The geothermal resource is not good in Scotland and it is generally not worthwhile sinking deep boreholes unless very localised pockets of energy have been identified.

Though the temperature above ground varies through the day and throughout the year, the Earth's crust is a huge storage system that maintains a temperature 5 metres below the surface equal to the mean annual temperature above ground. In Scotland, the average temperature is between 8 and 13 ^{o}C, dependent on location. By sinking pipes into the ground, this can act as the nearly constant reference (or **heatsink**) of a heat pump. Moving heat with a heat pump is up to four times as efficient as generating the heat electrically or by combustion. If a heat pump were used to raise the temperature of a building by heating circulating water to 50 (C, it would not be unusual to achieve an efficiency (or COP rating) of 3 in Scotland. This would mean a reduction in energy use (and cost) of two-thirds, particularly significant because 59% of the energy used in Scotland is for heating.

The difficulty is that the area under ground in contact with the pipes must be large enough that the source is not depleted. Heat should be removed at the rate it flows back in from the surroundings. This generally requires that the reference loop should ideally be in contact with flowing water, eg a stream could be used for the reference (open loop system).
The worldwide geothermal energy resource is thought to be a minimum of 138 GW.

Task 6. 2

How large should the reference coils of a ground source heat pump be and how deep do the pipes have to be buried?

HINT: Try and find out how much heat can be extracted from 50 m of pipe in dry soil, wet soil, and rock.

Biomass

Biomass or biomatter is living or dead, but non-fossilised, organic material. Organic matter is the product of photosynthesis and organic compounds and binds carbon dioxide that has been removed from the air. Encouraging the growth of trees and vegetation is a form of **carbon sequestration**, a method of removing carbon dioxide from the atmosphere, which works so long as the plant matter is not allowed to decay - the decay process releases carbon dioxide back into the atmosphere. **Carbon offsetting** is when trees or long-lived plants are deliberately grown to remove from the atmosphere the same quantity of carbon released by other processes. Forests are natural carbon sinks, but become less effective as the forests mature. The Forestry Commission's response to The Stern Review [https://en.wikipedia.org/wiki/Stern_Review] outlines the role of the UK Forestry Commission in fighting climate change.

Though the act of growing plants and trees in an annual cycle for burning or to make synthetic fuel does not remove carbon from the atmosphere, the process is nevertheless carbon neutral because the quantity of carbon dioxide released by burning is the same as that removed from the air during the growing season. Biomass production for heating, transportation and electricity generation is therefore a sustainable method of energy use.

Table 6.2 shows the amount of energy that will typically be trapped in organic material each year for different ecosystems. Less than 1% of the available solar energy is trapped. The process is therefore very inefficient.

Table 6.2: The amount of energy trapped each year by different types of ecosystem. The mean incident solar energy is 342 Wm^{-2}, and the energy content of 1 kg of carbon is 32.7 MJ. (Basic data sourced from en.wikipedia.org/wiki/Biomass)

	kg C m^{-2} yr^{-1}	**Energy (MJ)**	**Annual Solar Energy Incident (MJ)**	**Efficiency (%)**
Tropical forest	2.2	71.9	10773	0.67
Cultivated land	0.65	21.3	10773	0.20
Swamp and marsh	2	65.4	10773	0.61
Lakes and streams	0.25	8.2	10773	0.08
Ocean	0.12	3.9	10773	0.04

Remembering that a hectare is an area of 100 m x 100 m, we would expect a crop grown for energy production to produce about 100 GJ of energy per annum, the equivalent to 2.4 toe per hectare. The locked energy can be recovered by incineration, but in some plants a significant fraction of the stored energy is conveniently in the form of vegetable oil that can instead be extracted and used as transport fuel. The amount of oil produced from a variety of crops is shown in Table 6.3, and it is clear some plants deliver significantly above the average. Other plants produce sugar instead of oil, but this can be converted to ethanol and also used as fuel.
Table 6.3 Expected return from crops used to produce biodiesel [http://www.energyjustice.net/biodiesel]

	Tonnes of oil per hectare
rapeseed	1.0
olives	1.0
castor beans	1.2
pecan nuts	1.5
jojoba	1.5
jatropha	1.6
macadamia nuts	1.9
brazil nuts	2.0
avocado	2.2
coconut	2.3
oil palm	5.0

The problem is that Scotland consumes the energy equivalent of 20 million tonnes of oil a year, and of the crops in Table 3 only rapeseed grows well in Scotland. An area of 200,000 km^2 would need to be set aside to produce enough oil. This amount of land is just not available. There is already concern over how even a limited change of land use to grow crops for energy generation may actually be environmentally damaging, in conflict with the European biofuels directive (2003/30/EC) which required that 5.75% of road fuel be derived from bio sources by 2010. Whilst biomass can contribute as one of a suite of measures, it can never be the entire solution to the carbon problem.
It is also possible to use farm waste (including animal matter) for energy production, but in the UK, fast-growing trees with annual coppicing is the most common way of producing combustible biomatter.

Another common option is incinerating garbage, which has the added benefit that less rubbish needs to be buried in landfills.

Task 6.3

What is the advantage of taking organic waste material and creating biogas rather than simply burying the waste?

Defra paper on treatment of municipal waste

[https://www.gov.uk/government/publications/mechanical-biological-treatment-of-municipal-solid-waste]

Sub-Saharan Water and Waste and Resources

[http://documents.worldbank.org/curated/en/221391468009994131/pdf/NonAsciiFileName0.pdf]

Solar energy

The Sun emits energy over a wide range of frequencies. The **mean integrated energy** incident on a square metre of the Earth's surface, the **irradiance**, is 342 W (though the figure is much lower in Scotland).

Solar **photovoltaic devices** (**PV**) consist of a dense array of semiconductor diodes that can convert the incident solar energy over a wide frequency range to electricity. It is possible to extract 10% of the incident energy (much better than the ~1% that plants convert to biomass), and it is anticipated that with future breakthroughs in material development, this will rise to 30%. However, PV is very expensive and is quite uneconomic to install in places with a limited amount of direct sunlight. It is useful however for charging portable equipment, but the energy in sunlight does not need to be converted to electricity; a solar hot water system is a relatively cheap way of trapping solar energy and storing this energy as heat. It can then be used as required for showers, baths, cooking, and so on. Installation is a standard plumbing exercise with only an additional heating coil needed in the tank or cylinder (though there may also be an automated control system for the pumps and valves). Fig. 6.3 shows a typical solar hot-water system. The panel is placed on the roof facing south and can be fitted like a roof window (www.carbon-neutralhome.co.uk/hotwater.html). There are two types of panel: a flat collector is basically a metal plate which captures heat from the sun and transfers this to flowing water; a vacuum collector uses glass tubes to convert light to heat (the greenhouse effect) and is therefore effective on overcast days. However, vacuum collectors are much more expensive.

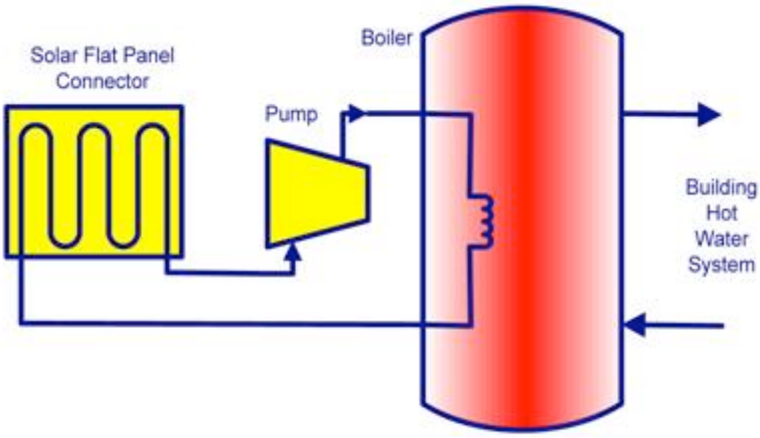

Figure 6.3: Typical solar hot-water collection system; easy to integrate into an existing heating system

Solar collectors available commercially range in size from 2 m^2 to 6 m^2. It is considered that 60-70% of the hot water in the home can be supplied in this way. What about the other 30-40%? Unfortunately, in winter when heat is most needed, there is little solar energy available. Panels cost about £300 per m^2 for flat collectors and up to £1000 per m^2 for evacuated tubes, and the additional pipes, pump, storage etc can cost £1,000-£2,000. Installation costs should be added to this. In all, a new flat collector system will cost £2,000-£3,000 and an evacuated system will cost £3,500-£5,000, though there may be grants or tax breaks available. You should be aware that the primary objective is to produce hot water and not to run the central heating system. Solar combisystems are available that can also provide space heating replacing 15%-25% of the total energy used for all heating in the home. Although there is little accurate information available, the payback time in Scotland is considered to be 10-15 years.

Passive solar heating is a lower cost alternative. This is where the building is designed to use the energy reaching the building in the most effective way possible. This might mean taking care with orientation and careful use of building materials. Glass could be installed in optimal places to capture and trap heat.

Task 6.4

How is the energy output of a PV system described? Is this kind of description effective (http://www.nef.org.uk/greencompany/active-pv-basics.htm)?

Notes

Types of energy

In simple terms, the potential energy of a body is the energy derived from position, whilst kinetic energy is energy associated with motion. Potential and kinetic energy can appear in many guises: Chemical energy is energy of molecular binding and nuclear energy is associated with the transmutation of elements (or isotopes). Radiant energy is energy propagation through space as either electromagnetic or gravitational radiation. Electrical energy is the potential energy of separated charged particles.
Energy is always conserved; it cannot be created or destroyed. However, the form of energy can readily change. For example, as hydrogen nuclei combine in the Sun to produce helium, the nuclear energy is converted to radiation. When the radiation reaches the Earth, it is absorbed by molecules whose kinetic energy increases. The increased energy manifests itself as heat.

Wind turbine power curve
The blue line on the graph in Figure 6.4 is the energy each second crossing an area of 1 m^2 perpendicular to the wind direction as it varies with wind speed. The energy increases in proportion to the cube of the velocity, and results in an enormous force when the wind speed reaches 30 m s^{-1} (67 mph).

However, a machine at a fixed location that continuously extracts energy from the wind is constrained by the Betz limit of 59%. This is shown as the red curve.

The **Betz limit** is a theoretical limit and a real machine could only achieve this if there were no energy losses, but energy is lost because of friction in the bearings and gearbox, less than perfect mechanical to electrical conversion efficiencies, and losses in the cables and power electronics. A real machine will in practice only achieve 40% energy conversion efficiency. This is the green line on the graph.

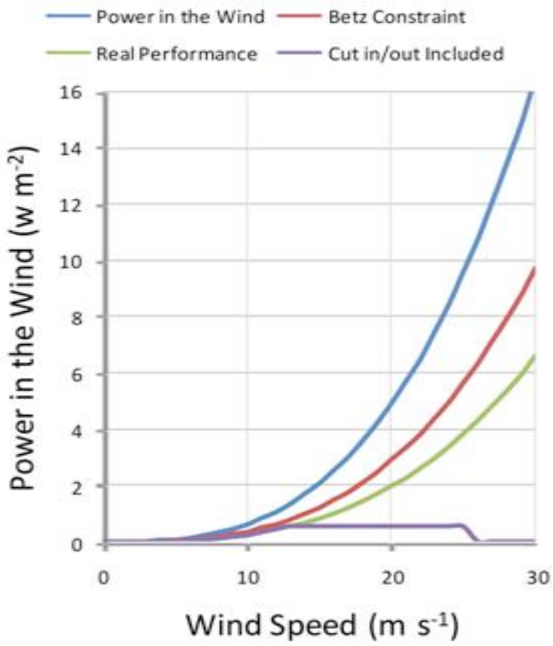

Figure 6.4 Wind turbine power curve

However real turbines have further limitations. The blades do not begin to turn until the **cut-in wind speed** is reached (about 3.5 m s^{-1}). Once the rated output power is reached (around 13 m s^{-1}), this is maintained as the wind speed rises by hydraulically feathering the blades out of wind, until eventually, to prevent damage, the blades are turned out of the wind (**cut-out speed**). The real output performance (shown in purple) is the **turbine power curve**.

Note how little of the energy available at high wind speeds is actually converted to electricity. Turbine major parts are labelled in Figure 5.

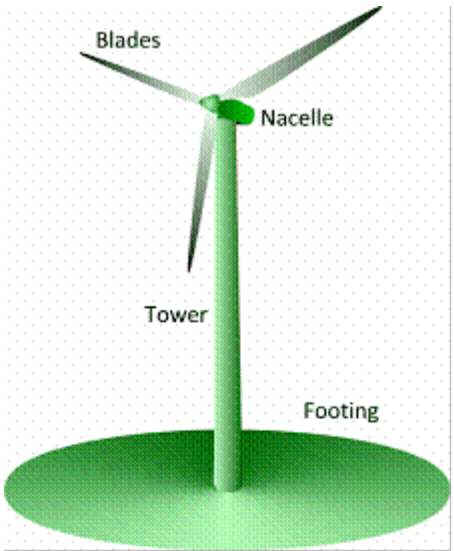

Figure 6.5: Wind turbine parts