Can renewable energy sources power the world?

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Can renewable energy sources power the world?

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Introduction and guidance

Introduction and guidance

Welcome to this free badged open course, *Can renewable energy sources power the world?*.

The course is made up of eight weeks, with approximately three hours of study in each. It is suggested that you do one session per week, but you can work through the course at your own pace, so if you have more time one week there is no problem with pushing on to complete another session.

The eight weeks cover the following:

1. Introduction to renewable energy
2. Solar energy for heating and daylighting
3. Solar photovoltaics
4. Bioenergy
5. Hydroelectrivity
6. Wind energy
7. Wave energy
8. Towards a renewable future.

Moving around the course

In the ‘Summary’ at the end of each session, you can find a link to the next one. If at any time you want to return to the start of the course, click on ‘Full course description’. From here you can navigate to any part of the course. Alternatively, use the session links at the top of every page of the course.

It's also good practice, if you access a link from within a course page (including links to the quizzes), to open it in a new window or tab. That way you can easily return to where you've come from without having to use the back button on your browser.

What is a badged course?

While studying *Can renewable energy sources power the world?* you have the option to work towards gaining a digital badge.

Badged courses are a key part of The Open University's mission *to promote the educational well-being of the community*. The courses also provide another way of helping you to progress from informal to formal learning.

To complete a course you need to be able to find about 24 hours of study time, over a period of about 8 weeks. However, it is possible to study them at any time, and at a pace to suit you.

Badged courses are all available on The Open University's OpenLearn website and do not cost anything to study. They differ from Open University courses because you do not receive support from a tutor. But you do get useful feedback from the interactive quizzes.

What is a badge?

Digital badges are a new way of demonstrating online that you have gained a skill. Schools, colleges and universities are working with employers and other organisations to develop open badges that help learners gain recognition for their skills, and support employers to identify the right candidate for a job.

Badges demonstrate your work and achievement on the course. You can share your achievement with friends, family and employers, and on social media. Badges are a great motivation, helping you to reach the end of the course. Gaining a badge often boosts confidence in the skills and abilities that underpin successful study. So, completing this course should encourage you to think about taking other courses.

How to get a badge

Getting a badge is straightforward! Here's what you have to do:

- read each session of the course

- score 50% or more in the two badge quizzes in Session 4 and Session 8.

For all the quizzes, you can have three attempts at most of the questions (for true or false type questions you usually only get one attempt). If you get the answer right first time you will get more marks than for a correct answer the second or third time. Therefore, please be aware that for the two badge quizzes it is possible to get all the questions right but not score 50% and be eligible for the badge on that attempt. If one of your answers is incorrect you will often receive helpful feedback and suggestions about how to work out the correct answer.

For the badge quizzes, if you're not successful in getting 50% the first time, after 24 hours you can attempt the whole quiz, and come back as many times as you like.

We hope that as many people as possible will gain an Open University badge – so you should see getting a badge as an opportunity to reflect on what you have learned rather than as a test.

If you need more guidance on getting a badge and what you can do with it, take a look at the OpenLearn FAQs. When you gain your badge you will receive an email to notify you and you will be able to view and manage all your badges in My OpenLearn within 24 hours of completing the criteria to gain a badge.

Get started with Week 1.

Week 1: Introducing renewable energy

Learning outcomes

After completing this course, you will:

- understand at an introductory level the basic physical principles underlying the operation of renewable energy systems
- understand the key role of the Sun as the main source of renewable energy
- be aware of the essential characteristics of energy demand and supply in the UK and the world
- be aware of the principal renewable energy technologies and their main characteristics
- be aware of some of the factors that are working to promote the deployment of renewable energies and those acting to inhibit it.

Introduction

In this first week you will look at the environmental concerns that have caused the rise in interest in renewable energy. You will also explore the wide variety of renewable energy sources, along with some energy concepts and definitions to help you understand the subject.

You will investigate the Sun, which powers most of the renewable energy sources, then move on to discuss energy supply and demand, in the world and the UK, and then look briefly at the problem of climate change.

Current European and UK targets for increasing the share of renewables in coming decades will also be covered.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- explain the concept of sustainability and how this relates to energy systems and primary energy sources
- understand the key role of the sun as the main source of renewable energy
- understand the concepts of energy, power, the difference between them and the essential units used to describe them.

1 Defining sustainable and renewable energy

Concerns about the ‘sustainability’ of humanity’s use of fossil and nuclear fuels have been a major catalyst of renewed interest in the renewable energy sources in recent decades. A sustainable energy source can be defined as one that:

- is not substantially depleted by continued use
- does not produce significant pollution or other environmental problems
- does not cause health hazards or social injustices.

In practice, few energy sources come close to these ideals, but *renewable energy sources* are generally more sustainable than fossil or nuclear fuels: they are essentially inexhaustible, and their use usually involves fewer health hazards and much lower emissions of greenhouse gases and other pollutants.

So, where do renewable energies come from, and why the renewed interest?

1.1 Renewed interest in renewables

Renewable energy sources are derived principally from the enormous power radiated by the Sun.

Solar power, both in the form of direct solar radiation and in indirect forms such as bioenergy, water or wind power, was the energy source upon which early human societies were based. When our ancestors first used fire fuelled by burning wood, they were harnessing the power of photosynthesis, the solar-driven process by which plants materials such as wood are created from water and atmospheric carbon dioxide. Societies went on to develop ways of harnessing the movements of water and wind, both caused by solar heating of the oceans and atmosphere respectively, to grind corn, irrigate crops and propel ships. As civilizations became more sophisticated, architects began to design buildings to take advantage of the Sun's energy by enhancing their natural use of its heat and light, so reducing the need for artificial sources of warmth and illumination.

Technologies for harnessing the power of the Sun, firewood, water and wind continued to improve right up to the early years of the Industrial Revolution, but by then, the advantages of coal, the first of the *fossil fuels* to be exploited on a large scale, had become apparent. These highly concentrated energy sources soon displaced wood, wind and water in the homes, industries and transport systems of the industrial nations. Today the fossil fuel trio of coal, oil and natural gas provides around 80% of the world's energy.

Concerns about the adverse environmental and social consequences of fossil fuel use have been voiced intermittently for several centuries, but it was not until the 1970s that humanity began to take more seriously the prospect of fossil fuels ‘running out’, and that their continued use could be affecting the planet’s natural ecosystems and global climate. The development of nuclear energy following the Second World War raised hopes of a cheap, plentiful and clean alternative to fossil fuels. But nuclear power’s contribution to electricity supply has in some countries stalled in recent years, due to concerns about safety, cost, waste disposal and weapons proliferation. In other nations nuclear power supplies continue to expand.

These concerns have been a major catalyst of renewed interest in the renewable energy sources in recent decades, but before going on to introduce the ‘renewables’ in more detail, let’s start by introducing some energy definitions and concepts.

2 Energy definitions and concepts

If someone asked you to define energy, what would you say?

The word *energy* is derived from the Greek *en* (in) and *ergon* (work). **Energy is defined as 'the capacity to *do work*'** – that is, the **capacity** to move an object against a resisting force. The scientific unit of energy is the **joule**.

The concept of energy reveals the common features in processes as diverse as burning fuels, propelling machines and charging batteries. These and other processes can be described in terms of diverse *forms* of energy, including:

- thermal energy (heat)
- chemical energy (in fuels or batteries)
- kinetic energy (in moving substances)
- electrical energy
- gravitational energy
- nuclear energy

In everyday language, the word 'power' is often used as a synonym for 'energy', but this is not strictly correct.

Power is the *rate* at which energy is converted from one form to another or transmitted from one place to another. The scientific unit of power is the **watt**.

Renewable energy can take a variety of these forms, and can be defined as:

> energy obtained from the continuous or repetitive currents of energy recurring in the natural environment
>
> (Twidell and Weir, 1986)

or as

> energy flows which are replenished at the same rate as they are 'used'
>
> (Sorensen, 2000)

Now you'll look at some frequently used units of energy and power that you'll come across regularly during this course.

2.1 Units of energy and power

A host of different units are used to describe energy and power, which can seem a bit confusing. But the following Table 1, where we have listed and described some of the most frequently used units, should clarify the meaning of the various terms.

Table 1 Common units of energy and power

Energy		**Power**	
Name	**Description**	**Name**	**Description**
Joule (J)	Main scientific unit of energy	**Watt (W)**	Main scientific unit of power – defined as 1 joule per second
Kilojoule (KJ)	Equal to 1000 (10^3) joules	**Milliwatt (mW)**	Equal to 1000th of a watt (10^{-3})
Megajoule (MJ)	Equal to 1 million (10^6) joules	**Kilowatt (kW)**	Equal to 1000 (10^3) watts
Gigajoule (GJ)	Equal to 1 billion (10^9) joule	**Megawatt (MW)**	Equal to 1 million (10^6) watts
Exajoule (EJ)	Equal to 1 quintillion (10^{18}) joules	**Gigawatt (GW)**	Equal to 1 billion (10^9) watts
Kilowatt-hour (kWh)	The amount of energy produced by a power of 1 Kilowatt (1 kW) in one hour		
Megawatt-hour (MWh)	The amount of energy produced by a power of 1 Megawatt (1 MW) in one hour		
Gigawatt-hour (GWh)	The amount of energy produced by a power of 1 Gigawatt (1 GW) in one hour		

As you can see from Table 1, most of the terms are used to describe larger quantities of the basic units – joules or watts.

2.2 Efficiency and capacity factor

When energy is converted from one to another, what comes out is never as much as what goes in. The ratio (usually expressed as a percentage) is called the efficiency of the process:

percentage efficiency = (energy output/energy input) x100

Some types of energy conversion can be really efficient, for example up to 90% in a water turbine; others very low - around 10-20% in a typical internal combustion engine.

If you're trying to assess an energy generator's productivity in practice, one useful measure is its *capacity factor* (CF):

capacity factor = actual energy output over time / maximum possible output

The period of time can be a year, a month, a week or an hour. The units for the output quantities can be kWh, MWh, GWh, etc., and the capacity factor can be expressed as either a fraction or a percentage. The time period to which the capacity factor relates (a year, a month, a week etc.) should be stated.

Have a look at a couple of examples:

Activity 1

What would be the annual capacity factor of a 1 MW plant running constantly at a full rated capacity for one year?

View answer - Activity 1

Activity 2

A 1 MW wind turbine generated 3000 MWh last year, so what would its annual capacity factor be?

View answer - Activity 2

3 Renewable energy from the Sun

Have a look at Figure 1, which summarises the origins and magnitudes of the Earth’s renewable energy sources. Clearly, their principal source is solar radiation.

The Sun radiates huge quantities of energy into the surrounding space, and the tiny fraction intercepted by the Earth’s atmosphere 150 million kilometres (km) away is nonetheless around 5.4 million Exajoules (EJ) per year. About one third of this is radiated back to space, but this still leaves around 3.8 million EJ per year available for use on Earth, which is equivalent to about 8,000 times humanity’s present rate of use of fossil and nuclear fuels.

The Sun’s radiation comes from nuclear fusion reactions between hydrogen atoms in its very hot interior. However, this very high temperature is not due to nuclear fusion. Rather, the radiation pressure from nuclear fusion prevents the Sun from getting hotter! The Sun should continue to radiate in this way for another five billion years.

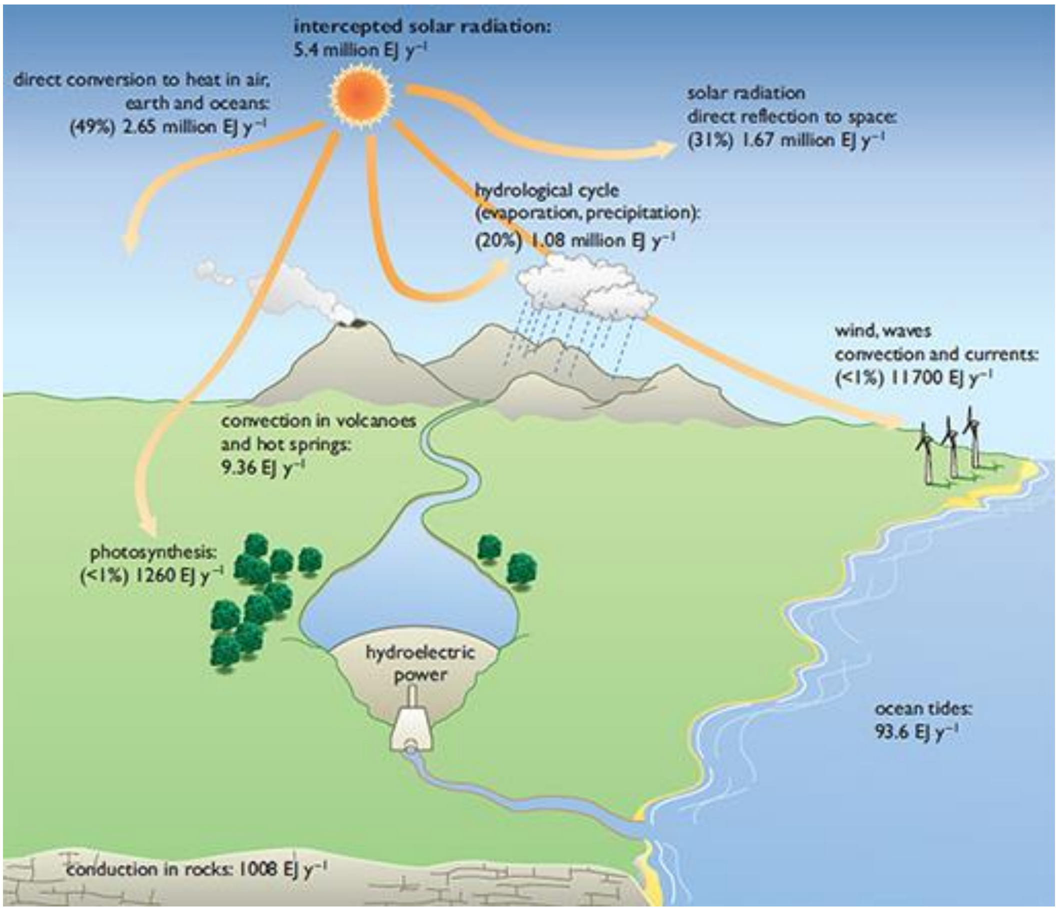

Figure 1 The various forms of renewable energy available on Earth depend primarily on intercepted solar radiation, which totals some 5.4 million EJ per year

Two non-solar renewable energy sources are also shown in Figure 1. One is the motion of the ocean tides, principally driven by the gravitational pull of the Moon, the source of *tidal energy*. The other is *geothermal energy* from the Earth’s interior, which manifests itself in heat emerging from volcanoes and hot springs, and in heat from hot rocks.

4 Energy supply and demand: world and UK

The energy used by a final consumer is usually the result of a series of energy conversions. For example, as you can see from Figure 2, energy from burning coal may be converted in a power station to electricity, which is then distributed to households and used for, say, lighting.

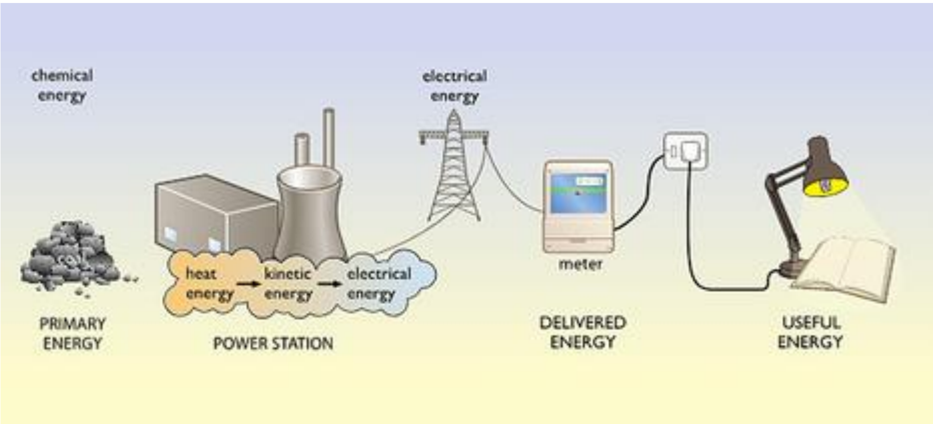

Figure 2 An example of primary, delivered and useful energy

The energy released when the coal is burned is called the *primary* energy required for that use. The amount of electricity reaching the consumer, after conversion losses in the power station and transmission losses in the electricity grid, is the *delivered* energy (sometimes called *final energy)*. After some losses in the local wires and light bulb, a quantity called the *useful* energy emerges as light.

Let's now have a brief look at the world's energy supplies.

4.1 World energy supplies

World total annual consumption of all forms of primary energy increased more than tenfold during the twentieth century. As Figure 3 shows, by the year 2016 it had reached an estimated 550 Exajoules, equivalent to the energy content of some 13.2 billion tonnes of oil.

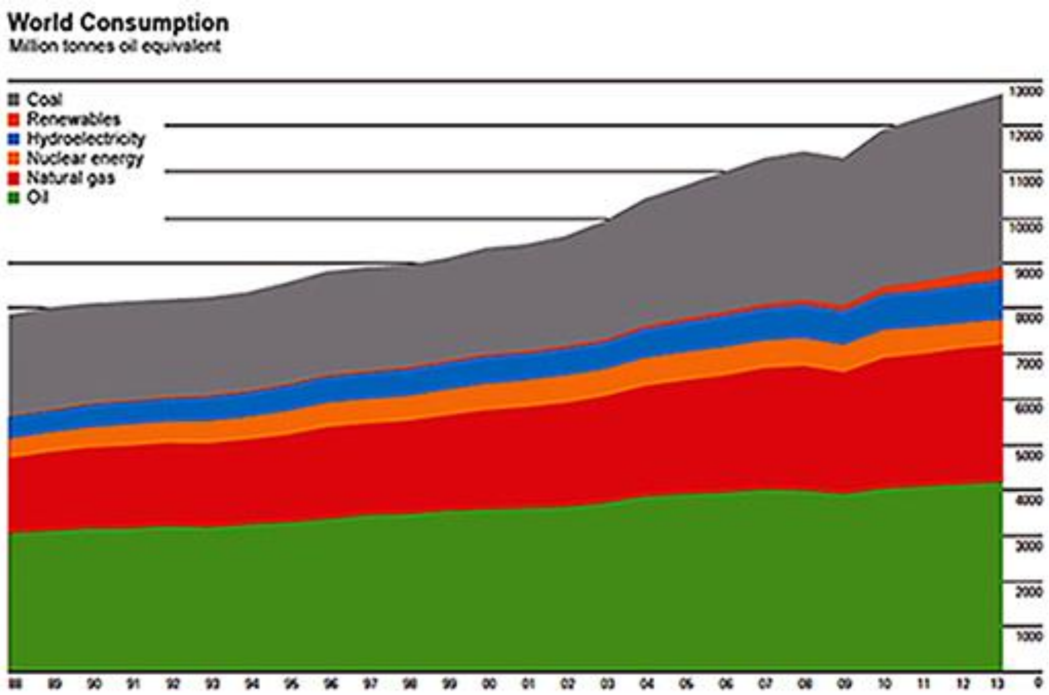

Figure 3 World primary energy consumption, 1988 to 2016. Source, BP, 2017. One million tonnes of oil is equivalent to c. 42 Petajoules.

Fossil fuels provided some four-fifths of the total. The world population in 2016 is some 7.5 billion, so the annual average energy consumption per person was about 74 GJ, equivalent to the energy content of approximately 5.3 litres of oil every day for every man, woman and child.

Activity 3

Do you think that there are differences in annual consumption rates depending on location in the world?

View answer - Activity 3

How much do renewables contribute to world energy supplies? As Figure 4 shows, traditional biomass, hydro power and a range of other renewable sources contributed an estimated 19% of the world’s final energy consumption in 2015.

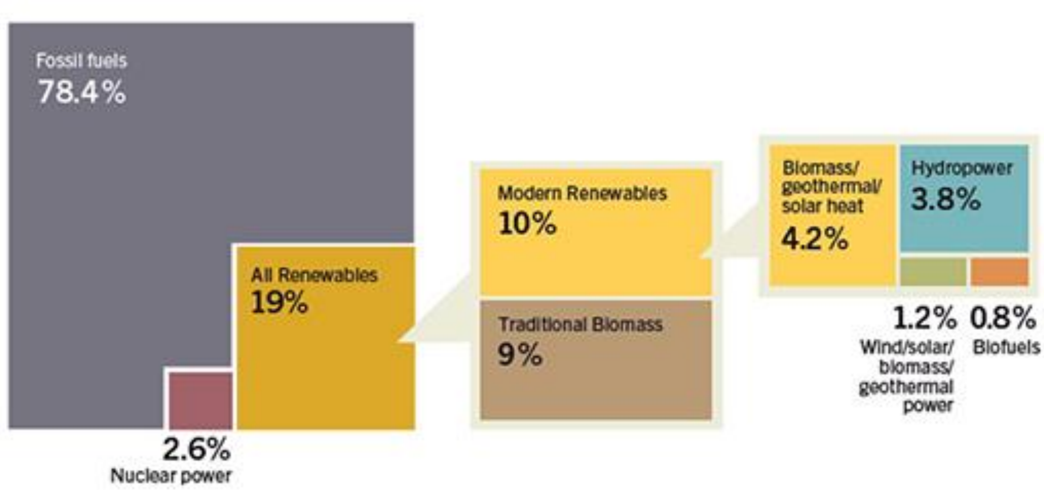

Figure 4 Chart showing the estimated percentage share of various renewable energy sources in supplying the world’s final energy demand in 2015. (Source, REN21, 2017)

The 19% share of renewables shown in Figure 5 differs from the smaller share that can be estimated from Figure 3 (adding hydro and renewables), which shows a share of around 10%. This is because primary energy includes a great deal of energy wastage (mainly waste heat). Also the BP data used in Figure 3 do not include energy from 'traditional' biomass, as this is not normally traded.

4.2 Energy supply and demand in the UK

In the UK, energy demand is categorised into four main sectors:

- domestic
- services (i.e. commercial and institutional)
- industry
- transport.

As Figure 5 shows, almost one third of UK primary energy is lost in the process of conversion and delivery – most of it in the form of 'waste' heat from power stations. And even when energy has been delivered to customers in the various sectors, it is often used very wastefully.

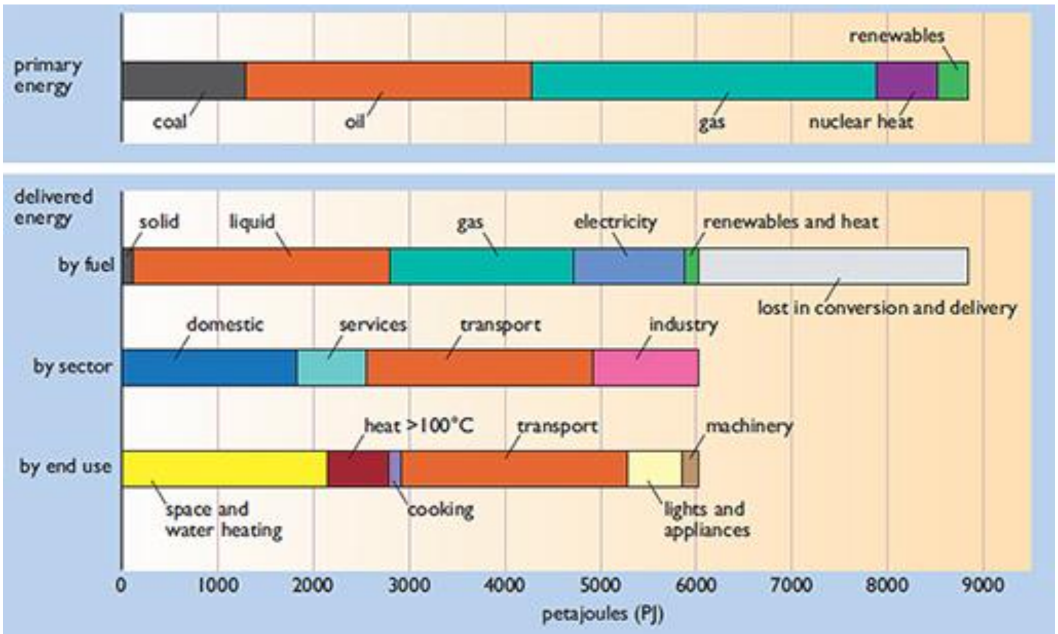

Figure 5 UK primary and delivered energy use in 2009 (sources: DECC, 2013, DECC, 2014)

If you look at Figure 6 you'll see that the contribution of a variety of renewables in 2013 to *primary energy* supply in the UK was quite small, just over 5%. This can be calculated by multiplying the 17,300 thousand tonnes of oil equivalent (toe) by 42 to get Petajoules (PJ) = 727 PJ, which is 5.2% of total UK primary energy.

However, the percentage contribution of renewables to UK electricity supplies in 2016 was somewhat larger, at nearly 15%, as you can see from Figure 7.

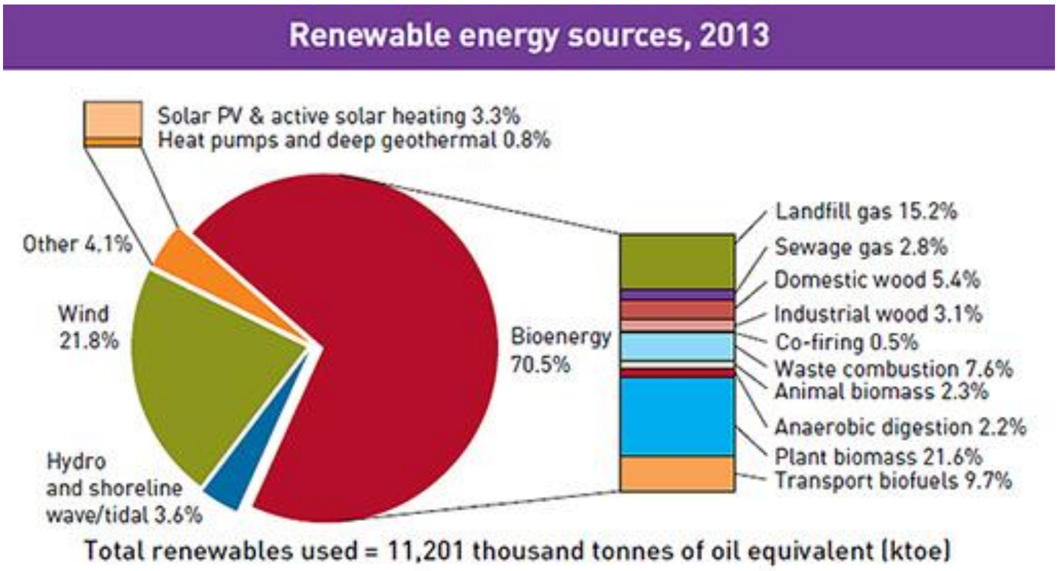

Figure 6 Primary energy contributions from renewable energy sources in the UK, 2016 (source DECC, 2017)

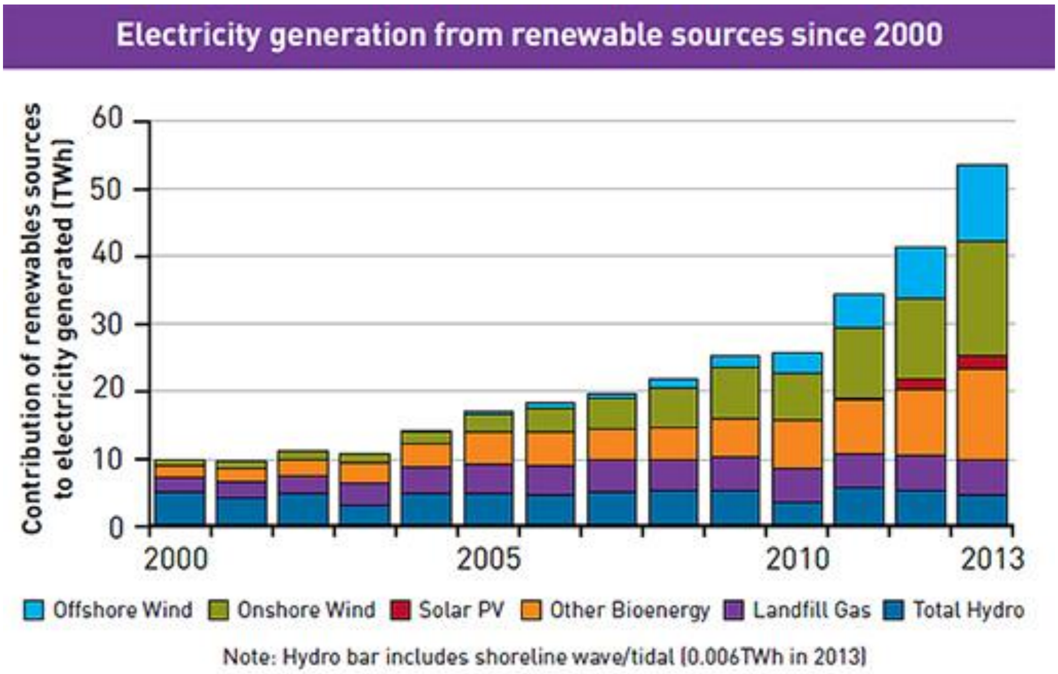

Figure 7 Growth in electricity generation from renewable sources in the UK 2000-2013. In 2016 renewables contributed almost 15% of UK electricity (source: DECC 2017)

The UK Government aims to increase to 15% the contribution of renewable energy to gross final consumption by 2020, in accordance with European Union agreements.

5 Fossil fuels, greenhouse gases and climate change

Society's current use of fossil fuels has many adverse consequences. Here we'll concentrate on their emissions of greenhouse gases that contribute to global climate change.

As you can see from Figure 98, humanity's emissions of carbon dioxide (CO_2) from these fuels have increased enormously since 1850. There have also been significant additional contributions from emissions of methane and other greenhouse gases.

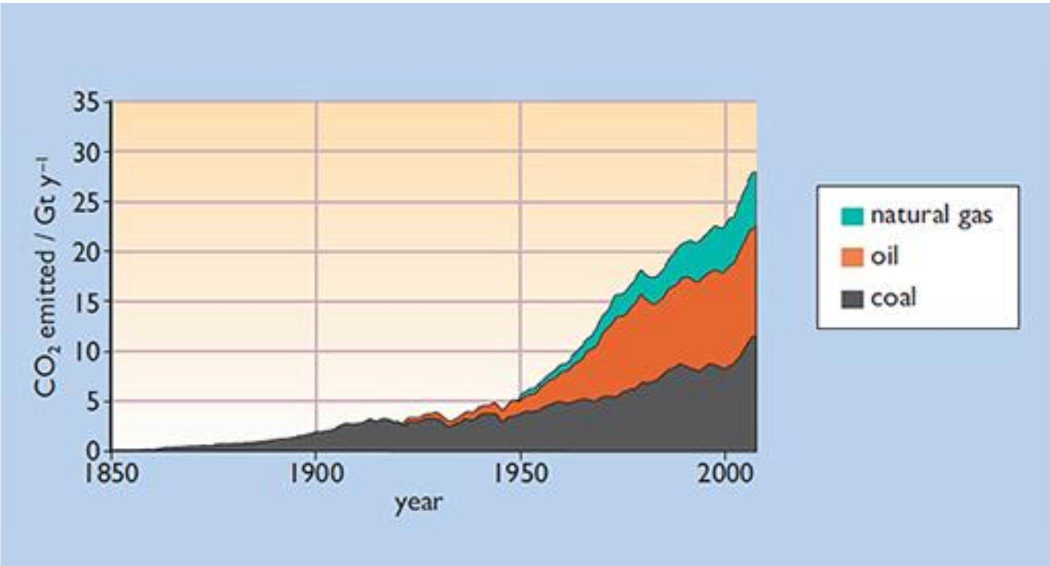

Figure 8 CO2 emissions from the burning of fossil fuels 1850–2009 (sources: Boden et al., 2010; IEA, 2010b; BP, 2010)

So what is the chain of events that cause climate change on a global level?

5.1 What are the causes of climate change?

The surface temperature of the Earth establishes itself at an equilibrium level where the incoming radiative power energy from the Sun balances the outgoing reflected amd re-radiated power from the atmosphere and surface, as we will discuss in more detail later in the course.

If the Earth had no atmosphere, its surface temperature would be minus 18 °C, but its atmosphere includes ‘greenhouse gases’. These gases absorb some of the re-radiated infra-red energy, causing the Earth’s mean surface temperature to rise to about 15 °C – suitable for the wide variety of life forms that we have on our planet.

Activity 4

What are principal greenhouse gases?

View answer - Activity 4

Since the Industrial Revolution human activities have been adding extra greenhouse gases to the atmosphere, with the principal contributor being carbon dioxide (CO_2) from the combustion of fossil fuels.

So, what will happen if this continues?

Climate scientists estimate (IPCC, 2007a) that these human-induced emissions caused a rise in the Earth's global mean surface temperature of approximately 0.7 °C between 1950 and 2005 (Figure 10). If emissions are not curbed they estimate that the temperature is likely to rise by between 1.4 and 5.8 °C by the end of the twenty-first century.

Such rises would increase the frequency of climatic extremes – floods or droughts – causing serious disruptions to agriculture and natural ecosystems. Thermal expansion of the world's oceans could also mean that sea levels would rise by around 0.5 m by the end of the century, inundating some low-lying areas. And beyond 2100, or perhaps before, much greater sea level rises could occur if major Antarctic ice sheets were to melt (Independent, 2017).

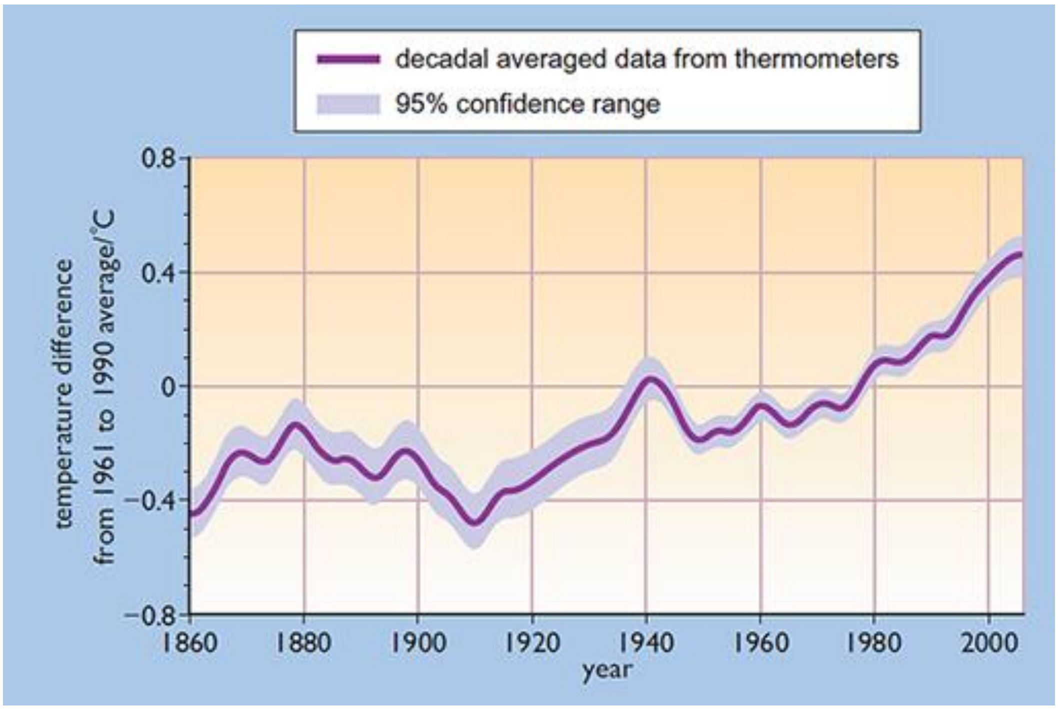

Figure 9 Observed changes in global average surface temperature 1860–2005 (source: IPCC, 2007b)

The threat of these global climate changes is one of the main reasons why there is a growing consensus on the need to reduce greenhouse gas emissions.

So what should we do to reduce emissions?

Climate change experts advise that global mean temperature rises by 2050 should not exceed 2°C above pre-industrial levels, and that to achieve this global carbon emissions will need to be reduced by approximately 80%.

This implies that global CO_2 emissions need to peak almost immediately and then fall sharply over the course of the rest of this century (Allen et al., 2009). Emission reductions on this scale will inevitably involve a switch to low- or zero-carbon energy sources such as renewables.

6 Overview of renewable energy sources

All the renewable energy sources will be covered in more detail over the coming weeks of the course, but here’s a short introduction to the main types, starting with solar derived forms.

Direct solar forms

Solar radiation can be converted into useful energy directly, using various technologies. Absorbed in solar ‘collectors’, it can provide hot water for washing or space heating. Buildings can also be designed with ‘passive solar’ features that enhance the Sun’s contribution to their space heating and lighting requirements.

The Sun’s rays can also be concentrated by mirrors to provide high-temperature steam that can be used to power electricity generators.

Solar radiation can also be converted directly into electricity using photovoltaic (PV) panels, normally mounted on the roofs or facades of buildings or as arrays in fields.

Figure 10 Electricity-generating photovoltaic panels arrayed in a field © Naypong / FreeDigitalPhotos.net

Indirect solar energy

Solar radiation can be converted to useful energy indirectly, via the other energy forms it causes.

Bioenergy, powered by solar-powered photosynthesis in plants, is an indirect manifestation of solar energy.

Solar radiation warms the oceans, adding water vapour to the air. This condenses as rain to feed rivers, into which dams and turbines can be located to extract hydropower from the flowing water.

Sunlight heats the tropics to a greater degree than the polar regions, resulting in massive heat flows towards the poles, carried by currents in the oceans and the atmosphere. The energy in such currents can be harnessed by wind turbines.

Also. where winds blow over long stretches of ocean they create waves, and wave power devices are being developed to extract their energy.

Figure 11 The Craig Goch drinking water reservoir in Wales which supplies a 480 kW hydro plant at its base © Robert Everett

However there are also non-solar forms of renewable energy.

6.1 Non-solar renewables

There are also two other sources of renewable energy that do not depend on solar radiation:

Tidal energy

Tidal energy is often confused with wave energy, but its origins are quite different, as this short video clip shows.

Video content is not available in this format.

Ocean tides are caused by the gravitational pull of the Moon (with a small contribution from the Sun's gravity) on the world's oceans, causing a regular rise and fall in water levels as the Earth rotates. The power of the resulting tides can be harnessed by building a low dam or 'barrage', behind which the rising waters are captured and then allowed to flow back through electricity-generating turbines.

Strong underwater currents found in some locations are mainly tidal in origin. After many years of research, development and commissioning, the world's first commercial tidal stream business, MeyGen, started operations in 2016. See Figure 13. (Atlantis Resources, 2017)

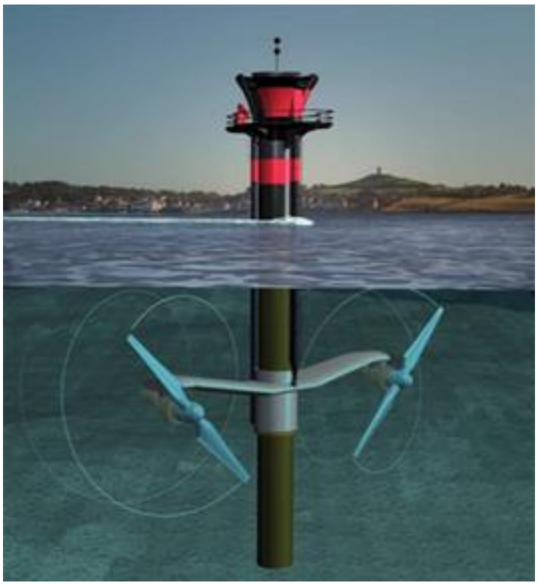

Figure 12 A MayGen marine current turbine (an underwater windmill)

Geothermal energy

Geothermal energy is heat from deep within the Earth, which in some locations heats rocks near the surface. These can heat water in underground aquifers (water bearing rocks), producing hot water that can be used for heating purposes, or in some cases to produce steam for electricity generation.

Watch the video ‘Geothermal Energy’ to learn more:

Video content is not available in this format.

In this short course we have decided to concentrate on the solar direct and solar indirect renewables, omitting further detailed coverage of tidal and geothermal energy.

7 EU and UK renewable energy prospects 2020–2030

As we have seen, renewable energy sources are already providing a significant and increasing proportion of the world's primary energy, and here we look briefly at the prospects for renewable energy in the EU as a whole, and in the UK in particular, in coming decades

EU 2020 targets

The EU's '20:20:20' Directive, passed in 2009, set a target for Europe to achieve by 2020 (CEC, 2009):

1. a 20% reduction in carbon (CO_2) emissions from their 1990 level.
2. a 20% contribution to gross final energy consumption from renewable sources.
3. Under the Paris Agreement at COP21, individual European states have made COP21 pledges of Intended Nationally Determined Contributions (INDCs). Some of these are statements of intended cuts in greenhouse gas emissions, others include specific renewable energy targets.

UK targets

The UK is bound by its Climate Change Act (2008), updated from time to time, to reduce its greenhouse gas emissions by 80% from 1990 levels by 2050 and has promised to phase out coal-fired electricity generation by 2025.

Activity 5

Are you aware of any support measures that have been, or could be introduced by the UK Government to ensure these targets are met?

View discussion - Activity 5

Those are some of the measures, but what else is in the pipeline?

7.1 Electricity market reform and new EU 2030 targets

In 2013 the UK Government passed an energy act introducing various electricity market reform measures, to take effect after 2015. These involve:

- setting ‘strike prices’ for generation from most renewables and other energy sources
- a ‘contracts for difference’ system to ensure that if the prevailing market price is lower than the strike price the difference will be topped up; equally, if the prevailing market price is higher than the strike price, the generator will have to repay the difference
- establishment of a 'capacity market' ensuring that sufficient generating capacity is available on standby in case other electricity generation is insufficient to meet demand.

In 2014 the EU decided on new targets, stipulating that by 2030:

- European carbon emissions should be reduced by 40%
- the contribution of renewable energy to EU supplies should reach 27%.

A target to achieve a 30% improvement in energy efficiency was also agreed, but not specific renewable energy targets for individual member countries, such as the UK.

However, the UK Committee on Climate Change in its 2011 report on Renewable Energy (CCC, 2011) envisaged four scenarios for UK renewables by 2030. As shown in Figure 13 it suggested that the renewable energy contribution could rise to:

- between 30% and 65% of electricity supplies
- between 35% and 50% of UK heat demand
- between 11% and 25% of transport energy needs.

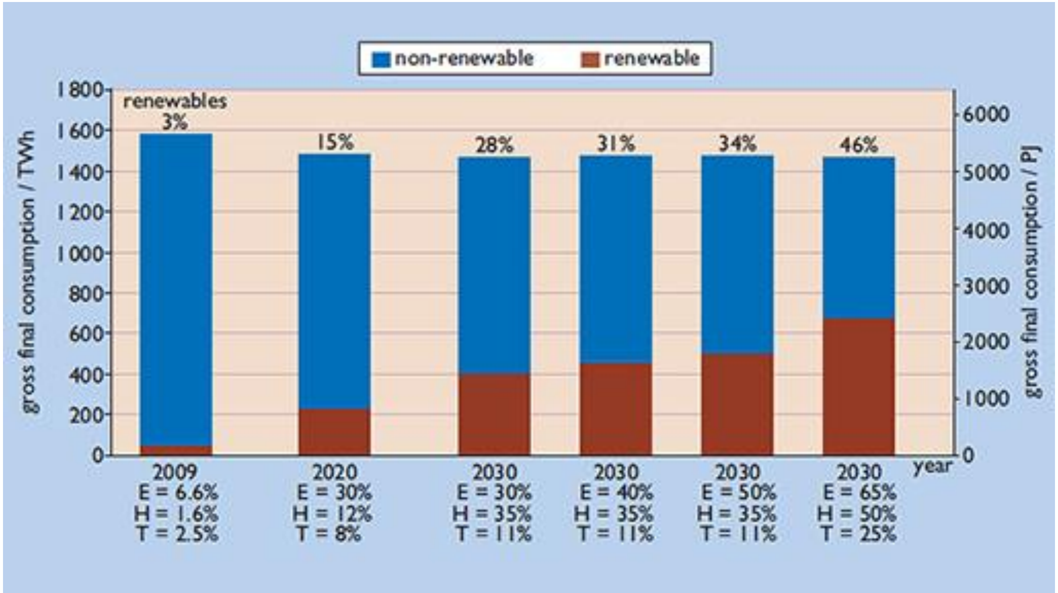

Figure 13 Scenarios from the UK Committee on Climate Change illustrating the potential contribution of renewables to UK heat (H), electricity (E) and transport energy (T)

Figure 13 also suggests that the total contribution of renewables to gross final consumption could be between 28% and 46%, and this, together with other similar analyses, suggests that the prospects for renewable energy in the coming decades look bright!

You will examine in more detail the future prospects for renewables in the UK, the EU and the world as a whole later in the course.

To conclude this week we look at a case study of a country that has adopted very ambitious renewable energy targets.

8 Case study: Scotland aims for 100% renewable electricity by 2020

Scotland has set ambitious targets for the contribution of renewable energy she aims to achieve in the coming decades. In the following three videos the different concepts, challenges and opportunities surrounding these aims are explored.

The following video explores the energy challenges and opportunities that might have been faced by Scotland if it had opted for full independence in the September 2014 referendum. It is still relevant from the perspective of energy supply within the UK specifically, and between regions internationally more generally.

Video content is not available in this format.

This video was filmed before Scotland voted ‘No’ to full independence in the 2014 referendum. However, the UK Government has agreed to devolve many more powers to the Scottish Parliament.

Watch the following video which asks what is the impact of Scotland’s political landscape on its energy policy, and why does Scotland’s current level of independence allow it to adopt an energy policy that is more ambitious than of the rest of the UK

Video content is not available in this format.

Watch the following video, which explores the energy challenges and opportunities Scotland would face if were to be granted greater independence in future.

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9 Week 1 quiz

Check what you've learned this week by taking the end of week quiz.

Week 1 practice quiz

Open the quiz in a new window or tab then come back here when you've finished.

10 Summary

To sum up this first week, you have:

- briefly described the historical evolution of renewable energy sources
- described the key characteristics of a 'sustainable' energy source and outlined some basic energy principles and terminology, along with some definitions of 'renewable energy', explaining that the primary source of nearly all forms of renewable energy is the Sun
- explained the differences between primary energy, delivered energy and useful energy, and gave data on world energy consumption per person, plus some statistics on total world energy consumption and the proportion contributed by renewables
- looked at the UK and the contributions of renewables to delivered energy in all forms, and to electricity in particular
- looked briefly at climate change and the contribution to global warming that is being made by the carbon dioxide emissions from fossil fuel combustion
- overviewed renewable energy sources, starting with direct solar thermal energy and solar photovoltaics,

followed by indirect solar sources – biofuels, hydropower, wind and wave energy

- looked briefly at UK and European targets for the contributions of renewable energy to be achieved by 2020 and by 2030, including projections of the potential renewable contributions to electricity, heat and transport fuel needs
- looked at a case study describing Scotland's ambitious plans for a major expansion of its renewable energy supplies over the coming decade.

You can now go to Week 2.

Week 2: Solar energy for heating and daylighting

Introduction

This week you will look at some of the methods employed to gather and use the Sun's thermal (i.e. heat) energy. You will also look briefly at the role of the Sun's light in reducing the need for artificial lighting in buildings.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of the week, you will be able to:

- describe at an introductory level the basic principles underlying the availability of solar radiation and the seasonal differences in solar radiation reaching the Earth at different locations
- understand at an introductory level the basic physical principles underlying the operation of solar thermal energy systems
- describe the main differences between active and passive solar heating systems, and the basic principles of solar ‘daylighting’
- understand at an introductory level the use of solar energy to drive engines for electricity generation and the main ways to concentrate the radiation to produce high temperatures.

1 Solar thermal energy and daylighting

There are lots of different solar energy technologies, and these include:

Passive solar space heating

This is the absorption of solar energy directly into a building to reduce its space heating demand.

Daylighting

Making the best use of natural daylight from the Sun through careful building design and by the use of controls to switch off artificial lighting when there is sufficient natural light available.

Active solar water heating and space heating

This involves discrete solar collectors, usually mounted on the roof of a building, to gather solar radiation to provide hot water for washing or for space heating.

Solar thermal power plants

These more complex solar collectors use mirrors to concentrate the Sun's energy, producing temperatures high enough to operate steam turbines, which then drive generators to produce electric power.

These technologies will be described in more detail later, but first we must discuss the nature and availability of solar radiation.

1.1 Solar radiation

The Sun is an enormous nuclear fusion reactor, in which at very high temperature hydrogen atoms fuse to form helium at the rate of 4 million tonnes per second. This fusion reaction causes the Sun to radiate energy, due to the resulting high surface temperature (around 6000 °C).

A very small proportion of the Sun’s radiated energy reaches the Earth, 150 million kilometres away, and if you look at Figure 1 you will see that approximately one-third of it is simply reflected back to space. You will also see that the rest is absorbed by the planet and eventually re-transmitted to space as long-wave infrared radiation.

On average, the Earth re-radiates as much energy as it receives and sits in a stable energy balance at a temperature suitable for life.

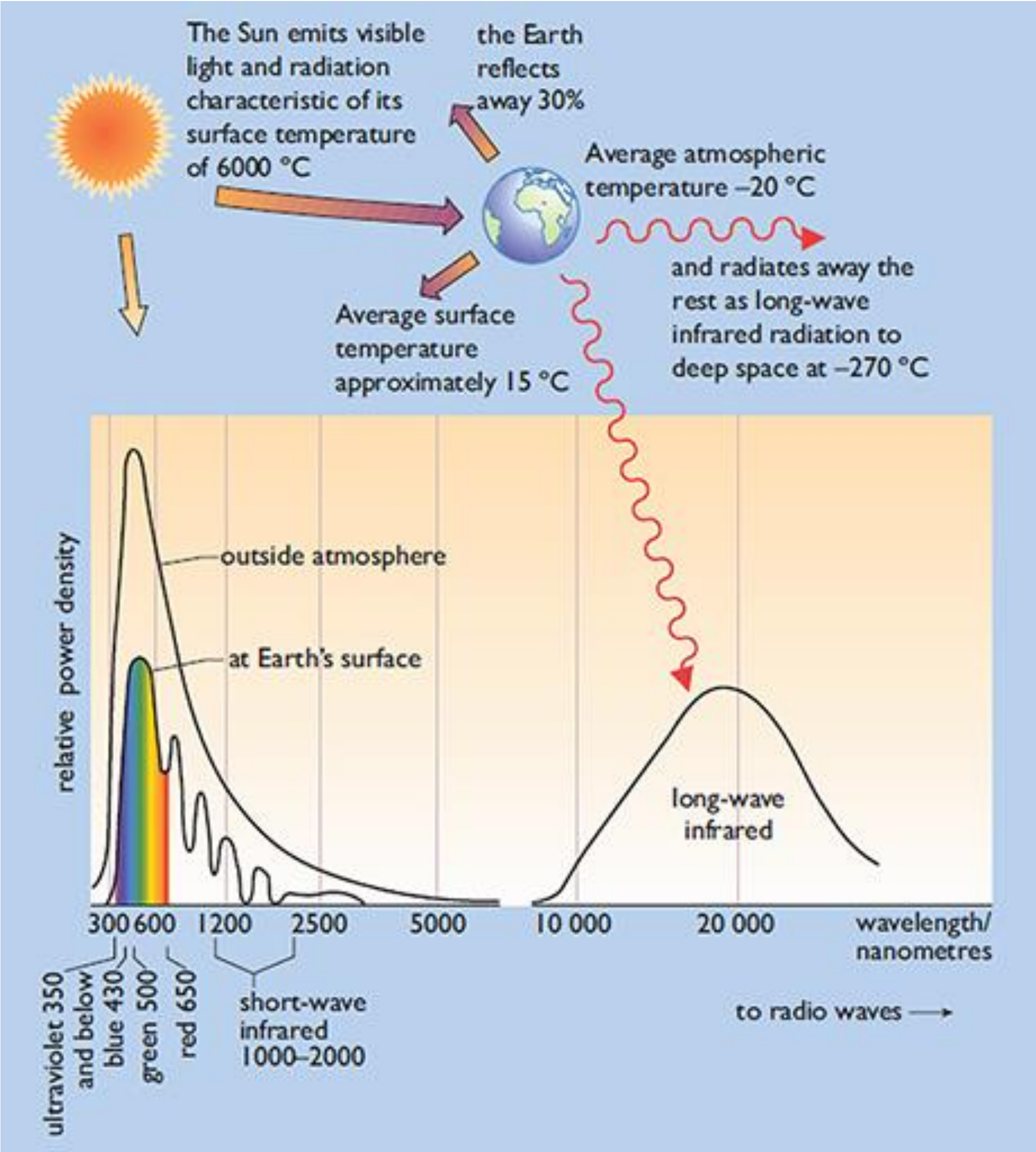


Figure 1 Radiation of energy to and from the Earth

As Figure 1 shows, solar radiation spreads over a wide spectrum of wavelengths - from ultraviolet light (shorter wavelength than visible violet light) to ‘short-wave’ infrared light (longer wavelength than visible red light). This wavelength distribution is determined by the surface temperature of the Sun.

Earth temperature and solar collection

The Earth has an average atmospheric temperature of –20 °C and a surface temperature of 15 °C. It re-radiates energy as long-wave infrared to deep space, the temperature of which is only a few degrees above absolute zero, –273 °C.

Activity 1 Collection of solar energy

How is solar energy collected differently at low or high temperatures?

View answer - Activity 1 Collection of solar energy

2 Direct and diffuse solar radiation

Some of the Sun's energy is diffuse, and some is direct. Both forms are useful in most solar thermal applications, but what are they, and what are the differences?

When the Sun's rays hit the atmosphere some of the light is scattered, depending on the cloud cover. A proportion of this scattered light comes to Earth as diffuse radiation. On the ground this appears to come from all over the sky. This diffuse radiation provides most of the 'daylight' in buildings.

The portion of light that appears to come straight from the Sun, normally called 'sunshine', is known as direct solar radiation. It can be focused to generate very high temperatures, or can be used without such concentration in active solar heating systems. On a clear day, its power density can approach 1000 watts (1 kW) per square metre.

In northern Europe and in urban locations in southern Europe, practical peak power densities are around 900 to 1000 watts per square metre. In Northern Europe, on average over the year approximately 50% of radiation is diffuse and 50% direct. In Southern Europe, where solar radiation levels are higher, most of the extra contribution comes from direct radiation, especially in summer.

Activity 2 Energy output of the sun

If the energy output of the Sun is constant, why does the UK, for example, receive more radiation in summer than in winter?

View answer - Activity 2 Energy output of the sun

So how much solar radiation is available in different locations?

2.1 Availability of solar radiation

The annual total solar energy on a horizontal surface is highest near the equator, where it can reach 2000 kilowatt-hours per square metre per year, and even more in some sunny desert areas.

kilowatt-hours per square metre per year = kWh m^{-2} y^{-1}

Many experimental solar projects, such as the solar thermal power stations described in Section 9, have been built in areas like southern France or Spain, where radiation levels are around 1500 kWh m^{-2} y^{-1}, or the southern USA, where levels can reach 2500 kWh m^{-2} y^{-1}. Northern Europe typically only receives about 1000 kWh m^{-2} y^{-1}

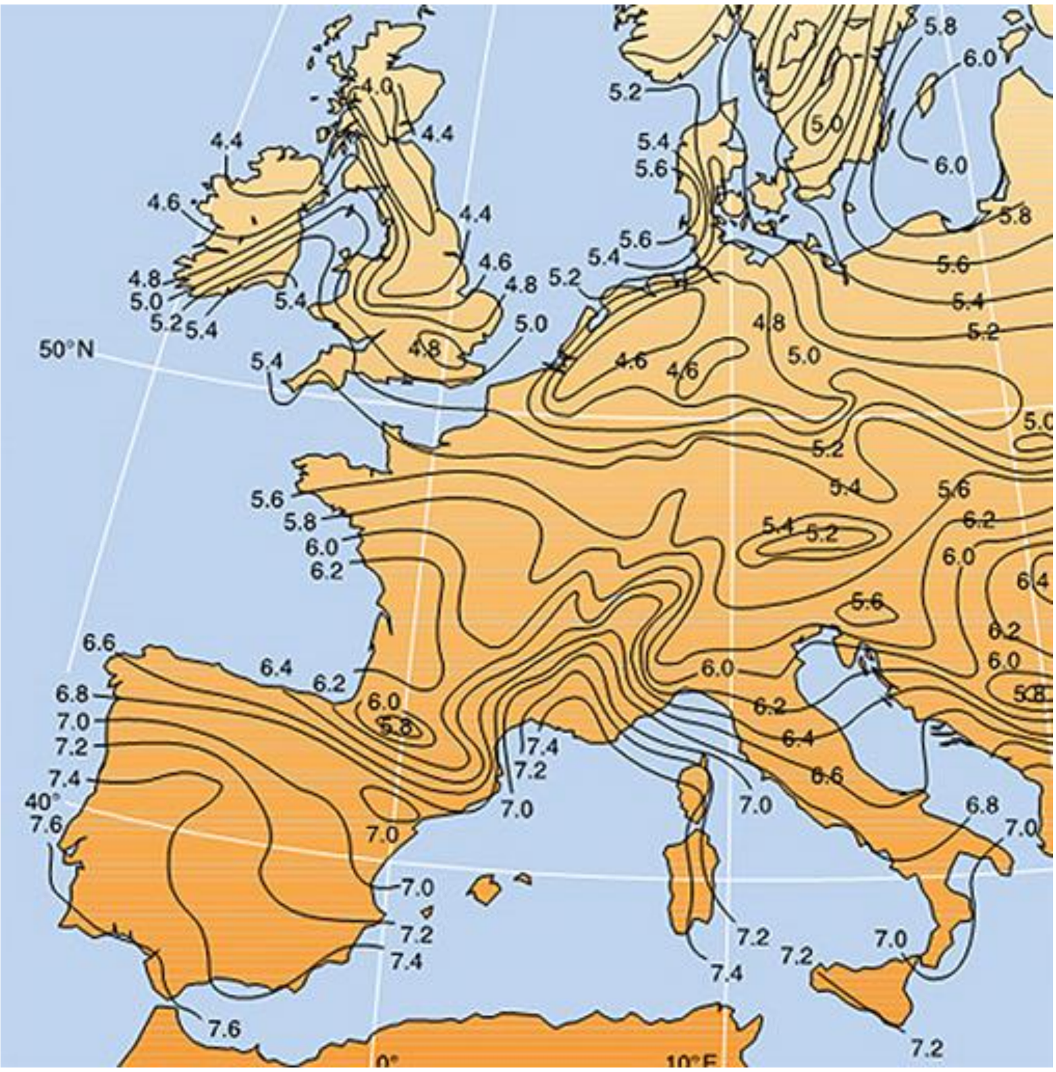


Figure 4 Solar radiation on horizontal surface (kWh per square metre per day) in Europe in July (source: CEC, 1994)

However, these levels vary greatly from summer to winter, as you can see if you study Figure 4 above and Figure 5 below. In July in northern Europe the solar radiation on a horizontal surface is between 4.5 and 5 kWh m^{-2} per day, but in southern Europe, solar radiation levels are higher – between 6 and 7.5 kWh m^{-2} per day.

Now have a look at Figure 5, which shows that in winter the levels of solar radiation are far lower. On average in January in northern Europe the radiation level can be only one-tenth of its July value - around 0.5 kWh m^{-2} per day, but in southern Europe there may still be appreciable amounts available – 1.5 to 2 kWh m^{-2} per day.

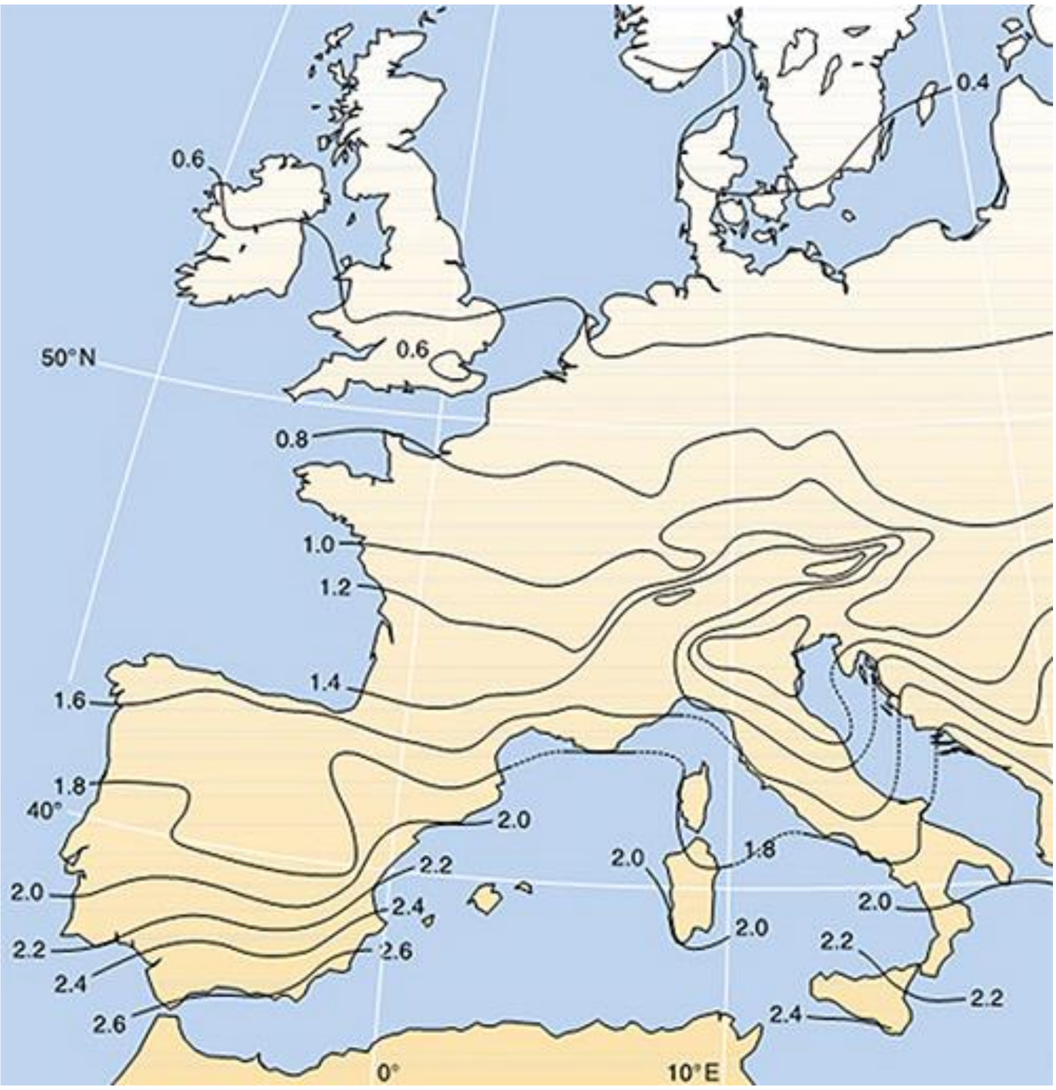


Figure 5 Solar radiation on horizontal surface (kWh per square metre per day) in Europe, January (source: CEC, 1994)

Now let’s look at how we can optimise the collection of solar energy.

2.2 Optimising solar energy collection

In the northern hemisphere, a surface should face south to collect as much radiation as possible, and must be tilted towards the Sun at an angle depending on the latitude and the time of year that most solar collection is required.

As you can see from Figure 6, in summer, when the most radiation is available and solar energy collection can be maximised, the tilt angle should be less than the latitude. In winter, when you may need more solar energy, the tilt angle should be more than the latitude angle.

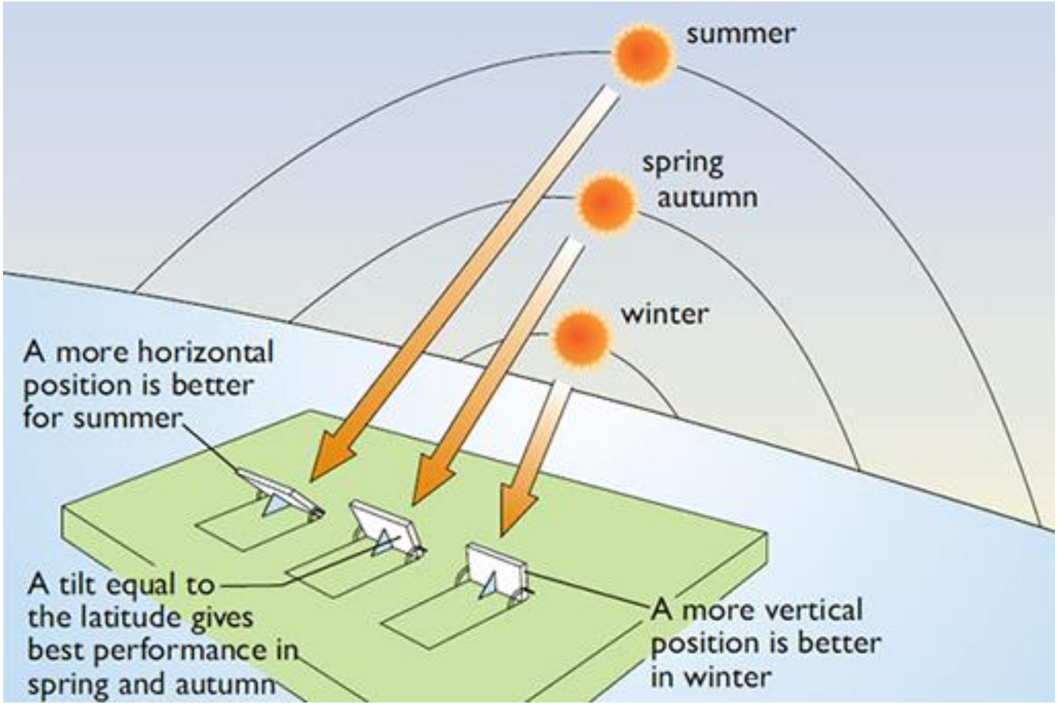


Figure 6 Optimising solar collector tilt for different seasons

Fortunately, the effects of tilt are not particularly critical. Similarly, the effects of orientation away from south are relatively small. For most solar heating applications, collectors can be faced anywhere from south-east to south-west.

This relative flexibility means that a large proportion of existing buildings have roof orientations suitable for solar energy systems. This conclusion applies to both solar thermal systems and the solar photovoltaic (PV) systems to be described in Week 3.

3 Passive solar heating of buildings

As mentioned in Section 1, there are various ways in which buildings can be designed to maximise their absorption of energy from the Sun, to contribute to their heating needs.

These 'passive solar heating' techniques include the following:

Conservatory (or 'Sunspace')

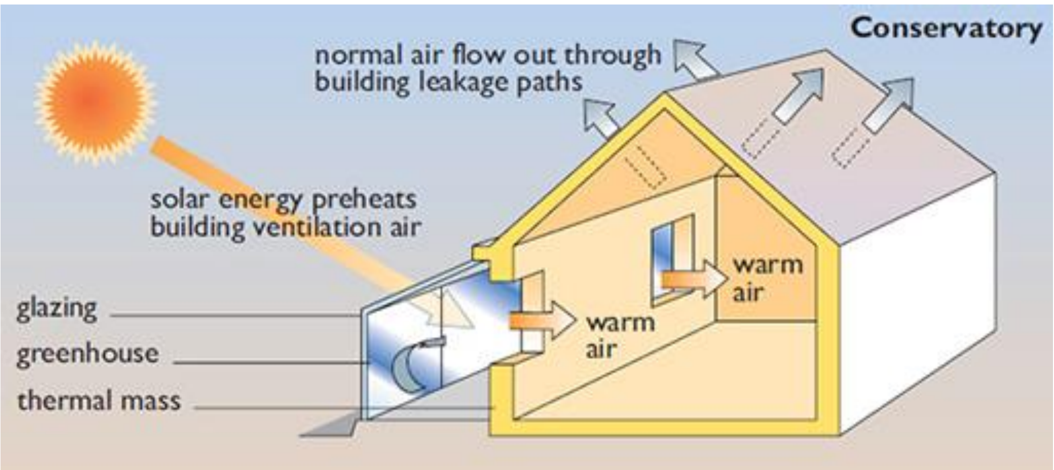


Figure 7 Passive solar heating system – Conservatory

Here a conservatory or greenhouse on the south side of a building can be thought of as a kind of habitable solar collector where air is the heat transfer fluid, carrying energy into the building behind, and the energy store is the building itself, especially the wall at the back of the conservatory.

Trombe wall

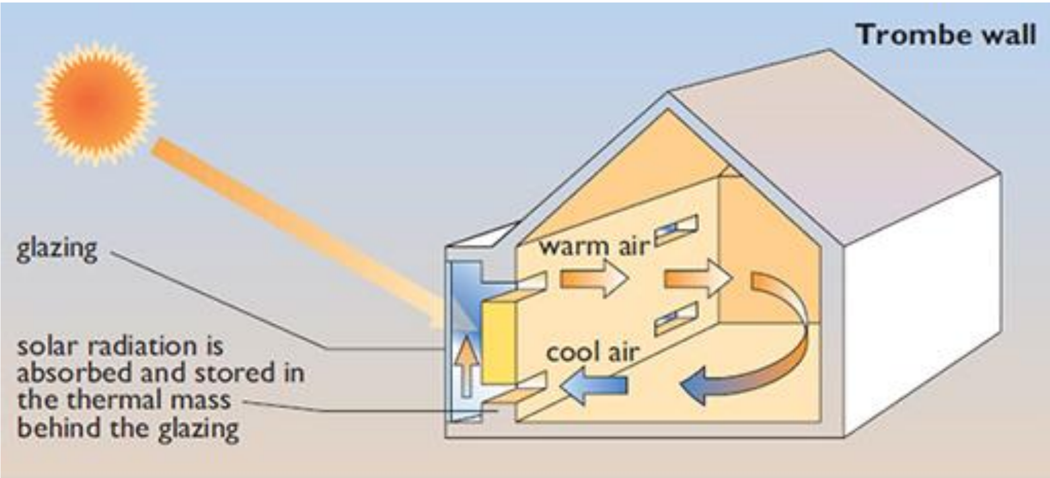


Figure 8 Passive solar heating system – Trombe wall

With a Trombe wall (named after its French inventor, Félix Trombe), the conservatory is replaced by a thin glazed air space in front of a storage wall. This is in effect a solar collector with heat storage immediately behind it.

Solar radiation warms the storage wall and is radiated into the house from its inner side. In addition, on sunny days air is circulated through vents in the air space into the house behind. At night and on cold days, this air flow is cut off.

Direct gain

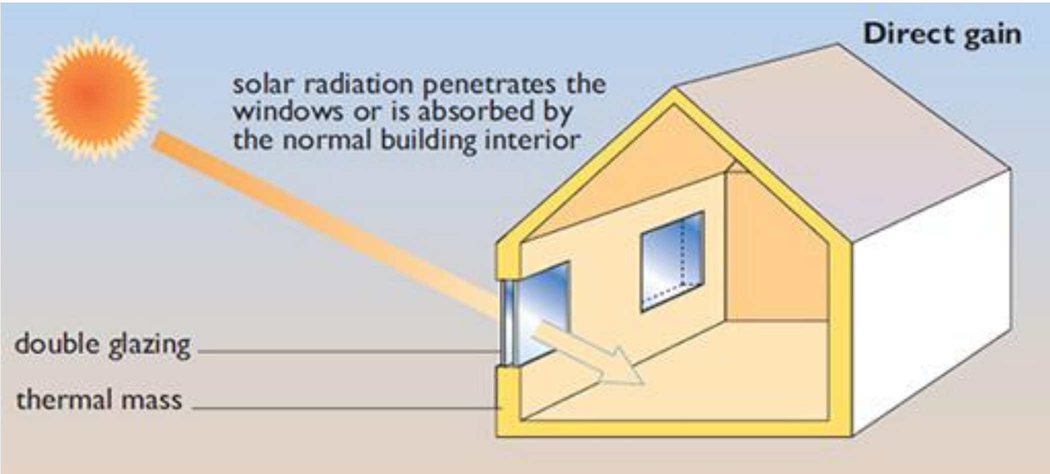


Figure 9 Passive solar heating system – Direct gain

This is the simplest and most common of all passive solar heating systems. All glazed buildings make use of ‘direct gains’ of energy from the Sun to some degree, as the Sun’s rays simply penetrate the windows and are absorbed into the interior.

If the building is ‘thermally massive’ enough, i.e. built of heavy materials such as concrete, and the heating system is responsive, the solar heat gains are likely to be useful. But if the building is too ‘thermally lightweight’, such as one of timber frame construction, it may overheat on Sunny days and the occupants will perceive the effect as a nuisance.

Passivhaus design

In Germany the idea of ‘superinsulation’ (i.e. very high levels of building insulation) has been promoted in the form of the 'PassivHaus' standard, developed during the 1990s. The house is termed ‘passive’ in the sense that it does not need a conventional large heating system (Mead and Brylewsky, 2011). This form of design has been used in over 30,000 buildings across the world to date. It involves using thick insulation, good quality windows and airtight construction to reduce the space heating demand of a building to a very low level. It can then be heated mainly by solar gains and heat from appliances and the occupants themselves.

Activity 3 Passive solar heating

What general guidelines can you think of for optimising the use of passive solar heating in buildings?

View answer - Activity 3 Passive solar heating

As well as heat, the Sun provides light too – we'll take a look at that next.

4 Daylighting

As well as providing heat, the Sun provides daylight – a commodity that we all take for granted. Replacing it with artificial light was, before the middle of the 20th century, very expensive. With the coming of cheap electricity and efficient lighting, daylight has tended to be neglected.

Houses are frequently designed to make use of natural daylight – in the UK in 2013 domestic lighting accounted for less than 3% of domestic energy consumption.

In some commercial offices, however, lighting can account for up to 30% of the delivered energy use. Modern factory units and hypermarket buildings are built with barely any windows, and some ‘deep-plan’ office buildings, such as those at Canary Wharf in London shown in Figure 10, have plenty of windows on the outside but include many areas on the inside that require continuous lighting, even when the Sun is shining brightly outside.

Figure 10 Modern deep-plan office buildings, such as those at Canary Wharf in London, require continuous artificial lighting in their centre, which may create overheating in summer

Although in winter the waste heat from lights can usefully contribute to space heating energy, in summer when there is most light available it can cause overheating, especially in well-insulated buildings. Making the best use of natural light saves both on lighting energy and on the need for air conditioning.

Daylighting design

Many of the design details to make the most of natural daylight can be found in the better quality 19th century buildings.

Activity 4 Lighting in buildings

Think about a few older buildings you have been in. What traditional techniques to enhance lighting can you think of that are used in these buildings?

View answer - Activity 4 Lighting in buildings

An extreme example is in the small Norwegian town of Rjukan, set deep in a mountain valley, which has installed large steerable mirrors on an adjacent mountain-top to reflect a small, but very welcome, patch of sunlight into the town square.

When artificial light has to be used, it should be used efficiently and turned off as soon as natural lighting is available. Control systems can reduce artificial lighting levels when photoelectric cells detect sufficient natural light. Payback times on these energy conservation techniques can be very short and savings of 50% or more are feasible.

In designing new buildings, compromises need to be made between lighting design and thermal design. Deep-plan office buildings, such as those shown in Figure 10, have a smaller surface area per unit volume than shallow-plan ones, so they will need less heating in winter, but will need more interior lighting energy.

5 Active solar heating

To most people, 'solar heating' means the familiar rooftop solar water heater, of which there are two basic forms: *pumped* and *thermosyphon*.

By the end of 2015 an estimated 622 million square metres of such solar collectors installed worldwide, a fourfold expansion since 2005. More than 70% have been installed in China. (Sawin et al., 2016). Most of these are of the simple 'flat plate' type, around 3–5 metres in area, mounted on the pitched roof of a house and tilted to face the Sun.

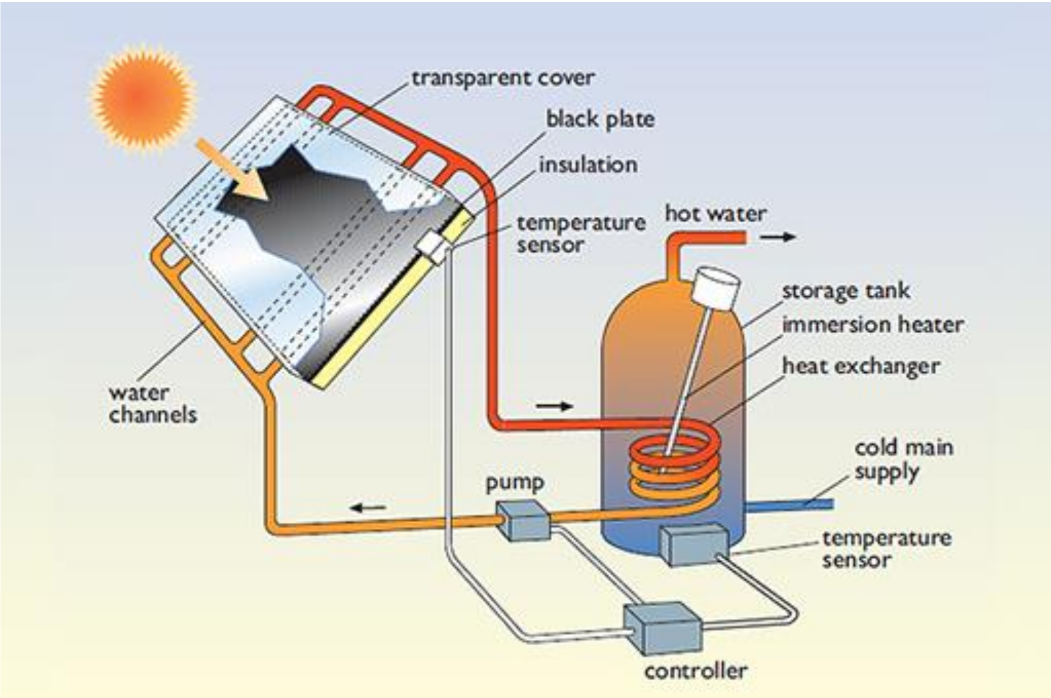


Figure 11 A pumped active solar water heating system

A typical pumped system as shown in Figure 11 consists of three elements:

1. a collector panel, consisting of glazing, an absorber plate, and insulation
2. an insulated hot water storage tank, typically of around 200 litres capacity, with hot water from the panel circulating through a heat exchanger situated at the bottom
3. a pumped circulation system containing an anti-freeze (needed in northern Europe) transferring the heat from the panel to the store.

In the UK, field trial results suggest that such a system can typically provide over 1100 kWh y−1 – about 40% of a household’s hot water energy (EST, 2011)

In frost-free climates such as the Mediterranean, it is safe to mount the storage tank outdoors, so a simpler *thermosyphon* arrangement can be used, as shown in Figure 12.

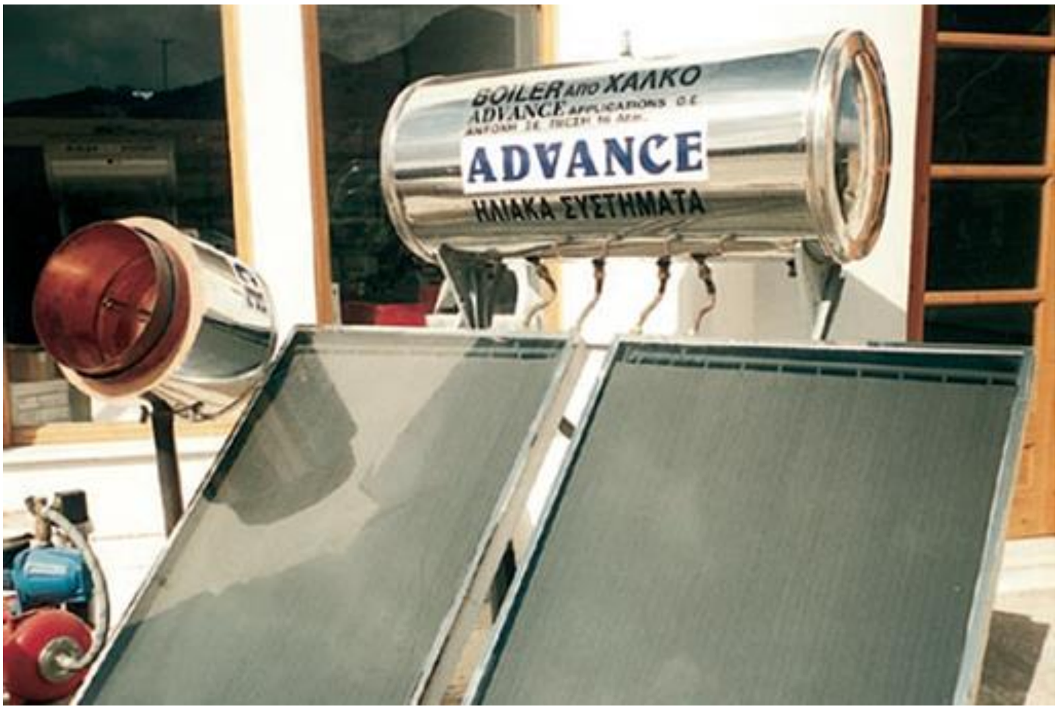


Figure 12 Typical thermosyphon solar water heater

This design dispenses with the circulation pump as it relies on the natural convection of hot water rising from the collector panel to carry heat up to the storage tank, installed above the collector. There is also no need for a heat exchanger as the required domestic hot water circulates directly through the panel. Normally the storage tank also contains an electric immersion heater for ‘topping up’ water temperature on cloudy days. Mediterranean systems are usually designed to be free-standing for mounting on buildings with flat roofs. These systems only usually require around 2 m^2 of collector area due to the higher levels of solar radiation in these countries.

6 Varieties of solar collector

Just as solar space heating systems can have several variants, so can solar collectors. The most common types for low temperature use are:

Unglazed panels

These are most suitable for swimming pool heating, as it's only necessary for the water temperature to rise by a few degrees above ambient air temperature, so heat losses are relatively unimportant.

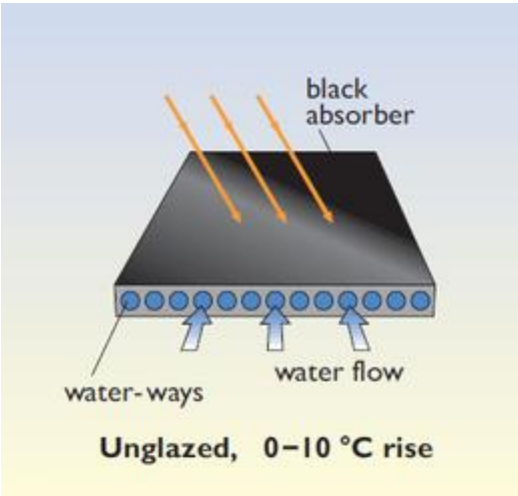


Figure 13 Unglazed panel solar collector

Glazed flat plate water collectors

These are the mainstay of domestic solar water heating They are usually single glazed but may have an additional second glazing layer, with a more elaborate glazing system a higher temperature difference can be sustained between the absorber and the external air.

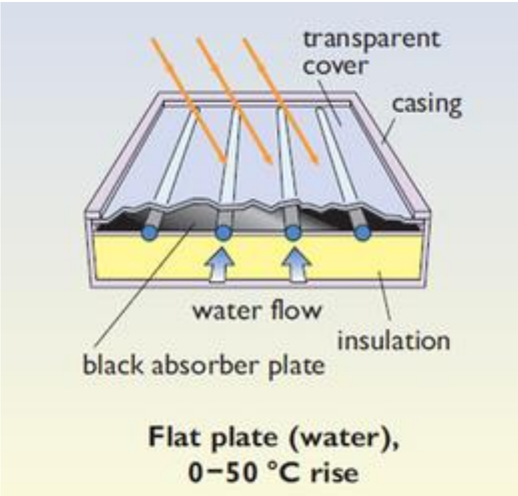


Figure 14 Glazed flat plate water collectors

Flat plate *air* collectors

These are not so common as water collectors and are mainly used for applications such as supplying warm air for crop drying.

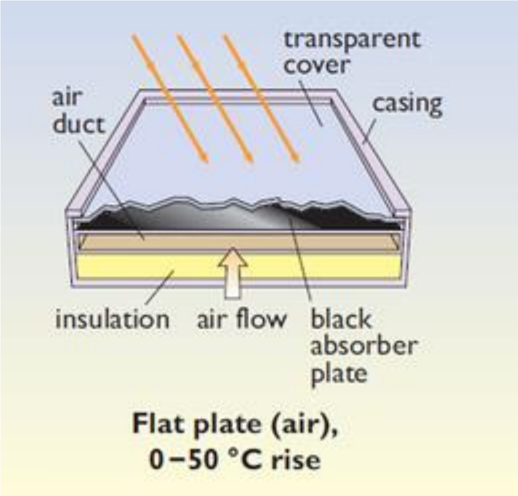


Figure 15 Flat plate air collectors

Evacuated tube collectors

The example shown in Figure 17 takes the form of a set of tubes similar to fluorescent tubular lamps. The absorber plate is a metal strip running down the centre of each tube. Heat losses due to convection are suppressed by a vacuum in the tube. The absorber plate uses a special ‘heat pipe’ to carry the collected energy to the water, which circulates along a header pipe at the top of the array. These collectors are generally more expensive than flat plate ones, but they have lower heat losses, allowing a better performance in winter.

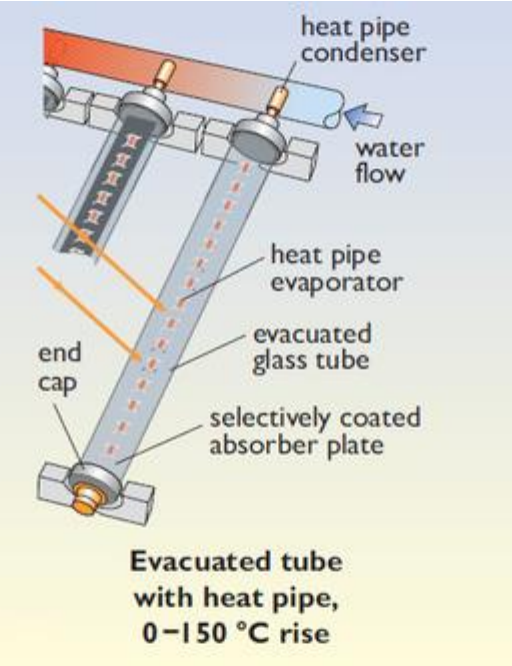


Figure 16 Evacuated tube collector

We now move from describing the use of solar energy on individual buildings to looking at its use on a larger scale, such as supplying heat to an entire district.

7 Solar district heating

Considerable economies can be achieved when solar collectors are purchased and erected in bulk for large projects.

Since the 1980s there has been a steady stream of construction of large arrays of solar collectors for district heating systems in mainland Europe, mainly in Denmark, Sweden and Germany. The arrays can be very large. The 18 000 m^2 array shown in Figure 18 includes a 12 100 m^3 heat store and supplies 30% of the annual heat requirement for a district heating system supplying 1600 households.

Since the photograph was taken the array has been increased by a further 15 000 m^2 with a further 75 000 m^3 of storage, increasing the share of heat production for the district heating system to 55%. You can find out more about this on the Sunstore4 website.

Figure 17 An 18 000 m^2 array of collectors feeding a district heating system at Marstal in Denmark

Marstal is not the largest such facility in Denmark, which boasts four larger ones that entered service between 2009 and 2016 (SDH, 2016).

In what other ways can the Sun's warmth be harnessed?

8 Heat pumps

Another way of harnessing the Sun's warmth is to use a heat pump. This works like a refrigerator, except that in countries such as the UK it is likely to be primarily used for heating rather than cooling.

Have a look at Figure 18, which shows the main elements within the most common type of heat pump.

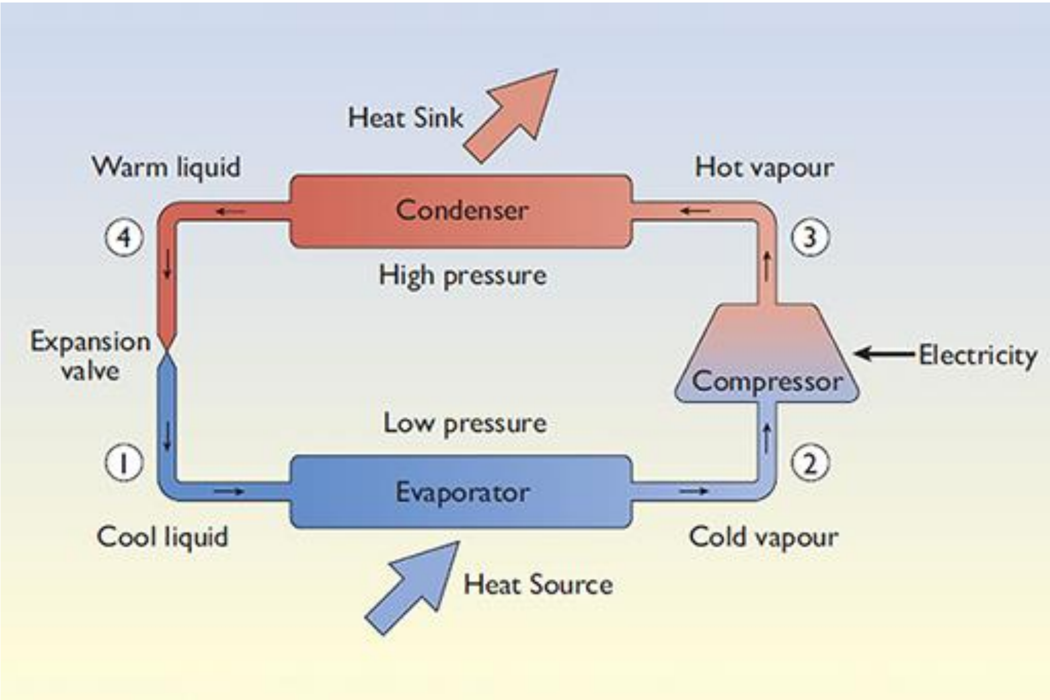


Figure 18 Schematic diagram of a heat pump (source: EST, 2010)

Essentially, electricity is used to ‘pump’ heat from a low temperature in the evaporator to a higher temperature in the condenser. Here’s a more detailed description:

a. The heat pumping process is made possible by the use of a special refrigerant liquid that boils at low temperature (about –15 °C). At point 1 in Figure 18 it starts as a cool liquid at a low pressure.
b. In order to convert this cool liquid to a vapour, it must be given energy – the so-called *latent heat of evaporation*.
c. The refrigerant absorbs heat from the heat source in a heat exchanger, called the *evaporator*, and it vaporizes (point 2).
d. The vapour then enters an electrically driven *compressor* that raises both its pressure and temperature (point 3).
e. The hot vapour then enters another heat exchanger, the *condenser*, where it condenses to a warm liquid and gives up its *latent heat of evaporation* (point 4).
f. Finally the liquid is forced through a fine expansion valve where it loses pressure, vaporising and dropping in temperature.
g. The cycle is then repeated

There are two main types of heat pump and we'll look at these next.

8.1 Air and ground source heat pumps

There are two main types of heat pump:

Air source heat pumps

In buildings, a heat pump may be used for heating or for cooling (air conditioning). When used for heating, the evaporator is located somewhere in the external environment.

Figure 19 Fan-coil unit for an air-source heat pump

An *air-source* heat pump, such as that shown in Figure 19, is likely to have a fan blowing external air over a coil-type evaporator unit.

Ground source heat pump

These heat pumps use evaporator pipes usually buried in a shallow horizontal trench surrounding a building as in Figure 20. Alternatively, they may be laid in a vertical borehole 10 metres or more in depth.

Figure 20 Evaporator pipes being laid in a trench for a ground-source heat pump

Heat is then pumped from the outside environment to a compressor inside the building, normally connected to its central heating system. Electrical energy is required to operate the compressor. The ratio of the heat output to the electrical input is known as the *coefficient of performance* (COP). For systems in the UK this typically has a value of 2 to 3.

In an air-source heat pump, the heat that is drawn from the external environment is taken immediately from the outside air, cooling it in the process. In a ground-source heat pump, the same process takes place, but by cooling the ground (by only a degree or two).

Can the heat from heat pumps be classed as renewable energy?

8.2 Heat gains from heat pumps

The difference between a heat pump's heat output and its electricity input is known as the *heat gain*.

Under the 2009 European Union Renewable Energy Directive (CEC, 2009) the heat gains from heat pumps are classified as renewable energy, but there are several classifications, which can be a source of confusion:

- **aerothermal gains** – heat gains from air-source heat pumps
- **hydrothermal gains** – heat gains from rivers or lakes
- **geothermal gains** – gains from energy stored in the form of heat beneath the surface of solid earth – although here the source of energy is normally fairly near the surface and essentially *solar* in origin, not geothermal heat from deep inside the Earth.

Heat gains from heat pumps are beginning to feature in national renewable energy statistics and may be classified together with solar gains, although they do not *directly* depend on solar radiation for their performance.

For the UK energy statistics the heat gains from all heat pumps (ground source and air source) are classified together with heat from deep geothermal wells. Together in 2015 they supplied an estimated 7.1 PJ of heat (BEIS, 2016). This was roughly 1% of the UK's total renewable energy supply for that year.

You'll now move on to look at solar thermal electricity generation.

9 Solar thermal electricity generation

If the Sun's rays are concentrated using mirrors, high enough temperatures can be generated to boil water to drive steam engines, which can produce mechanical work for water pumping or, more commonly nowadays, for driving an electric generator.

This solar thermal-electric generation is known *as concentrating solar power* (CSP). There are trade-offs between the complexity of design of a concentrating system and its concentration ratio. The concentration ratio is the ratio of the power per unit area at the *focus* to the incoming power per unit area at the *aperture*. No concentrating collector can deliver in total any more energy than falls on its aperture, but what it does receive is all concentrated into one small area.

How do concentrating collectors work?

One common method of concentrating solar energy is to use a parabolic mirror like the one shown in Figure 21.

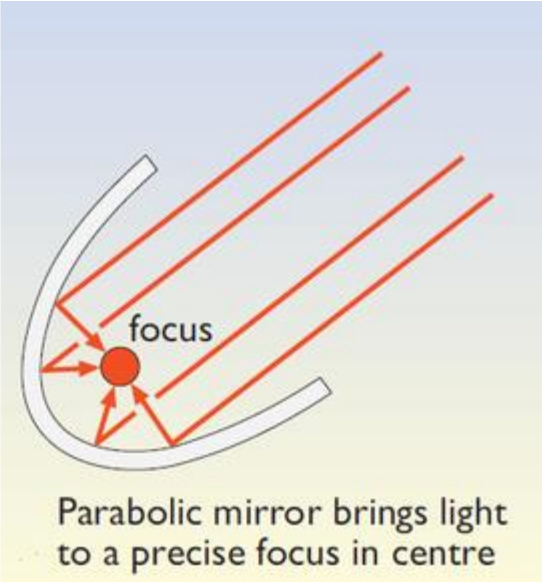


Figure 21 Parabolic mirrors for high-temperature applications – principles of focusing

As you can see, rays of light that enter parallel to the axis of a mirror formed in this parabolic shape will be reflected to one point, the focus.

Activity 5 Rays of light and reflection

What happens if the Sun’s rays enter off-axis?

View answer - Activity 5 Rays of light and reflection

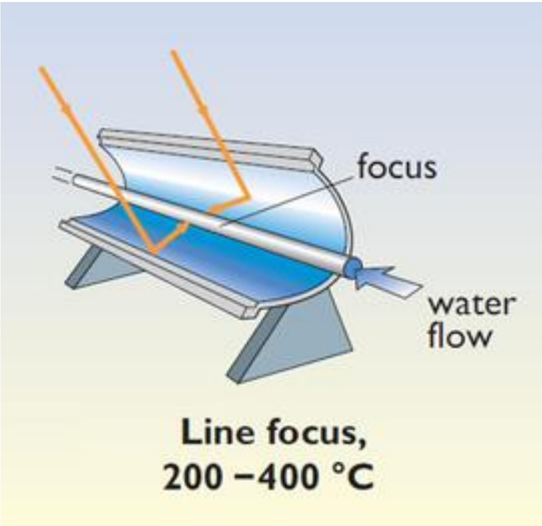


Figure 22 Parabolic mirrors for high-temperature applications – a line focus or ‘trough’ collector

Now look at Figure 22, which shows a line focus or trough collector, mainly used for generating steam for electricity generation. Here the Sun’s rays are focused onto a pipe running down the centre of a trough. The pipe is likely to carry a high temperature heat transfer fluid such as a mineral oil. The trough can be pivoted to track the Sun up and down or east to west.

A line focus collector can be oriented with its axis in either a horizontal or a vertical plane and can produce a temperature of 200–400 °C, usually achieving a 'concentration ratio' of 50, which is adequate for most power plant systems – but the ratio required depends on the desired target temperature.

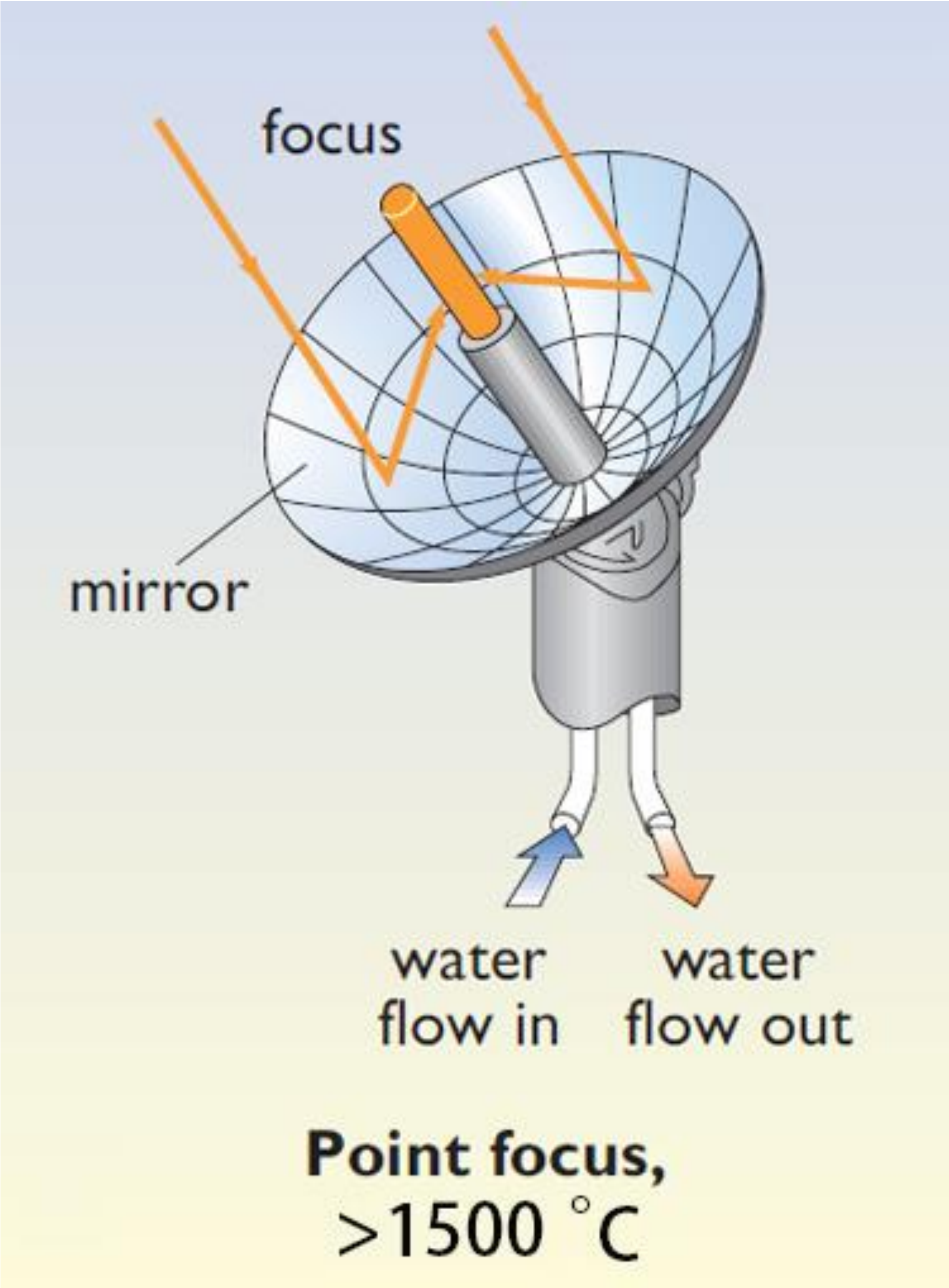


Figure 23 Parabolic mirrors for high-temperature applications – the point focus or ‘dish’ collector

In the point focus or dish collector shown in Figure 2.24, the Sun's image is concentrated on a steam boiler in the centre of the mirror. For optimum performance, the axis must be pointed directly at the Sun at all times, so it needs to track the Sun both up and down and east to west. A well-built and well-aimed parabolic dish collector can produce a temperature of over 1500 °C, and achieve a concentration ratio of over 1000.

Another form of concentrating solar electricity generation involves the use of power towers, which we'll look at next.

9.1 Power towers

Since the early 1980s a number of large, experimental solar thermal electricity generation schemes have been built to generate very high temperatures. Several are of the 'power tower' type, shown in Figure 224. These use a large array of steerable 'heliostats' (large mirrors) on the ground to focus the Sun's rays onto a central receiver at the top of a tower.

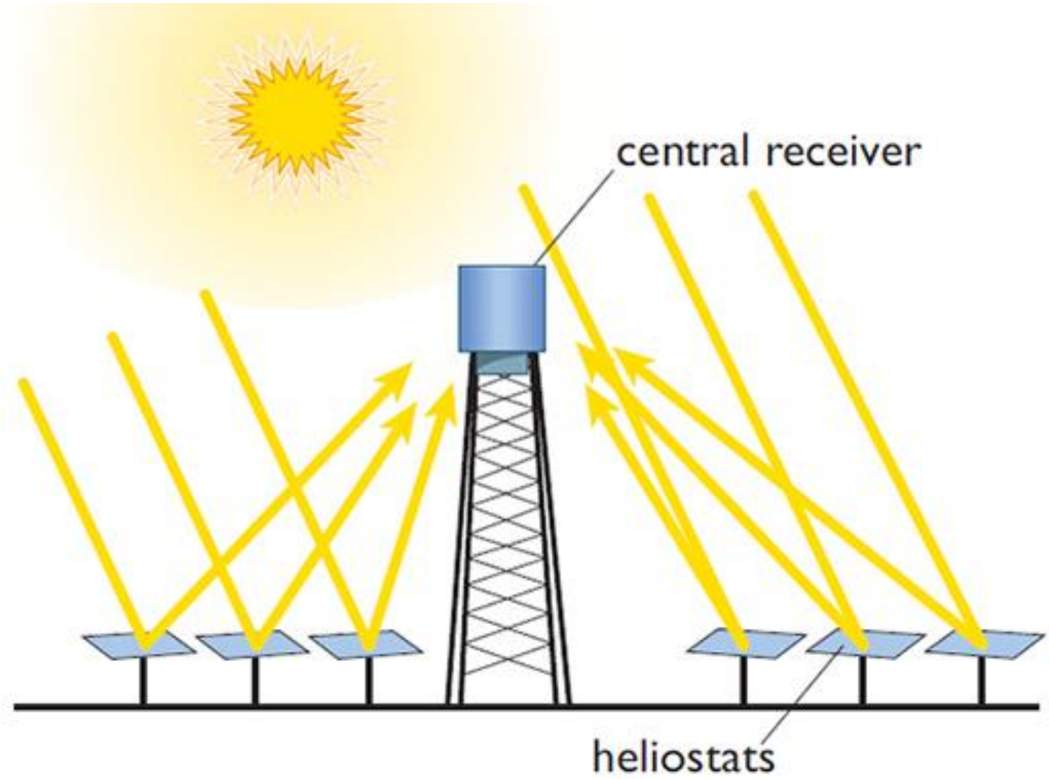


Figure 24 The central receiver on a power tower is heated by a large array of steerable ‘heliostat’ mirrors on the ground

The receiver is a chamber where either steam is produced directly, or a heat transfer fluid such as mineral oil or molten salt is raised to a high temperature, to be pumped away to generate steam at ground level. The steam is then used to drive a turbine to generate electricity.

Figure 25 shows two Power Tower plants near Seville in southern Spain, the 11 MW Planta Solar 10 (PS10) completed in 2007, and the adjacent Planta Solar 20 (PS20) completed in 2009. These have limited heat storage and can use natural gas as back-up. The newer Gemasolar 20 MW plant commissioned in 2011 and also near Seville, has increased thermal storage using molten salt.

Figure 2

You'll find it interesting (and amusing) to watch this short BBC video describing the Seville CSP plants, presented by James May – better known as a motoring journalist with a sense of humour. The video was shot in 2008 when PS10 had been completed and

PS20 was under construction. It gives a vivid picture of the scale and complexity of a concentrating solar plant.

Video content is not available in this format.

Next you’ll have a chance to practise what you've learned in the weekly quiz.

10 Week 2 quiz

Check what you've learned this week by taking the end of week quiz.

Week 2 practice quiz.

Open the quiz in a new window or tab then come back here when you've finished.

11 Summary

To sum up this week, you have:

- described the nature of solar radiation, starting with the important distinction between its ‘light’ (i.e. visible short-wave radiation) and its ‘heat’ (long-wave radiation)
- noted that direct solar radiation, the unobstructed rays of the Sun, is important for concentrating collectors, and diffuse radiation is important for natural lighting
- discussed how optimising the amount of radiation falling on a flat plate collector requires an understanding of the appropriate tilt, which will depend on the latitude of the site
- turned briefly to the properties of glass and other glazing materials, particularly their ability to transmit light but block the re-radiation of long-wave infrared radiation
- looked at some low-temperature applications for solar energy, particularly domestic solar water heating and space heating, and described basic solar collector types and their applications
- described three ‘passive solar’ technologies, where the solar collector is an integral part of a building: the

Conservatory, the Trombe wall and the Direct Gain type

- outlined the role of daylighting in avoiding excessive use of artificial light
- introduced the ‘heat pump’, which although not *directly* a ‘solar’ technology, does draw heat from the outside environment, ultimately warmed by the Sun, producing low-temperature heat
- discussed the use of solar thermal energy to generate electricity in concentrating solar power (CSP) systems, and looked at the basic forms of concentrating collector: the line focus or parabolic trough, the point focus or dish collector, and the ‘power tower’ design.

You can now go to Week 3.

Week 3: Solar photovoltaics

Introduction

In Week 2 you saw how solar energy can be used to generate electricity by producing high-temperature heat to power an engine, which then produces mechanical work to drive an electrical generator.

This week is concerned with a more direct method of generating electricity from solar radiation, namely solar photovoltaics: the conversion of solar energy directly into electricity, using a solid-state device.

The term ‘photovoltaic’ is derived by combining the Greek word for light, *photos*, with *volt*, the name of the unit of potential difference (i.e. voltage) in an electrical circuit.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- describe at an introductory level the range of different photovoltaic technologies, their essential characteristics, their differences and similarities, advantages and disadvantages
- understand at an introductory level the main characteristics of energy systems using photovoltaic modules and the different types of system that are employed for different applications
- be aware of the basic economic and environmental factors relevant to the use of photovoltaic system.

1 Basic physical principles of photovoltaics

Solar photovoltaic (PV) cells directly harness an energy source that is by far the most abundant of those available on the planet: as you have seen, the net solar power input to the Earth is more than 6 500 times humanity's current rate of use of fossil and nuclear fuels.

Figure 1 The International Space Station is powered by large arrays of solar photovoltaic panels with a combined output of around 130 kW

The PV cell in its most common form is made almost entirely from silicon, the second most abundant element in the Earth’s crust. It has no moving parts and can therefore in principle (if not yet in practice) operate for an indefinite period without wearing out. And its output is electricity, probably the most useful of all energy forms.

Photovoltaic cells consist, in essence, of a junction between thin layers of two different types of semiconductor, known as p-type (positive) and n-type (negative), which we’ll look at next.

1.1 Semiconductors

Semiconductors are materials whose electrical properties are intermediate between those of conductors, which offer little resistance to the flow of electric current, and insulators, which inhibit the flow of electricity. They are usually made from silicon, although as you’ll see PV cells can be made from other materials.

The silicon semiconductors used in photovoltaics are of two types: n-type (negative) and a p-type (positive)

N-type semiconductors are made from crystalline silicon that has been ‘doped’ with tiny quantities of an impurity, usually phosphorus, in such a way that the doped material possesses a *surplus* of free electrons. Because electrons possess a ***negative*** electrical charge, silicon doped in this way is known as an ***n-type*** semiconductor.

P-type semiconductors are doped with very small amounts of a different impurity, usually boron, which causes the material to have a *deficit* of free electrons. These missing electrons are called ‘holes’. Because the absence of a negatively charged electron can be considered equivalent to *a* ***positively*** charged particle, silicon doped in this way is known as a ***p-type*** semiconductor.

P–n junctions

A *p–n junction* is created by joining these dissimilar Negative (n) and Positive (p) semiconductors. This sets up an electric field in the region of the junction, which causes negatively charged particles to move in one direction and positively charged particles to move in the opposite direction.

Light can be considered to consist of a stream of tiny particles of energy, called photons. When photons from light of a suitable wavelength fall within a p–n junction, they can transfer their energy to some of the electrons in the material, so ‘promoting’ them to a higher energy level.

Normally, these electrons help to hold the material together by forming so-called ‘valence’ bonds with adjoining atoms, and in this ‘valence band’ they cannot move. But in their new ‘excited’ state, these electrons have been raised to an energy level known as the ‘conduction band’ and become free to conduct electric current by moving through the material. The difference in energy between the ‘valence’ band and the conduction band is known as the *band gap*.

The essential principles underlying the operation of a silicon solar cell are described in Box 1 below, Figure 2

Box 1: The essential principles underlying the operation of a silicon solar cell

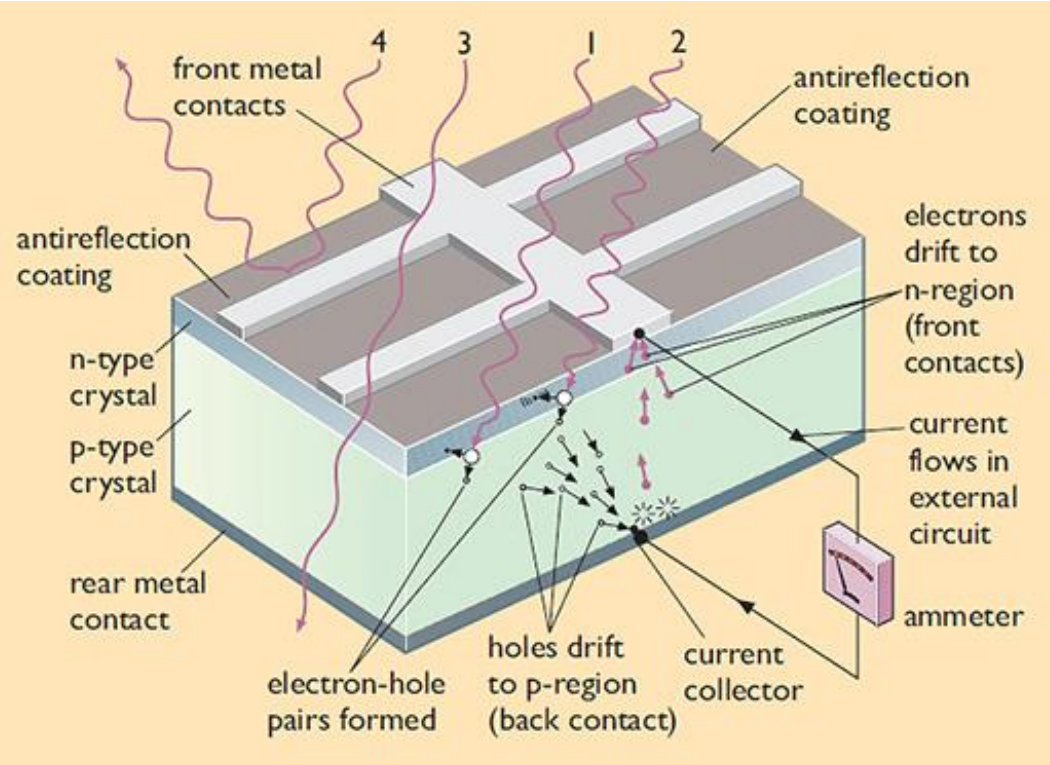


Figure 2 How a silicon solar cell operates

The silicon solar cell shown in Figure 2 above is a wafer of p-type silicon with a thin layer of n-type silicon on one side. When a photon of light with the appropriate amount of energy penetrates the cell near the junction of the two types of crystal and encounters a silicon atom (1), it dislodges one of the electrons, which leaves behind a hole.

The electron tends to migrate up into the layer of n-type silicon and the hole tends to migrate down into the layer of p-type silicon. The electron then travels to a metallic current collector on the front surface of the cell, generates an electric current in the external circuit and then re-emerges in the layer of p-type silicon, where it can recombine with waiting holes.

If a photon with an amount of energy greater than the band gap strikes a silicon atom (2), it again gives rise to an electron–hole pair, and the excess energy is converted into heat. A photon with an amount of energy smaller than the band gap will pass right through the cell (3), so that it gives up virtually no energy along the way.

Some photons are reflected from the front surface of the cell even when it has an antireflection coating (4). Still other photons are lost because they are blocked from reaching the crystal by the current collectors that cover part of the front surface.

(Source for all above text and figure: adapted from (Chalmers, 1976)

Now that you've looked briefly at some basic principles of semiconductors and photovoltaics, we can move on to describe the main PV materials and technologies.

2 Photovoltaic materials and technologies

This section will introduce the principal photovoltaic materials and technologies: crystalline silicone PV, gallium arsenide PV and thin-film silicon PV. You wil also be introduced to some other thin-film PV technologies and concentrating PV systems.

2.1 Crystalline silicon PV

The most efficient silicon solar cells are made from extremely pure monocrystalline silicon – that is, silicon with a single, continuous crystal lattice structure with virtually no defects or impurities.

Monocrystalline silicon is usually grown from a small seed crystal that is slowly pulled out of a molten mass of polycrystalline silicon, in the sophisticated ‘Czochralksi’ process developed originally for the electronics industry. You can see the overall process of monocrystalline PV cell and module production in Figure 3

Polycrystalline silicon essentially consists of small grains of monocrystalline silicon. Solar cell wafers can be made directly from polycrystalline silicon in various ways, which include the controlled casting of molten polycrystalline silicon into cube-shaped ingots, which are then cut into thin, square wafers and fabricated into complete cells in the same way as monocrystalline cells. Polycrystalline PV cells are easier and cheaper to manufacture than their monocrystalline counterparts, but are less efficient.

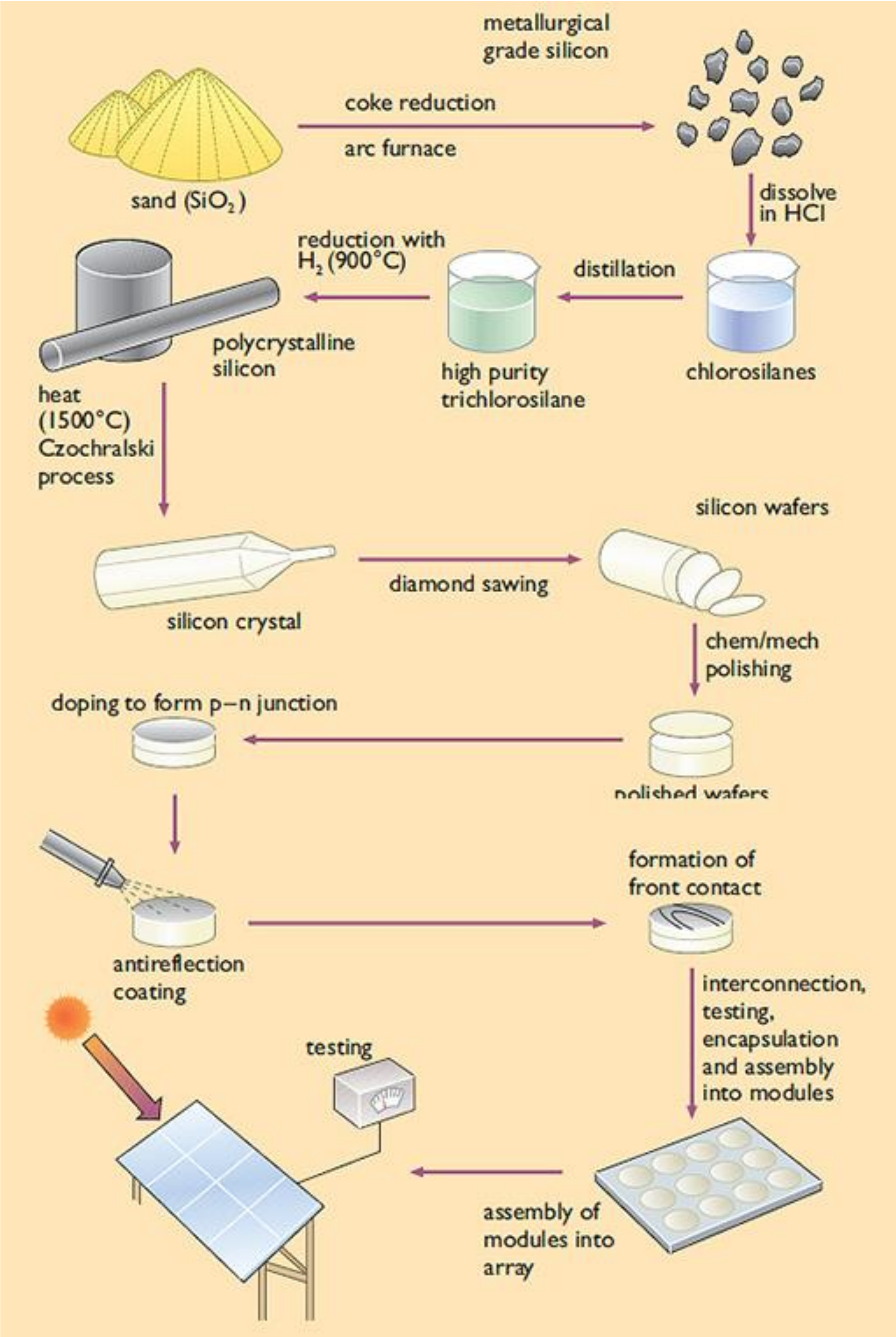

metallurgical
grade silicon
coke reduction
arc furnace
sand (SiO_2)
dissolve
in HCl
reduction with
H_2 (900°C)
distillation
polycrystalline
silicon
high purity
trichlorosilane
chlorosilanes
heat
(1500°C)
Czochralski
process
silicon wafers
diamond sawing
silicon crystal
chem/mech
polishing
doping to form p–n junction
formation of
front contact
antireflection
coating
interconnection,
testing,
encapsulation
and assembly
into modules
testing
assembly of
modules into
array

Figure 3 The overall process of monocrystalline silicon solar cell and module production.

Commercially available polycrystalline PV modules (sometimes called ‘multicrystalline’ or ‘semicrystalline’), typically attain energy conversion efficiencies of around 20%, whereas monocrystalline module efficiencies can exceed 24%.

Activity 1

How much voltage does a typical silicon PV cell produce?

View answer - Activity 1

2.2 Gallium arsenide PV

Another photovoltaic material is gallium arsenide (GaAs) with a crystal structure similar to that of silicon, but consisting of alternating gallium and arsenic atoms - a so-called compound semiconductor. GaAs PV cells are more efficient than cells made from monocrystalline silicon. They have a high light absorption coefficient, so only a thin layer of material is required, and they can operate at relatively high temperatures without substantial reduction in efficiency, which makes them well suited to use in concentrating PV systems (covered in Section 2.5).

But GaAs cells are more expensive than silicon cells, partly because the production process is not so well developed and partly because gallium and arsenic are not abundant materials. They are often used when very high efficiency is required, regardless of cost – as in many space PV applications.

You'll next look at PV using *thin films* of silicon.

2.3 Thin-film silicon PV

Solar cells can also be made from very thin films of silicon, in a form known as amorphous silicon (a-Si), in which the silicon atoms are much less ordered than in the crystalline forms described above.

Amorphous silicon cells are much cheaper to produce than those made from crystalline silicon, and are also better absorbers of light, so thinner, and therefore cheaper, films can be used.

There are also advantages in the manufacturing process:

- it operates at a much lower temperature than that for crystalline silicon, so less energy is required
- it is suited to continuous production
- it allows quite large areas of cells to be deposited onto a wide variety of both rigid and flexible substrates, including steel, glass, and plastics.

However a-Si cells are currently much less efficient than their single-crystal or polycrystalline silicon counterparts. Commercially available a-Si modules achieve module efficiencies of around 10%, and are already widely used as power sources for a variety of consumer products, such as calculators, where the requirement is for low cost rather than high efficiency.

Now you’ll look at other thin-film PV technologies.

2.4 Other thin-film PV technologies

Among the many other thin film PV technologies, some of the most attractive are those based on compound semiconductors, in particular:

- *copper indium diselenide* ($CuInSe_2$, usually abbreviated to CIS)
- *copper indium gallium diselenide* ($CuInGaSe_2$, usually abbreviated to CIGS)
- and *cadmium telluride* (CdTe).

Modules based on these technologies are in production from various manufacturers, with CIGS cells attaining the highest *laboratory* efficiencies of all thin-film devices, around 21%. CIGS modules with stable efficiencies over 17% are *commercially* available.

Cadmium telluride modules can be made using a relatively simple and inexpensive process, and efficiencies over 18% have been achieved under strictly controlled test conditions. But because cadmium is a highly toxic substance, stringent precautions need to be taken during manufacture, use, and eventual recycling.

Other thin-film and innovative technologies entering production or in development include *multi-junction* PV cells, in which there are layers of different p–n junctions, each ‘tuned’ to absorb light from a different part of the solar spectrum. An array of more than 2000 Sharp triple-junction PV cells, with a peak power output of 1.8 kW and an efficiency of 30%, was used to power the electric motors in the prize-winning Tokai Challenger solar car shown in Figure 4. It covered 2998 km in 29 hours 49 minutes at an average speed (during daylight) of 100.54 km per hour.

Figure 4 The winner of the 2009 World Solar Challenge race across Australia was the Tokai Challenger – a solar car (source: Sharp Solar, 2009)

In another innovative approach, photoelectrochemical cells use dye-sensitised layers of titanium dioxide. Still at the research and development stage are ‘third-generation’ photovoltaic systems based on nanotechnology (technology based on the manipulation of materials at an extremely small scale, measured in nanometres) or using organic materials.

You’ll now look at *concentrating* PV systems.

2.5 Concentrating PV systems

The energy output of PV cells can be increased by using mirrors or lenses to concentrate the incoming solar radiation onto the cells.

This enables fewer PV cells to be used for a given power output. As you saw last week (Section 2.9), the concentration ratio can vary from as little as two to several hundred or even several thousand times.

The concentrating system must have an aperture equal to that of an equivalent flat plate array to collect the same amount of incoming solar energy. In concentrating photovoltaic systems, the cells are often cooled, either passively or actively, to prevent overheating that would decrease the efficiency of the cells.

Activity 2

What is the main difference between systems with high and low concentration ratios?

View answer - Activity 2

Photovoltaic systems are often used to supply power in remote locations, and you'll now look at some examples.

3 Photovoltaic systems for remote power

Photovoltaic modules are now widely used in ‘developed’ countries to provide electrical power in locations where it would be inconvenient or expensive to connect to conventional grid supplies. They are often used to charge batteries to ensure continuity of power.

Some common examples are shown in Figure 5.

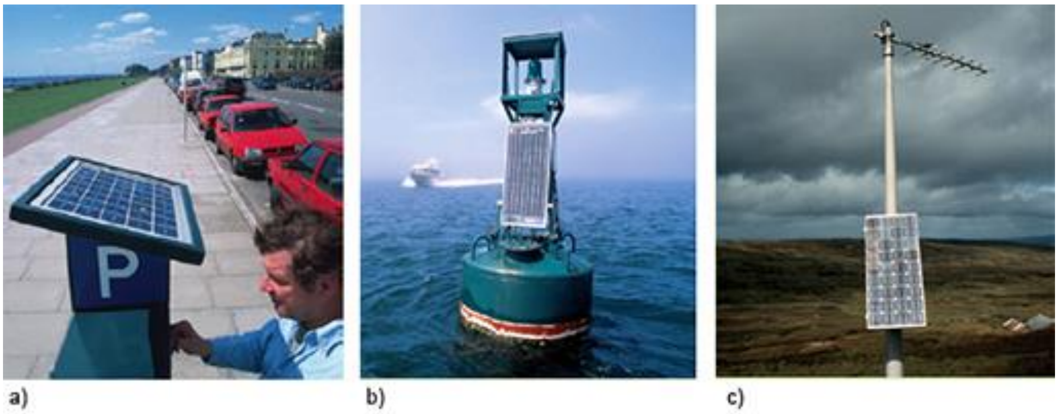


Figure 5 Common examples of PV remote power use (a) PV parking meter (b) PV navigation buoy (c) PV telemetry system

But in many ‘developing’ countries electricity grids are often non-existent or rudimentary, particularly in rural areas, and all forms of energy are usually very expensive. In such countries electricity from PV can be highly competitive with other forms of energy supply – especially in countries with high solar radiation levels – and its use is growing very rapidly.

Applications include:

- PV-powered water pumping
- PV refrigerators to help keep vaccines stored safely in health centres
- PV systems for homes and community centres, providing energy for lights, radios, audio and video systems
- PV-powered telecommunications systems
- PV-powered lighting for streets.

You'll now look at PV systems connected to electricity grids in 'developed' countries, starting with PV systems for individual houses.

4 PV systems for houses

In most parts of the ‘developed’ world, grid electricity is easily accessible as a convenient backup to PV or other fluctuating renewable energy supplies. The grid can absorb PV power that is surplus to current needs (say, on sunny summer afternoons), making it available for use by other customers and reducing the amount that has to be generated by conventional means; and at night or on cloudy days, when the output of the PV system is insufficient, the grid can provide backup energy from conventional sources.

Figure 6 In this solar house in Oxford, UK, the 4 kW grid-linked array of monocrystalline PV modules supplies the house's annual electricity requirements, plus a small surplus used to provide some of the power for a small electric car

In these *grid-connected* PV systems, such as the one shown in Figure 6, an *inverter* transforms the direct current (DC) power from the PV arrays into alternating current (AC) power at a voltage and frequency that can be accepted by the grid, while 'debit' and 'credit' meters measure the amount of power bought from or sold to the utility. In the UK and some other countries, 'Feed-in Tariffs' (FiTs) have been introduced which provide for premium payments to be made for power produced by grid-connected PV arrays and other renewable sources.

In the UK, surveys have suggested that about half of all roofs are oriented in a direction sufficiently close to south to enable them to be viable for solar collection purposes. PV arrays can be added to the roofs of existing dwellings, and in new dwellings they can in some circumstances replace all or part of the conventional roof.

PV arrays can also be used on non-domestic buildings, as you'll see the next section.

5 PV systems for non-domestic buildings

The large development at Amersfoort in the Netherlands shown in Figure 7 has a total of 1 MW of PV generating capacity installed on the roofs of houses, schools and community buildings. The PV arrays are owned by the local electricity company, which pays homeowners for the electricity they produce.

Figure 7 Large PV arrays at Amersfoort, Netherlands

Watch this video for more details of the Amersfoort PV project. The first speaker is Professor Erik Lysen of the University of Utrecht.

Video content is not available in this format.

PV arrays can also be integrated into the roofs and walls of commercial, institutional and industrial buildings, replacing some of the conventional wall cladding or roofing materials that would otherwise have been needed and reducing the net costs of the PV system (see Figure 8 and Figure 9). In the case of some prestige office buildings, the cost of conventional cladding materials can exceed the cost of cladding with PV. Commercial and industrial buildings are normally mainly occupied during daylight, which correlates well with the availability of solar radiation.

Figure 8 This solar office building at Doxford, near Sunderland in the UK, has a 73 kW PV array integrated into its south-facing façade. The building also incorporates energy-efficient and passive solar design features to minimise its need for heating and lighting.

Figure 9 This 30 kW crystalline silicon PV array is installed on the roof of the central catering 'hub' at The Open University in Milton Keynes, UK

In many countries the PV market has been stimulated by Feed-in Tariffs (FITs) giving PV system owners and operators high prices for their output electricity. In the case of large schemes these payments are based on metered output. For small domestic users they are based on estimates from the system size and orientation. The price of electricity from PV projects around the world has been falling and appears to be reaching ‘grid parity’ in many sunny countries, i.e. a price competitive with conventional electricity generation. This has led to reductions and even withdrawals of FITs for new schemes.

Next you’ll look at PV systems for supplying power on a much larger scale, to local or regional electricity grids.

6 Large PV power plants

Large, PV power systems, many on a multi-megawatt scale, have been built to supply power for local or regional electricity grids in a number of countries, including Germany, Switzerland, Italy, China, India and the USA.

Land used for PV can often be compatible with its use for other purposes. For example the 1 MW ‘sun farm’ shown in Figure 10 has been designed to allow ‘wildlife-friendly’ plants to live underneath the PV arrays. The need to avoid overshading of one ground-mounted panel by another, particularly in winter, means that they may only occupy 30–50% of the ground area, particularly at high latitudes, leaving space for wildlife and plants.

Figure 10 This 1 MW ‘sun farm’ in Lincolnshire, UK, is adjacent to a wind farm, with the aim of enabling the higher electricity contribution from wind in winter to compensate for lower electricity output from PV, and vice versa in summer (source: Ecotricity)

Large PV power plants are attractive in those areas of the world that have substantially greater annual total solar radiation than northern Europe, such as North Africa or southern California. Such areas also have clearer skies, which means that the majority of the radiation is direct, making tracking and concentrating systems effective and further increasing the annual energy output.

Figure 11 A 48 MW_p solar PV facility in Boulder City, Nevada, USA commissioned in 2011. It uses cadmium telluride cells (Source: Sempra generation).

Activity 3

What do you think are the advantages and disadvantages of large, stand-alone PV plants compared with building-integrated PV systems?

View answer - Activity 3

7 Energy yield from PV systems

The annual and monthly amounts of energy that will be produced by a PV system depend on a number of factors, including:

- the annual total quantity of solar radiation available at the site
- the orientation and tilt of the PV arrays
- the peak power rating of the arrays
- the energy conversion efficiency of the PV modules
- the variation in the efficiency of the modules with temperature
- the power-reducing effects of array shading by trees, nearby buildings, accumulation of dirt etc
- the efficiency of the inverter, and any losses that occur in the wiring between the PV system and the final consumer.

The European Union's Joint Research Centre at Ispra, Italy, has produced PVGIS (PV Geographical Information System), an online tool giving solar radiation data and estimated PV outputs for Europe, Africa and parts of Asia. Users can input the geographic location, type of module, its power rating, array orientation etc., and the software will calculate the expected monthly and annual energy yield ((EU-JRC-IET, 2012)

Key aspects of this information are summarised in the map Figure 12

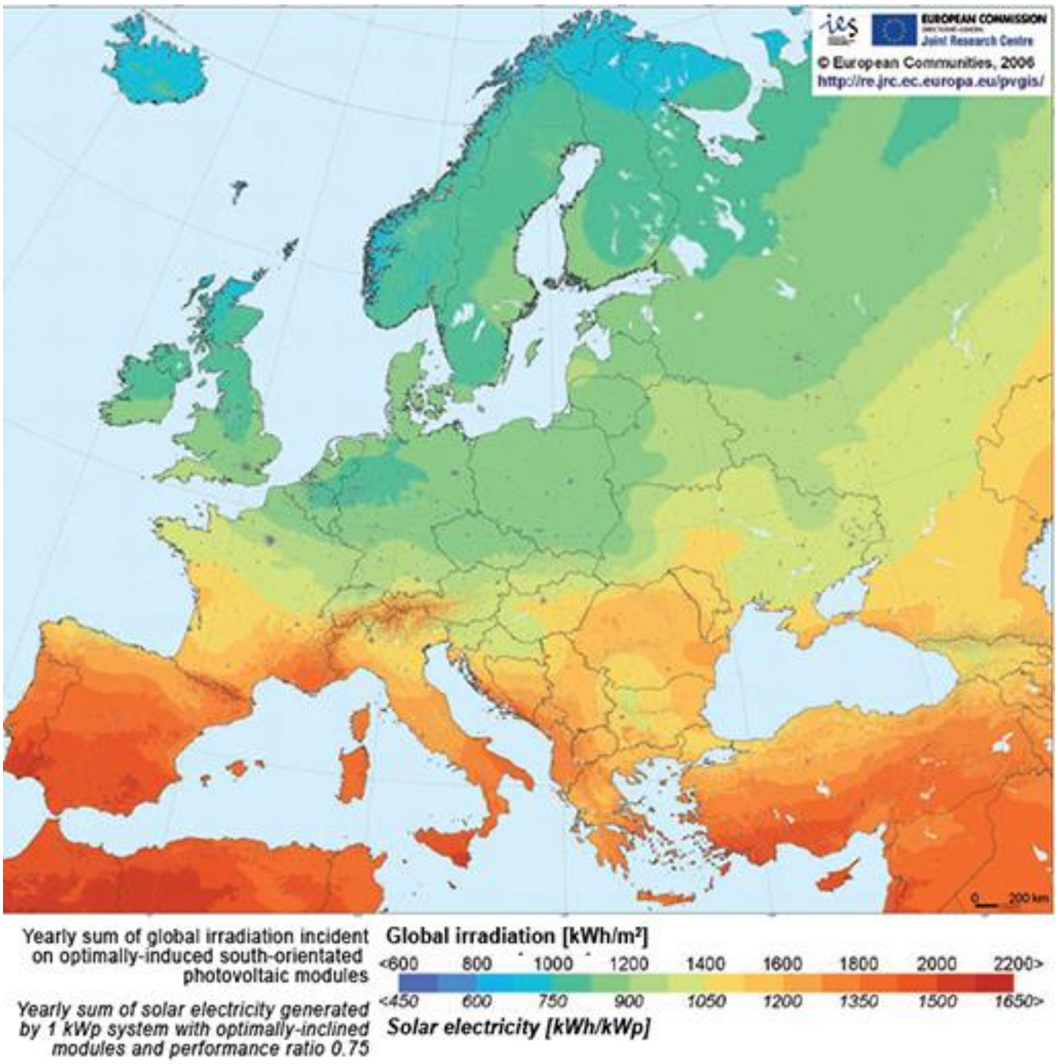


Figure 12 Solar radiation map of Europe, showing annual energy yields of optimally oriented PV arrays in various European locations. (‘Performance Ratio’ is the ratio of actual to theoretical maximum PV array output.)

You'll now look at the economics and environmental impact of energy from photovoltaics.

8 PV economics and environmental impact

As with any energy source, the cost per kilowatt-hour of power from PV cells consists essentially of a combination of repayment of the capital cost, including interest, and the operation and maintenance (O&M) cost.

The *capital* cost of a PV energy system is proportional to its rated power output, usually quoted in £ (or euros or dollars) per peak kW (£ kW_p^{-1}). This includes not only the cost of the PV modules themselves, but also the ‘balance of system’ (BOS) costs, i.e. the costs of the interconnection of modules to form arrays, the array support structure, land and foundations (if the array is not building-mounted), the costs of cabling, charge regulators, switching, metering and inverters, plus the cost of either storage batteries or connection to the grid.

Activity 4

From what you have learned so far, what would you say are the economic pros and cons of PV systems?

View answer - Activity 4

Over the past decade in many countries there has been a rapid decline in the price of electricity from PV and a steady increase in the price of electricity from conventional sources. In many regions with high solar radiation levels the price of PV power is already competitive with expensive daytime ‘peak’ power from electric utilities and auction prices for future developments are close to parity with off-peak ‘bulk’ prices, as you can see from Figure 13 which also shows projections of costs up to 2040.

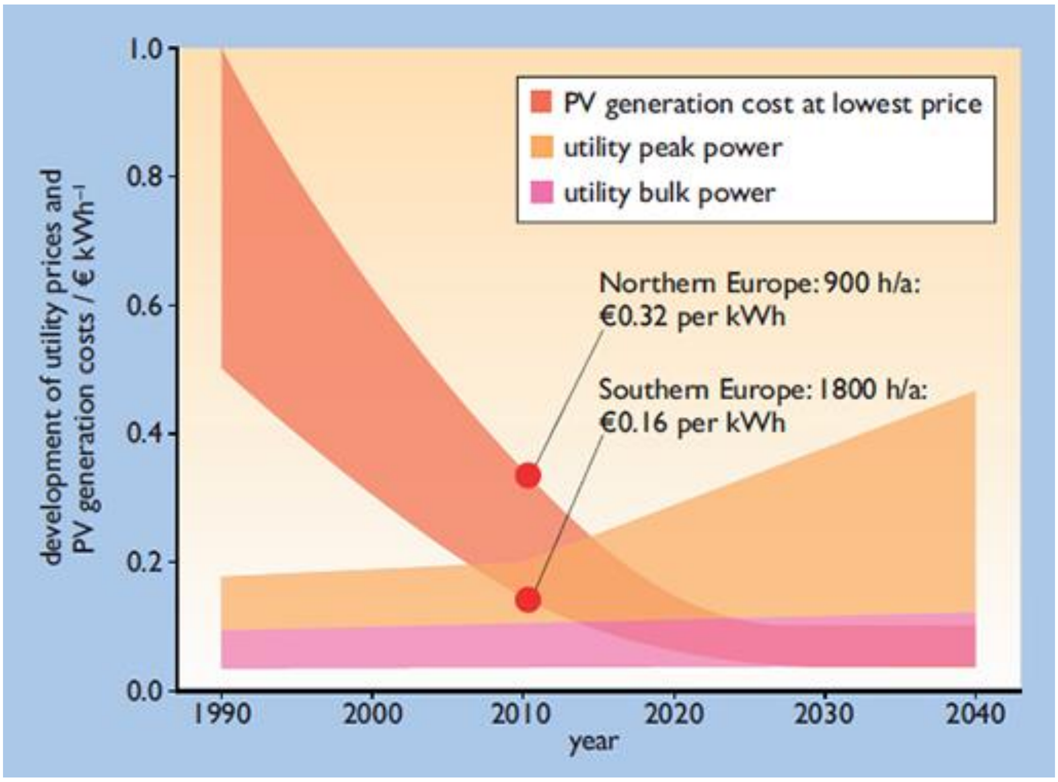


Figure 13 Progress towards ‘grid parity’: convergence of utility electricity prices and PV costs, 1990 to 2010 and projection to 2040 (source: (EPIA; Greenpeace, 2011); bid data from (IRENA, 2016)).

In many countries contracts for very large PV systems >500 MW_p are currently being sold in auctions for the lowest ‘bid price’. This has resulted in very low prices of under 4p kWh^{-1} in Mexico, Brazil, the USA, Saudi Arabia and the United Arab Emirates (IRENA, 2017). These prices are truly competitive with conventional fossil-fuelled generation from oil and gas.

In order for full grid parity to be reached in less sunny regions the *installed* cost per peak kilowatt of PV systems needs to decrease still further. The key to this lies in mass production, although technological improvements can also make a contribution. Historically, PV module production costs have dropped by more than 20% for every doubling of production quantity and in the past decade PV production has doubled every 2–3 years.

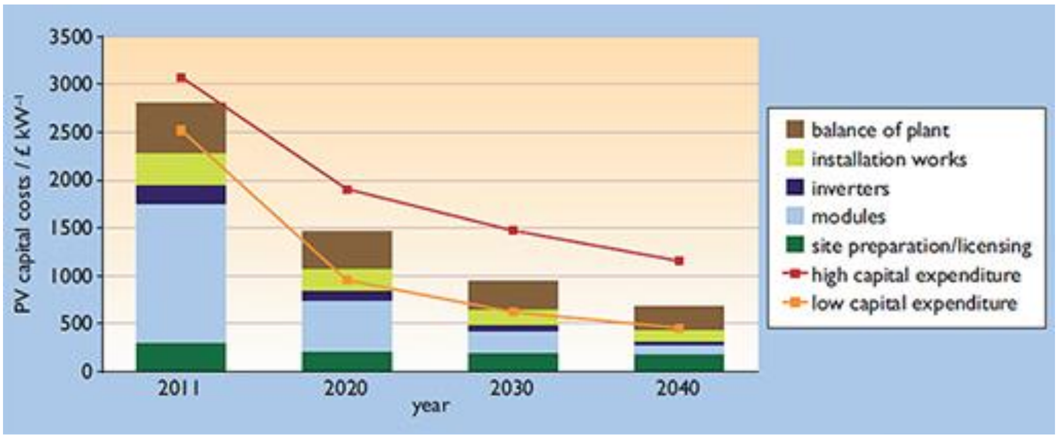


Figure 14 Capital costs of solar PV systems in the UK in 2011, and projected capital costs in 2020, 2030 and 2040 (source: (CCC, 2011)).

Figure 14 shows a breakdown of the capital costs of a large PV system in the UK in 2011, together with long-term projections of its likely costs in 2020, 2030 and 2040, these costs relating to a large, 10 MW ground-mounted system. The lines indicate the range of variation of capital cost estimates. They suggest that capital costs could be halved by 2030 and fall to perhaps a quarter of 2011 levels by 2040. The capital costs of smaller PV systems are expected to fall in similar fashion (CCC, 2011).

Having looked at the economics of PV, let's now move on to its environmental impact.

8.1 Environmental impact and safety

The environmental impact of photovoltaic energy is probably among the lowest of all electricity generating systems.

This is because:

- In normal operation PV energy systems emit no gaseous or liquid pollutants and no radioactive substances.
- Crystalline silicon PV cells contain only minuscule quantities of dopants such as boron and phosphorus. (However CIS or CdTe modules include very small quantities of indium, cadmium and tellurium, so there is a slight risk that a fire in an array might cause small amounts of toxic material containing these elements to be released into the environment and it is important that these cells are properly recycled at the end of their working life.)

- PV modules have no moving parts, so they are also safe in the mechanical sense, and they emit no noise.
- The electrical hazards of a well-engineered PV system are no greater than those of other comparable electrical installations.

PV arrays do, of course, have some visual impact. Rooftop arrays will normally be visible to neighbours, and may or may not be regarded as attractive, according to aesthetic tastes. Several companies have produced special PV modules in the form of roof tiles that blend into roof structures more unobtrusively than conventional module designs.

PV arrays on buildings require no additional land, but large, multi-megawatt PV arrays will usually be installed on land specially designated for the purpose, and this will entail some visual impact.

Environmental impact and safety of PV production

The environmental impact of manufacturing *silicon* PV cells is unlikely to be significant – except in the unlikely event of a major accident at a manufacturing plant. The majority of PV cells are made from silicon, which is not intrinsically harmful although it is important that workers not be exposed to dust produced during the manufacturing process.

The chemicals used in silicon production must also be treated with care. Silane gas, SiH_4, from which pure silicon is produced, is inflammable and waste silicon tetrachloride ($SiCl_4$), which is highly toxic, can also be produced. Sulphur hexafluoride and nitrogen trifluoride, which are both potent greenhouse gases, are used for cleaning purposes and must not be released into the atmosphere.

Cadmium is obviously used in the manufacture of CdTe modules and very small amounts of cadmium may also be used in manufacturing CIS and CIGS modules – although zinc may potentially be substituted.

As in any chemical process, careful attention must be paid to plant design and operation, to ensure the containment of any harmful chemicals in the event of an accident or plant malfunction.

PV arrays are potentially very long-lived devices, but eventually they will come to the end of their useful life and will have to be disposed of – or, preferably, recycled. Since 2014 EU recycling regulations under the Waste Electrical and Electronic Equipment (WEEE) directive make it compulsory for manufacturers to take back and recycle at least 85% of their PV modules free of charge.

Energy balance of PV systems and potential materials constraints

A common misconception about PV cells is that almost as much energy is used in their manufacture as they generate during their lifetime. In the early days of PV production, manufacturing processes were very energy-intensive, and the efficiency of the cells was relatively low, leading to low lifetime energy output.

However, modern cells are more electrically efficient and the use of modern PV production processes and thin film cells has made the energy balance of PV much more favourable. The time it takes for a PV array to produce as much energy as was used in its production (its *energy payback time*) varies depending on the array type and the conditions. For new multicrystalline silicon PV rooftop systems in northern European conditions it is about 2.1 years. This falls to only 1.2 years for systems in southern Europe, while cadmium telluride PV systems pay back their energy investment in about 0.6 years in southern European conditions (Fraunhofer ISE, 2017).

Concerns have also been expressed over the availability of ‘rare earth’ elements such as indium and tellurium, used in thin film PV. PV cell manufacture was, in 2015, using about 5% of the world’s silver production for cell contacts (Wirth, 2015). Given that this is expensive, there is commercial pressure to reduce the amounts used.

9 PV integration into electricity systems

During daylight hours in locations with mainly clear skies, PV power is quite reliable, but in places where passing clouds reduce array output it can be more intermittent. In the UK, most PV power would be produced in summer, when electricity demand is relatively low, but less is produced in winter when demand is higher.

Activity 5

In what ways would national energy systems need to be modified to cope with long, medium and short-term fluctuations in the output of PV arrays?

View answer - Activity 5

The subject of integration of PV and other renewables into electricity systems will be covered in more detail in Week 8

And for the last topic this week, you’ll now look at how the global PV market is growing.

10 The growing world PV market

Since the beginning of the 21st century world installed PV capacity has grown extremely, from some 1.5 GW in 2000 to just under 306.5 GW in 2016. Before 2010 most of the expansion occurred in the EU but in recent years China, Taiwan and India have become the main engines of growth with China alone expected to reach nearly 200 GW_p installed capacity by 2021 but with significant increases in all regions. Ironically the trailblazer, Europe, has fallen behind in recent years though a combination of the need to reach the EU 2020 renewable energy targets, renewed commitments under the Paris accords and the rapid reduction in cost is expected to lead to a new growth phase in most European states over the next few years.

Crystalline silicon still dominates PV technology in the marketplace, and in 2015 monocrystalline and polycrystalline modules accounted for some 93% of world production, with almost all the remainder consisting of thin-film technologies such cadmium telluride (CdTe). However significant developments in both cell technologies and manufacturing processes hold the potential for greater flexibility and higher efficiency at a lower cost, so this hegemony may not last much longer. (IRENA, 2017)

Medium-term projections of the world PV market by Solar Power Europe (formerly the European Photovoltaics Industry Association) suggest that strong growth is likely to continue, resulting in between 625 GW and 930 GW of installed capacity by 2021 (see Figure 15). Much of this growth will be driven by newly emerging markets such as India and Brazil, and even though the growth of the PV market in China is expected to slow, the country is still expected to add 120 GW capacity between 2017 and 2021, giving it more than one fifth of the world’s total.) (Solar Power Europe, 2017).

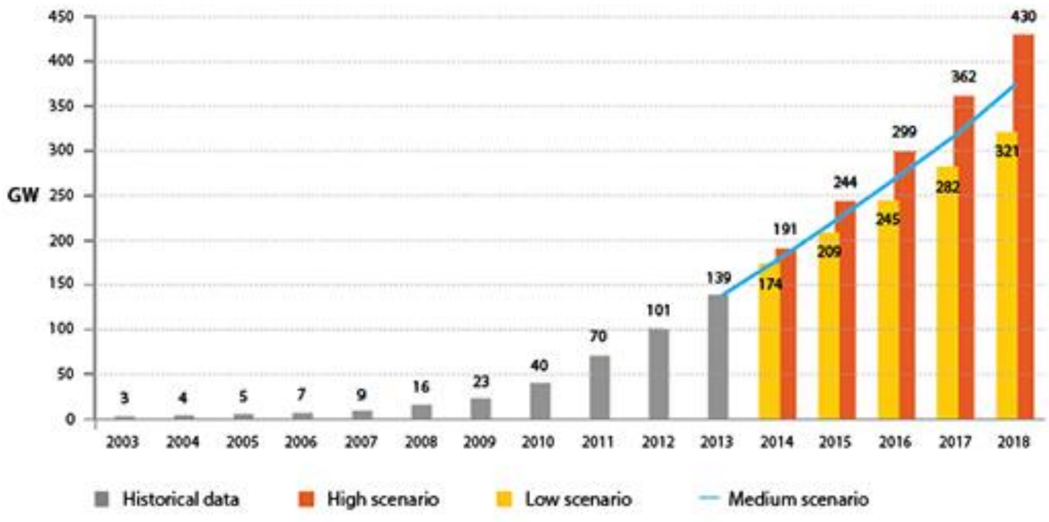


Figure 15 Growth in cumulative global photovoltaics capacity, 2010 to 2021. Source, (Solar Power Europe, 2017)

Looking much further ahead, to 2050, the International Energy Agency, in its 2014 *Energy Technology Perspectives* report (IEA, 2014) has produced a number of 'Two Degree Scenarios' (2DS) illustrating the measures the world needs to adopt if the increase in global surface temperature is to be limited to two degrees. In one of these, the Two Degree High Renewables (2DS hi-Ren) scenario shown in Figure 16, the share of PV electricity generation capacity rises to over 6 000 terawatt hours, supplying some 18% of projected world electricity, by 2050.

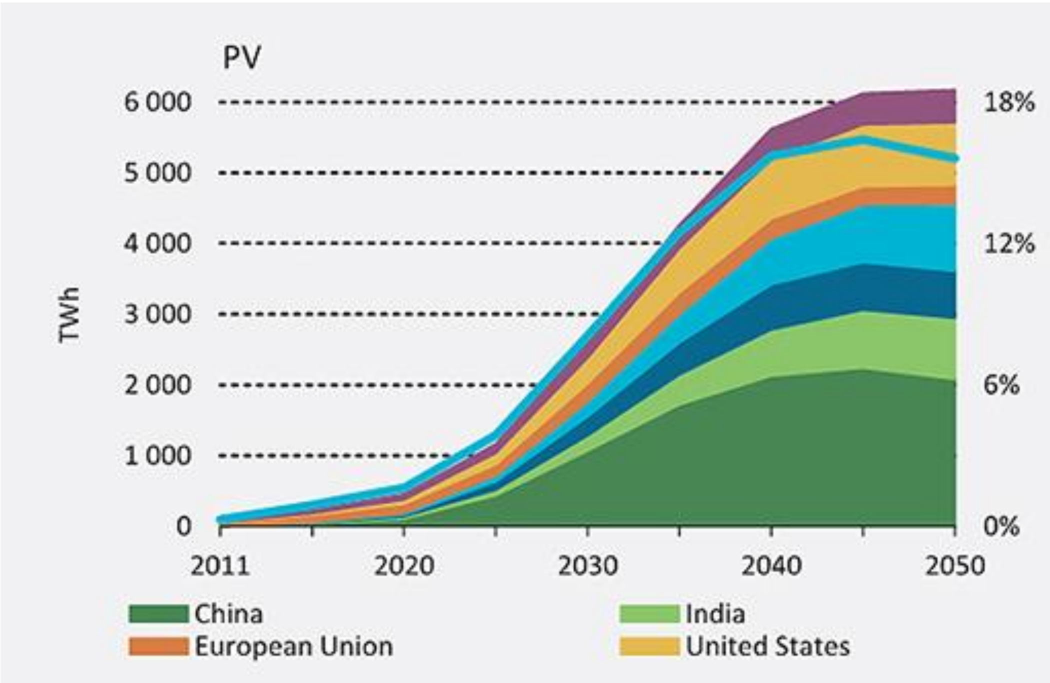


Figure 16 Growth of World PV generation 2011-2050 in the High renewables version of the IEA Two Degree Scenario (2DS hi-Ren)

Long-term expert projections such as those of the SolarPower Europe, the IEA, and in the UK the Climate Change Committee, are subject to a very wide range of uncertainty.

Nevertheless, the future prospects of photovoltaics as a clean, renewable source of energy for the world by mid-century do seem bright.

For an inspiring – and literally uplifting – symbol of the rising hopes of the global PV industry: have a look at the ‘Solar Impulse’ project shown in Figure 17. This solar PV-powered single-seat aircraft is powered by some 11 625 monocrystalline PV cells of 22% efficiency, mounted on the wings and tail. Four 7.5 kW electric motors drive the propellers and electrical storage is provided by lithium polymer batteries. From its maiden flight in 2009 the aircraft successfully completed flights of increasing duration in Europe before finally achieving the ultimate aim of a PV-powered round-the-world flight in 2016.

Figure 17 The Solar Impulse, a PV-powered single-seater aircraft. (Solar Impulse, 2011b)

The leaders of the project, Bertrand Piccard and André Borschberg, don't see PV powered aircraft replacing conventional aircraft in the foreseeable future. On landing after Solar Impulse's first international flight, Piccard indicated that the project's goal was not to cause a revolution in aviation: its aim was to promote a revolution in the mindset of people when they think about renewable energy, energy saving and new technologies (Solar Impulse Foundation, 2016)

Next you can have a go at the Week 3 quiz.

11 Week 3 quiz

Check what you've learned this week by taking the end of week quiz.

Week 3 practice quiz.

Open the quiz in a new window or tab then come back here when you've finished.

12 Summary

To sum up the learning this week, you have:

- had a brief look at basic principles of photovoltaic energy conversion, concentrating initially on devices using monocrystalline silicon
- described the basic electrical characteristics of PV cells and modules
- discussed the various roles of PV energy systems in supplying power to homes and other buildings, and in feeding power into local or national electricity grids
- reviewed the economic prospects and the environmental impact of photovoltaic electricity
- examined how PV might be increasingly integrated into electricity supplies
- looked at the world market and future prospects for photovoltaics.

You can now go to Week 4.

Week 4: Bioenergy

Introduction

This week you'll look at *bioenergy* – the most ancient form of renewable energy, if we think of the wood fires used by our early ancestors. This form of 'traditional biofuel' is still widely used in many 'developing' countries. As you'll see, bioenergy is now a much more modern energy source – but still essentially derived from the growth of plants.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- discuss at a basic level the main processes by which bioenergy in various forms can be extracted from biomass
- Present an overview of the merits of different biomass sources and processes in specified contexts, and discuss the environmental and social issues involved
- understand at an introductory level the potential contribution from a specified biomass source, and its cost, given relevant data.

1 Introducing bioenergy

Bioenergy is the general term for energy derived from materials which are, or were recently, living matter, such as:

- wood
- straw
- oilseeds
- animal wastes.

They are collectively referred to as *biomass*.

All the Earth's living matter, its total biomass, exists in the thin surface layer called the *biosphere,* which forms only a tiny fraction of the total mass of the Earth but represents an enormous store of chemical energy.

Although the majority of this is unavailable for human use, it is a store that is continually replenished by the flow of energy from the Sun, through the process of *photosynthesis*. As you can see from Figure 4.1, in this process carbon dioxide is taken from the air and combined with water from the surrounding environment to make living organic material, releasing oxygen in the process. In addition, a small fraction of the carbon from decomposing animal and plant residues (including roots) is transformed into soil organic matter, a significant carbon store.

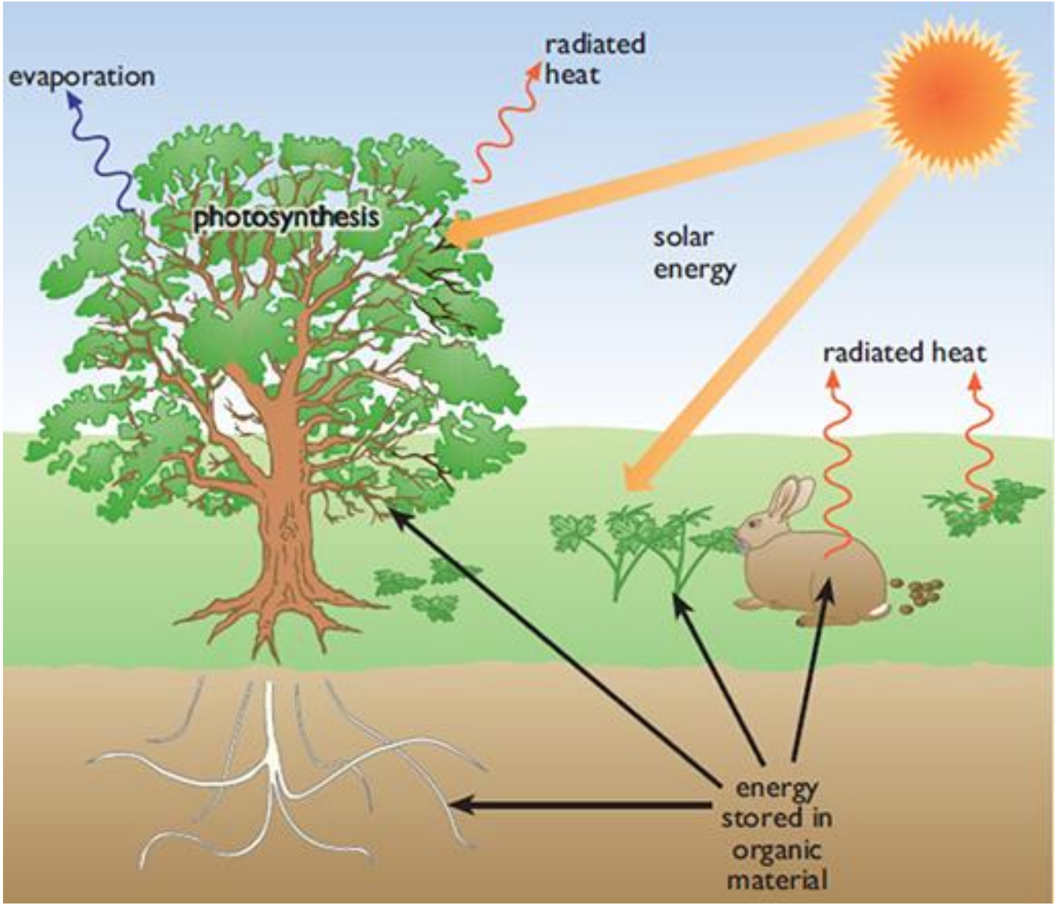


Figure 1 The bioenergy cycle on a local scale

If we intervene and 'capture' some of the biomass at the stage where it is acting as a store of chemical energy, we can use it as a *fuel*, that is, a material that can release useful energy through a change in its chemical composition, usually through burning. This generates heat that can be used directly or to raise steam for electricity generation.

Biomass can also be converted into intermediate *biofuels* such as:

- charcoal
- biogas
- bioethanol
- biodiesel.

Provided our consumption does not exceed the natural level of production, the burning of biomass should generate no more heat and create no more carbon dioxide than would have been formed in any case by natural processes.

> Recent estimates of the annual contribution to world primary energy from *traditional* biomass fall in the range 40–60 EJ.
>
> (Bauen et al., 2009)

The estimate given in Week 1 is based on a contribution of 30 EJ, with industrially processed biomass adding a further 9 EJ or so (BP, 2010).

Traditional biomass energy accounts for about a third of total primary energy consumption in the developing countries. In the industrialised world, the energy contribution from biomass is significant and rising, particularly in countries with large forestry industries such as Sweden and Finland.

Next you'll look at how biomass works as a solar energy store.

2 Biomass as a solar energy store

The key mechanism in the use of bioenergy is photosynthesis, in which plants take in carbon dioxide (CO_2) and water (H_2O) from their surroundings and use energy from sunlight to convert these substances into plant biomass.

The essential features of the process can be represented by the chemical equation:

Figure 2 Chemical equation for photosynthesis

The first product – glucose ($C_6H_{12}O_6$), is a carbohydrate, which can be converted within the plant into more complex carbohydrates including starches and cellulose, or can be combined with nitrogen and other elements to form proteins and other components. The second product is oxygen, which is released to the atmosphere.

Some of the energy-rich carbohydrate formed is broken down elsewhere in the plant through the process of *respiration* (photosynthesis in reverse) with oxygen taken in, carbon dioxide given off and energy released. You can see by looking at Figure 3 how this carbon cycle works on a local scale:

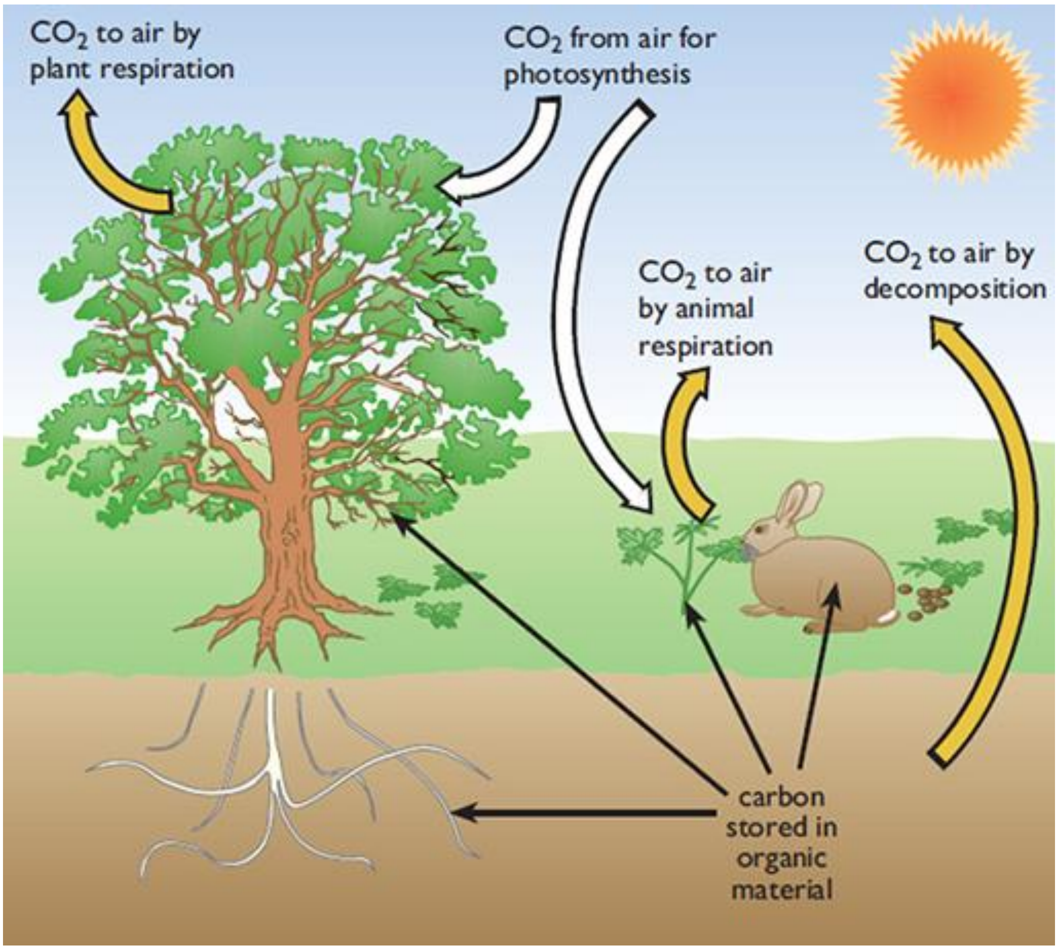


Figure 3 The carbon cycle on a local scale

How much energy can you obtain from biomass? You'll look at that in the next section.

2.1 How much energy from biomass?

The *yield* of a crop (whether grown for food, fibre or fuel) is the mass of biomass produced per hectare per year and is the primary determinant of the energy we can obtain from that crop.

Activity 1 Variations in yield of crops

What factors do you think would contribute to variations in the yield of a crop?

View answer - Activity 1 Variations in yield of crops

These variations mean that for energy crops the air-dry mass of plant matter produced annually on an area of one hectare can be as little as one dry tonne or as much as thirty dry tonnes. In energy terms, this represents a range from perhaps 15 GJ to 400 GJ per hectare per year.

How can this energy produced be extracted and turned into something useful? You’ll see in the next section.

3 Biomass as a fuel

Fuels are materials from which useful energy can be extracted. In using biomass as fuel, this release of energy usually involves burning – known as *combustion*.

Some essential features of combustion are:

- it needs air – or to be more precise, oxygen
- the fuel undergoes a major change of chemical composition
- heat is produced, i.e. energy is released.

Consider for example, *methane* – the principal component of the fossil fuel natural gas and also one form of gaseous biofuel. As shown in Figure 4.4, each methane molecule consists of one carbon and four hydrogen atoms: CH_4. Atmospheric oxygen has molecules consisting of two atoms (O_2). In combustion, each methane molecule reacts with two oxygen molecules to produce carbon dioxide and water. The heat energy released is the difference between the chemical energy of the original fuel plus oxygen, and the chemical energy of the resulting carbon dioxide plus water. It is the *energy content* (or heat content) of the methane.

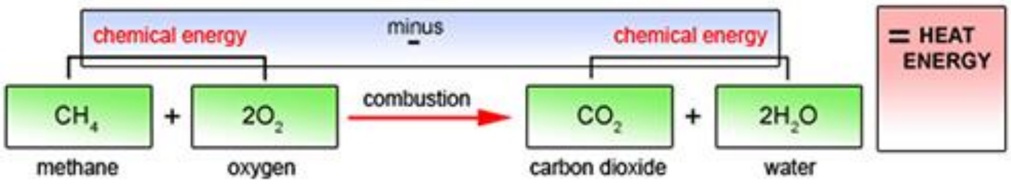


Figure 4 Chemical equation representing the combustion of methane yielding carbon dioxide, water and heat

Table 1 shows the energy content of the crop produced by burning one tonne, or one cubic metre, of various biological materials.

Table 1 Typical heat energy content per unit of dry mass and volume of various forms of biomass and fossil fuel

Category	**Major energy-rich components**	**Structural strength/resistance to natural decay**	**Examples**	**Typical yields of dry matter /4 ha^{-1} y^{-1}**
Woody biomass	Lignin/lignocellulose (complex carbohydrates)	High	Trees (deciduous or hardwoods)	10 (temperate) to 20 (tropics)
Cellulosic biomass	Lignin/lignocellulose (complex	Medium	Grasses (e.g miscanthus). Water hyacinth, seaweeds	10 (temperate) to 60 (tropical aquatics)

	carbohydrates)			
Starch/sugar crops	Simpler carbohydrates	Low	Cereaks (maize, sugar cane, wheat)	10 (temperate cereals) to 35 (sugar-cane)
Oily crops	Lipids (i.e. oils/fats)	Low	Oilseeds (rape, sunflower, oil palm. Jatropha)	8 to 15
Micro organisms	Oils	Low	Microalgae	Unknown – still speculative

* Indicates dependence on specific types of material.

Data from various sources including former UK Biomass Energy Centre (Carbon Trust, 2008) and (BEIS, 2016) via

4 Biomass energy from plants

Energy crops – plants grown specifically to provide bioenergy – have attracted increasing attention in recent years.

From Table 2, you'll see that these plants can be categorised broadly according to the physical and chemical nature of the biomass involved. It shows typical yields and the energy content of the crop produced by burning various biological materials. The heat content combines the calorific value of biofuels produced from the crop and the heat content of the residue that can be burned. A wide variation both in crop yield and energy content may be seen, though clearly tropical areas such as Brazil and Indonesia have significantly greater biomass potential per unit area than temperate climes such as Europe.

Table 2 Typical yields and heat energy content produced per unit area of various forms of biomass. Adapted from (Long et al., 2015)

Category	Major energy-rich components	Structural stength/resistance to natural decay	Examples	Typical yields of dry matter /t ha^{1} y^{1}
Woody biomass	Lignin/lignocellulose (complex carbohydrates)	High	Trees (deciduous or hardwoods)	10 (temperate) to 20 (tropics)

Cellulosic biomass	Cellulose/lignocellulose (complex carbohydrates)	Medium	Grasses (e.g. miscanthus), water hyacinth, seaweeds	10 (temperate) 60 (tropical aquatics)
Starch/sugar crops	Simpler carbohydrates	Low	Cereals (maize. sugar cane, wheat	10 (temperate cereals to 35 (sugar-cane)
Oily crops	Lipids (i.e. oil/fats)	Low	Oilseeds (rape, sunflower, oil palm, jatropha)	8 to 15
Micro organisms	Oil	Low	Microalgae	Unkown - still speculative

These categories overlap to a considerable extent, so some crops may be grown primarily for their sugar or starch content but their supporting lignocellulosic (woody) structural materials may also be used for other purposes.

4.1 Woody biomass

Well-managed forests can provide a sustainable fuel source, reducing atmospheric CO_2 as the trees grow, storing it for up to a few centuries and providing a substitute for fossil fuel when felled.

Figure 5 A field of short rotation coppice (SRC) willow

In recent years there has been increased interest in woody crops planted and harvested entirely for energy production.

Activity 2 Management system for woody crops

What is the most common management system for these types of woody crops?

View answer - Activity 2 Management system for woody crops

The cellulose in plants that are non-woody is also used to provide fuel, and you'll move on to this subject next.

4.2 Cellulosic materials

The structural integrity of non-woody (i.e. herbaceous) plants is provided mainly by *cellulose*, which is a major component of the straw and other supporting tissues of all the major food crops.

The most common cellulosic bioenergy crop for temperate climates is the tall grass *miscanthus*.

Figure 6 Harvesting miscanthus using conventional agricultural machinery

Other common plants that may be suited to production of cellulosic biomass are:

- bracken
- *Gunnera*
- kelp
- water hyacinth.

What other crops can be used? You'll find out in the next section.

4.3 Other energy crops

Starchy and sugary crops

The major biomass energy component of these crops, examples of which are shown in Figure 7, is their sugar or starch, which can be fermented to produce ethanol. Their supporting cellulosic tissues may also be used in the same way as the mainly cellulose crops. Globally, the most important crops for bioenergy purposes are sugar cane and maize.

Figure 7 Starch/sugar crops: (a) sugar cane, (b) maize harvesting, (c) sugar beet

Another sugar-rich crop of interest in Europe is sugar beet, where the roots contain 15–20% sugar. Sugar-cane bagasse (the sugar cane's fibrous residue) and the straw from maize and other cereals can also be used for energy, in the same way as for cellulosic crops.

Oilseed crops

Sunflowers, oilseed rape and soya beans are grown widely for the oil in their seeds, while in tropical areas, oil palm (*Elaeis guineensis*) is a major crop.

The oils from these crops can be converted to a diesel substitute known as *biodiesel*. As with the starchy/sugar crops considered above, there is a residue left from these processes that is currently often used as animal feed, but which could be a bioenergy feedstock.

The oil from all these crops has a vast number of uses, for example in foods and cosmetics/ However, there are widespread misgivings about the conversion of mature forests to palm oil plantations in South-East Asia and elsewhere. The use of palm oil for bioenergy could lead to an increase in such problems.

Some types of algae can also be used to produce energy, as they too photosynthesise. You'll look at this in the next section.

4.4 Microalgae and other microorganisms

Seaweeds are one form of large algae, but there are also single-celled aquatic microalgae and cyanobacteria that photosynthesise.

Designs for bioreactors to enable microalgae to be used as an energy source have been suggested, as shown in Figure 8.

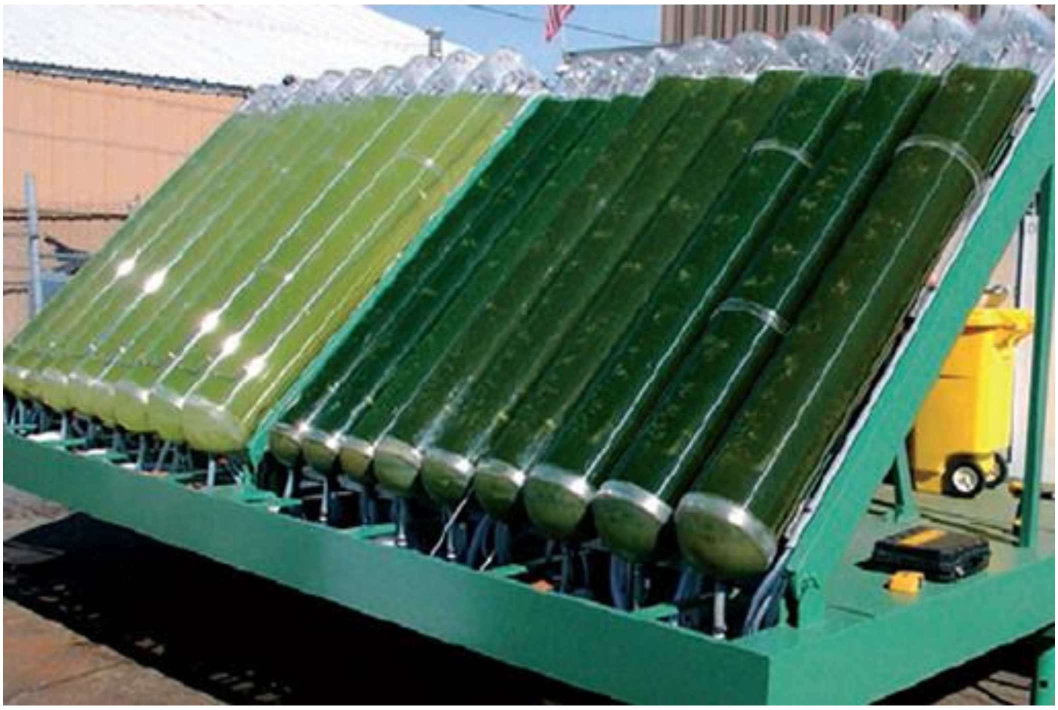


Figure 8 A possible bioreactor design for use of microalgae as an energy source

They could potentially make a very attractive bioenergy source because:

- they grow in water, and are tolerant of wide ranges of salinity and temperature

- they do not occupy land that could be used for other products
- under appropriate conditions, the cells of the algae can contain high percentages of oils, and the cyanobacteria can excrete oil into their surroundings: the microbial residues after oil extraction can also be used as an energy source
- it is possible that they could be used simultaneously to clean up waters polluted with plant nutrients, and the resulting biomass, including the oil, used for energy (Clarens et al., 2010)
- some microalgae forms are also seen as candidate material for the capture of carbon dioxide from power plants.

Can leftover products from non-energy uses be used as additional ‘secondary’ bioenergy sources? You look at that question next.

5 Secondary biomass energy from wastes, residues and co-products

Many materials such as straw or rice husks resulting from 'non-energy' uses of biomass are also potential sources of biomass for energy. In addition, mixed urban and industrial waste will release energy if burned. Only wastes of biological origin are considered true renewables, excluding, for instance, polymeric materials ('plastics') that have been synthesized from fossil fuels.

5.1 Wood residues

Around 15% of the standing tree crop is left behind as forestry residues during operations such as thinning plantations and de-limbing felled trees. However integrated harvesting techniques used in countries such as Sweden can enable a fraction of the residues to be used for heat and/or power generation.

Possibly the largest use of wood wastes as fuel is in the pulp and paper industries, where the production plant has ready access to such wastes. There are also by-products from cereal crops, which will be discussed next.

5.2 Temperate and tropical crop co-products

Worldwide, residues from the two main temperate cereal crops – wheat and maize (corn) – amount to more than a billion tonnes per year, with an estimated energy content of 15–20 EJ, For use as a bioenergy source, straw must be baled, removed from the fields, stored in a dry atmosphere and transported to its point of use. Although it has a reasonable energy density of up to 15 GJ t^{-1}, it has a relatively low mass density and occupies a substantial volume, making transport and storage expensive.

Several European countries already have wide experience of straw burning for electricity generation, as you will see in the large power station at Avedore near Copenhagen shown in this short video clip.

Video content is not available in this format.

There are also energy co-products from **tropical food crops**.

The energy content of the annual residues of two major tropical food crops, sugar cane and rice, is estimated at about 18 EJ, and significant quantities of tropical crop residues are already being used as fuels.

Bagasse, the fibrous residue of sugar cane, is used in sugar factories as a fuel for raising steam and to produce electricity for use in the plant, in much the same way as wood residues are used in pulp and paper mills.

Rice husks are among the most common agricultural residues in the world, making up about one-fifth of the dry weight of un-milled rice. Their uniform texture makes them suitable for technologies such as gasification.

In the next section you move on to types of waste used as secondary energy sources.

5.3 Wastes

Various types of waste can be used as secondary energy sources.

Animal manure can be a major source of greenhouse gases. Wet slurry from housed livestock stored in bulk decomposes anaerobically (which means decomposition in the absence of air) releasing methane - a more potent greenhouse gas than carbon dioxide. Farmers are therefore encouraged to invest in controlled anaerobic digestion (see Section 4.6.3) which does not result in such emissions.

Another source is poultry litter, a mixture of chicken droppings, straw, wood shavings etc., which has an energy content in the range 9–15 GJ t^{-1}, enabling its direct combustion for electricity generation.

Household waste is mostly collected as **municipal solid waste (MSW)** with an energy content of about 9 GJ per tonne. The average household in an industrialised country generates more than a tonne of solid waste per year.

In continental Europe and elsewhere, refuse incineration with heat recovery, or energy-from-waste (EfW), is an important part of waste management. The heat generated is used directly for district heating or power production.

Commercial and industrial wastes of organic origin can be used as fuel. The UK generates about 36 Mt of such specialised wastes each year, of which about two thirds are combustible, and include:

1. commercial food processing waste
2. fats (used oil/meat off cuts)
3. incinerated hospital waste
4. tyres.

You have now looked briefly at some of the products that can be used as secondary biomass energy sources. Now you will look at how biomass is processed.

6 Biomass processing

As you have seen, biomass resources come in a variety of physical forms with widely varying energy content, but they are likely to require processing to make them more acceptable to users or easier to transport, and then they may require special equipment to release their energy in a useful form. This can involve physical, thermochemical or biochemical processes, either singly or in combination.

6.1 Physical processing

Wood is not the most convenient fuel, but chipping it produces a more homogeneous material that is easier to handle in bulk. Further processing can form the material into consistently sized pellets that can be bagged for retail sale, or transported in bulk.

Systems have also been developed for producing high density pelleted straw, which allows boilers to be fed automatically, and transport and storage costs to be reduced.

The oil in crops such as rapeseed, soya and oil palms is contained within the seed. The oil has to be separated from the surrounding tissues, either by pressing or by using a solvent that dissolves the oil, making it easier to separate from the remaining material.

6.2 Thermochemical processing

Thermochemical processes involve the use of heat, and possibly chemical reagents, to convert biomass into energetically more useful forms. The output may be heat or intermediate gaseous or liquid fuels.

Pyrolysis and torrefaction

Pyrolysis is one of the oldest and simplest methods of processing wood to produce a better fuel, *charcoal*. Charcoal is almost pure carbon with about twice the energy density of the original wood, making it easier and more efficient to transport and store. It burns at a much higher temperature, so it is much easier to design a simple and efficient stove for its use. However, the charcoal fuel cycle is potentially highly wasteful and polluting.

Torrefaction is the industrial-scale thermochemical treatment of biomass in the 200–340 °C range. The resulting solid 'torrefied' biomass, sometimes referred to as *biocoal* , has an approximately 30% higher heat energy content, increased density and reduced content of undesirable elements such as chlorine, in comparison to the original biomass.

Both pyrolysis and torrefaction release volatile components. The term *pyrolysis* is now normally applied to processes where the aim is to collect these volatile components and condense them to produce a liquid fuel or *bio-oil*.

Gasification

Gasification is a thermochemical process where a gaseous fuel is produced from a solid fuel. There are two basic processes: pyrolysis and transesterification.

Pyrolysis is used to release the volatile matter from the heated solid, then the tars in the gas stream can be condensed out, leaving *producer gas*. The energy content of this gas is only about a tenth of that of natural gas from fossil fuels, but this is sufficiently good to run internal combustion engines, and higher quality gas can be made by using oxygen rather than air for combustion. A complete industrial gasification process using oxygen can produce a stream of carbon monoxide and hydrogen known as *synthesis gas*, or *syngas*, from which almost any hydrocarbon compound may be synthesized, including premium liquid fuels such as methanol.

Transesterification

Vegetable oils can be burned directly in some modern diesel engines, as in the car shown in Figure 4.9, either pure or blended with diesel fuel. Upgrading of vegetable oils to *biodiesel* results in a fuel that can blend with or replace petroleum diesel in cars with unmodified engines. The conversion process from vegetable oil to biodiesel is called *transesterification*.

Figure 9 A car powered by vegetable oil against a background of oilseed rape fields

European Union production of biofuel, around 80% of which is biodiesel, reached nearly 6 EJ in 2015 from almost nothing in 1990 though the rapid growth of the early 2000s has slowed considerably in recent years (Eurostat, 2017).

The final type of processing you'll look at in this course is biochemical.

6.3 Biochemical processing

Biochemical processes rely on the use of microorganisms to convert biomass into more useful forms of bioenergy. Processes include anaerobic digestion, fermentation and enzymatic conversion.

Anaerobic digestion

Anaerobic digestion (AD), is digestion in the absence of air. In this process, bacteria break down organic material into sugars and then into various organic acids, which are further decomposed to produce biogas. The feedstock may include dung or sewage, food processing wastes or discarded food, agricultural residues or specially grown silage crops that are harvested green. Digestion can take place in either wet or dry systems.

Figure 10 Anaerobic digestion plant on a farm in Scotland

The biogas produced can be burned to produce heat or used to fuel an internal combustion engine to drive a generator for electric power.

At present, the majority of the UK’s anaerobic digestion capacity is in the landfill sector, as much of municipal solid waste is of biological origin, and its disposal in landfill sites provides conditions for anaerobic digestion to occur naturally. The gas is mainly used for electricity generation.

Municipal Solid Waste can also be subject to more *controlled* anaerobic digestion, enabling much higher and quicker gas yields.

Fermentation to produce ethanol

Here the simple sugars from the biomass feedstock are converted to ethanol and carbon dioxide by the action of a different set of microorganisms, usually yeasts. The ethanol is then separated from other components using heat to distil the mixture, so that the ethanol boils off and can then be cooled and condensed back to liquid.

Enzymatic conversion

Fermentation to produce ethanol requires some form of soluble sugar, but much biomass consists mainly of cellulose, hemicellulose and lignin. Following a pre-treatment of such material by, for example, hydrothermal processing, the watery suspension of cellulose and hemicellulose that results can be treated with enzymes. These biological catalysts are usually derived from microorganisms such as bacteria or fungi, and can break down the cellulose and hemicellulose to simpler carbohydrates that can be used in traditional fermenters.

Such combinations of thermochemical and enzymatic conversion processes that allow cellulosic biomass to be used for the production of ethanol are now termed *advanced or second/next* *generation* bioethanol technologies. They can increase supply of feedstocks while avoiding competition with food or fodder supply and more easily meet bioenergy sustainability standards.

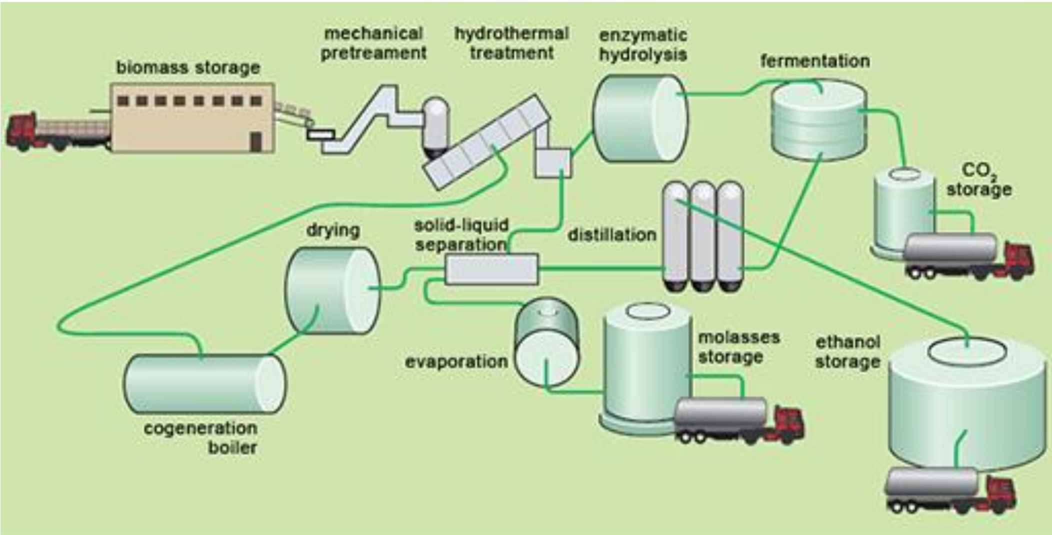


Figure 11 Integrated process for ethanol production from straw. The cogeneration boiler supplies steam to the hydrothermal treatment.

An schematic view of a pilot-scale second generation plant set up by Inbicon in Kalundborg, Denmark (Inbicon, 2010) is shown in Figure 11.

You will now move on to discuss the environmental impacts of bioenergy.

7 Environmental impact of bioenergy

It is important to consider not only the benefits of harnessing bioenergy but also any possible deleterious effects, global or local. These can include emissions and the use of land. You'll now learn more about these.

7.1 Emissions

Carbon dioxide, SO_2 and NO_x

The concept of 'fixing' atmospheric CO_2 by planting trees on a very large scale has attracted much attention. Halting deforestation would bring many environmental benefits, as would re-planting large areas with trees. However, absorption of carbon dioxide by a new forest plantation is a once-and-for-all measure, 'buying time' by fixing atmospheric CO_2 while the trees mature, say for 30–60 years, after which the CO_2 would probably be released. A wider bioenergy strategy, concentrating on the substitution of biofuels for fossil fuels, may be a more effective lasting solution.

To analyse the benefits of substitution, it is essential to assess all the effects in a life-cycle analysis (LCA). Table 3 shows a LCA for electricity generating plants that are either operating or near to commercial implementation. It shows the emissions of carbon dioxide and two of the main contributors to acid rain: sulfur dioxide and nitrogen oxides.

Table 3 Net life cycle gaseous emissions from electricity generation systems in the UK

	Emissions [1]/t GW h^{-1}		
Combustion, steam turbine	**CO_2**	**SO_2**	**NO_x**
Poultry litter	10	2.42	3.90
Straw	13	0.88	1.55
Imported wood pellets	50	0.1	1.58
Forestry residues	29	0.11	1.95
MSW (EfW)	364	2.54	3.30
Anaerobic digestion, gas engine			
Sewage gas	4	1.13	2.01
Animal slurry	31	1.12	2.38
Landfill gas	49	0.34	2.60
Gasification, BIGCC[2]			
Energy crops	14	0.06	0.43
Forestry residues	24	0.06	0.57
Fossil fuels			
Natural gas: CCGT[2]	446	0.0	0.5
Coal: with minimal pollution abatement	955	11.8	4.3
Coal: Flue Gas Desulfurization and low NO_x[3] burner	987	1.5	2.9

Even the best systems are not entirely carbon-neutral, but all the bioenergy systems, even MSW combustion, have lower CO_2 emissions than any of the fossil fuel plants.

Nitrogen and sulfur oxides

Nitrogen oxides (NO_x) are an inevitable product of the combustion in air of any fuel, because four-fifths of the air is nitrogen. High temperatures – in furnaces or internal combustion engines increase NO_x production, and bioenergy systems will need to meet the same ‘clean-up’ requirements as those using fossil fuels. This also applies to the removal of *particulates*. The emissions of *sulfur oxides* depend on the sulfur content of the biofuel, which will vary with the particular characteristics of the feedstock concerned.

Dioxins

Dioxins are complex, carcinogenic compounds formed during combustion, and are a continuing source of public concern. However, it has been estimated that EfW accounts for only 0.1% of UK dioxin emissions. The UK and the EU are enforcing increasingly stringent emission standards and the installation of pollution control technology.

Methane

Methane (CH_4) is a powerful greenhouse gas produced from the anaerobic breakdown of biomass. A molecule of CH_4 is about 22 times as effective as a molecule of CO_2 in trapping the Earth’s radiated heat.

With careful storage and efficient combustion, the methane emissions from MSW should be low. However, with landfill it is never possible to collect all the gas, and there are inevitably methane emissions to the atmosphere. This is the case whether the gas is being collected and used or not, so the most important consideration is whether the methane emissions from anaerobic digestion plants are greater or less than those that occur would occur naturally in landfill anyway.

7.2 Land use

At some stage, all forms of biomass require a surface area of land or water for plant growth. Using this land for non-biological forms of renewable energy rather than for biomass might do more to mitigate the impacts of CO_2 (Smith et al., 2000). How do the various land areas compare?

Assuming a bio-fuelled power plant with an annual electrical output of 10 GWh (the equivalent of a small 1.5 MW thermal power station running with a 75% capacity factor), with reasonable yields and conversion efficiencies the area of energy crops required to fuel this power plant would be in the range 600–900 ha (6–9 km2).

A small wind farm might need approximately 100 ha, (including necessary separation distances).

However, PV and wind systems are more likely to be complementary than to be competing for the same land, and as you saw in Week 3, PV arrays could be deployed to considerable advantage in semi-arid and desert areas with high solar input, or on rooftops in urban areas.

Nevertheless, there have been widespread concerns about the use of land for biofuels rather than for food, and about possible reductions in biological diversity through conversion of existing vegetation to fuel crops.

Activity 3 Bioenergy systems

Are there any bioenergy systems you can think of that could allay the above concerns?

View answer - Activity 3 Bioenergy systems

Bioenergy's effects on soil also need to be considered. Soils can contain large amounts of organic matter or humus formed from the remains of crops that are hard to break down, and act as a store of large amounts of carbon over long periods. However, cultivating the soil exposes this organic material to the air, and it then begins to break down more rapidly, releasing carbon dioxide.

8 Energy balance of bioenergy

The *fuel energy ratio* (FER) is the ratio of useful energy in the fuel compared to the total amount of fossil fuel used in *producing* that fuel, including that used to construct equipment. Where the ratio is less than one, more energy is used to produce the fuel than is available from that fuel.

Woody energy crops perform well, with FERs between 10:1 and 20:1 on a heat output basis, but biodiesel may achieve only 3:1. Ethanol from grain may barely break even at just over 1:1 in the worst case, though there is little consistency among estimates (Davies et al., 2009).

Table 4 The range of fuel energy ratios for selected bioenergy systems reported in the literature to 2016

Fuel energy ratio	Lowest	Highest
Lignocellulosic alcohol (generalized)	0.75	1.24
Switchgrass (combustion)	0.44	4.43
Corn (alcohol)	0.9	1.14
Miscanthus (rhizome to pellet combustion)	1.77	9.23

Only one set of data for miscanthus systems was available.

Source: (Scurlock et al., 2018) (derived from and (Hastings et al., 2013))

Energy ratios can be improved by good design of the production and processing systems to ensure that no energy is wasted. Co-products, such as straw or bagasse, associated with biofuels can also be used to replace fossil fuels in supplying heat for the processes involved.

How much does bioenergy cost? You'll look at this next.

9 Costing bioenergy

For most renewable energy systems, the initial capital cost is the major component of the energy cost. However bioenergy systems, unlike many other renewable energy technologies, can also have significant fuel costs. Energy crops, for example, must be planted, fertilised, protected against weeds and pests, harvested and transported.

On the other hand, EfW may have negative fuel costs in the form of savings in payments for disposal of wastes.

Table 5 Estimated costs of biofuels and the costs of fossil fuels (Biofuel prices in US cents per litre excluding any possible taxes)

Fuel Type	2006 (price/c l^{-1})		2030 (price/cl^{-1})	
	Low	High	Low	High
Petrol excluding tax	45	60		
Petrol including tax (Europe)	150	200		
Petrol including tax (USA)	80	80		
Ethanol from sugar cane	25	50	25	35
Ethanol from maize	60	80	35	55
Ethanol from sugar beet	60	80	40	60
Ethanol from wheat	70	95	45	65
Ethanol from lignocellulose	80	110	25	65
Biodiesel from animal fats	40	55	49	50

Biodiesel from oilseeds	70	100	40	75

In 2008, the UK Royal Society produced estimates of current and possible future costs of a range of biofuels. Ethanol from sugar cane is the cheapest biofuel, with biodiesel from surplus animal fats a reasonably close second. The data suggested that ethanol from lignocellulose would ultimately (by around 2030) be comparable in cost to ethanol from sugar cane. (The Royal Society, 2008)

Since then progress toward parity between fossil fuel and biofuel costs in the transport domain have slowed and even reversed as crude oil prices have retreated from the historic highs of 2008 and 2011 – 2014 and biofuel costs, sensitive to feedstock prices, have stagnated rather than falling as predicted. While certain fuels in specific regions – such as ethanol from sugar cane in Brazil – are competitive it is anticipated that incentives, in the form of subsidies, will be needed for the foreseeable future. However, this is highly dependent on the taxation régime for fossil fuels. (IEA, 2016)

Lastly for this week’s topics you will take a look at the future prospects for bioenergy.

10 Future prospects for bioenergy

Bioenergy is the world's largest source of renewable energy and the fourth most important source of energy overall, delivering a total of 59.2 EJ or 10.3% of global energy in 2014 (WBA, 2017). More than 90% of bioenergy is used in heating: both direct heating including traditional biomass use and derived heating in Combined Heat and Power (CHP) plants.

IEA projections based on the commitments in the Paris Agreement see limited growth in renewable heat (from 9% in 2015 to 15% in 2040) as well as biofuel in transport (from 3% in 2015 to 8% in 2040), while maintaining a 2% share of electricity generation in an expanding market. With a more aggressive approach to emissions reductions scenarios the growth could be considerably greater but it is not clear that the necessary policy frameworks will be put in place globally though regional actors such as the European Union may be more ambitious.

A range of studies reviewed by the Imperial College Centre for Energy Policy and Technology (Slade et al., 2010) suggest that a rise from some 250 PJ per annum from bioenergy to perhaps 600 PJ by 2030 seems possible. As shown in Figure 12, the two sources suggested as having most potential for increased production by 2030 are wastes and perennial energy crops such as SRF/SRC.

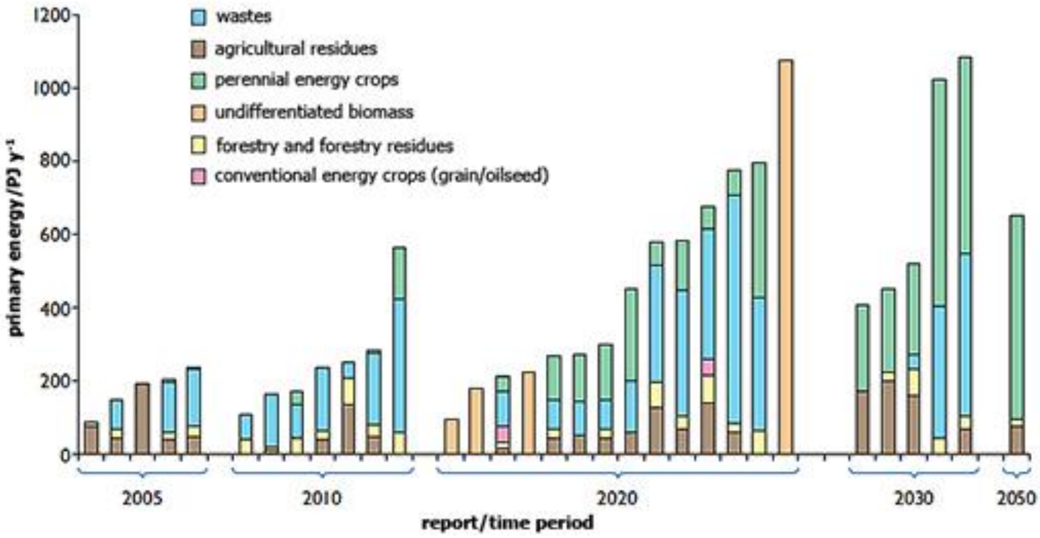


Figure 12 Estimates for the potential contribution from biomass to UK primary energy derived from individual studies (source: Slade et al., 2010)

In the developing countries, future demand for biomass energy is likely to be determined mainly by two opposing factors:

1. the rise in overall energy demand due to increasing population
2. the reduction in the demand for traditional forms of biomass due to a shift to more 'modern' forms.

Most projections suggest that biomass consumption will continue to rise during the next few decades, but at a lower rate than renewables in general or total primary energy. Nevertheless traditional biomass will remain the sole domestic fuel for a large proportion of the world's population – more than a third of whom rely on solid biomass for cooking (IEA, 2016) - for a long time to come. It is therefore arguable that the improvement of traditional wood and charcoal stoves should be the most important technical aim in the field of bioenergy today: improving safety, reducing harmful emissions and reducing costs for some of the world's poorest people.

Activity 4 Needs for energy and needs for food

In the medium term what factors are likely to increase competition for land between needs for energy and for food?

View answer - Activity 4 Needs for energy and needs for food

The most optimistic recent forecast for the potential future contribution of bioenergy suggests over 1500 EJ per year, way beyond total current world energy. A more widely accepted figure might be of the order of 100–200 EJ of bioenergy per year. 200 EJ would represent a fivefold increase on current levels – a new contribution equal to over a fifth of present world total primary energy consumption.

Next you can try the mid-course quiz.

11 Week 4 quiz

Now it's time to complete the Week 4 badge quiz. It is similar to previous quizzes, but this time instead of answering five questions there will be fifteen.

Week 4 compulsory badge quiz.

Remember, this quiz counts towards your badge. If you're not successful the first time, you can attempt the quiz again in 24 hours.

Open the quiz in a new tab or window then come back here when you've finished.

12 Summary

This week you have:

- seen how bioenergy use depends on the process of *photosynthesis*, and how the initial products of photosynthesis can be converted into other energy-rich forms
- looked at the different materials that can be used for bioenergy
- learned about the different processes of converting raw materials into bioenergy sources, by physical, thermochemical or biochemical means
- reviewed the by-products, costs and environmental impact of bioenergy
- discussed the factors likely to affect the uptake of bioenergy systems and their future prospects

You can now go to week 5, hydroelectricity.

Week 5: Hydroelectricity

Introduction

This week begins with a discussion of the nature of the hydro resource and its present contribution to world energy. This is followed by a summary of the basic science and an account of the development of water power, leading to a discussion of modern hydro turbine systems. The remaining sections are concerned with the problems and the potentialities of hydroelectricity.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- discuss at a basic level the magnitude of the world's hydro resource and its present contribution to world total primary energy consumption
- describe at an introductory level the main features and the modes of operation of the principal types of water turbine
- describe at an introductory level the principle of pumped storage plants and their role in an integrated electrical supply system
- understand at an introductory level the environmental and social effects, beneficial and deleterious, of large-scale hydroelectricity, and the potentialities and problems of small-scale systems.

1 Background to hydroelectricity

Water power, or hydropower, became a major 'modern' energy source over a hundred years ago, supplying the input for some of the earliest electric power stations. *Hydroelectricity* has now become a well established technology, delivering in 2014 a little over 16% of the world's annual electricity; or nearly 4000 terawatt hours (TWh). (IEA, 2016).

This type of power, like most renewable energy sources, is indirect solar power, and has been contributing to local energy supplies for many centuries, for example in the water wheels shown in the figures below.

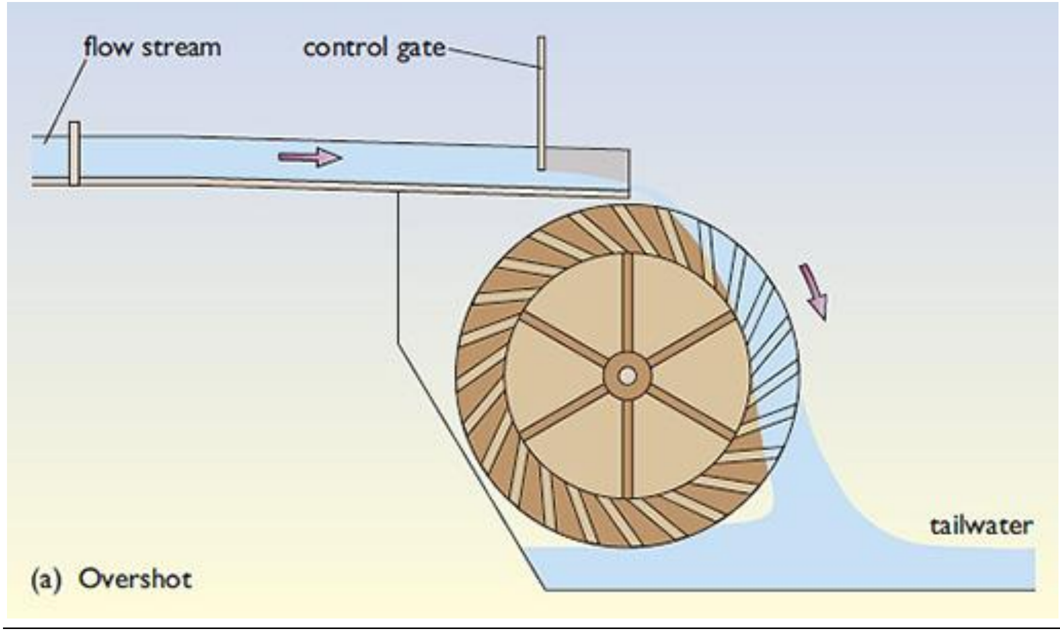


Figure 1 Waterwheel type – overshot – water falls onto blades with closed sides

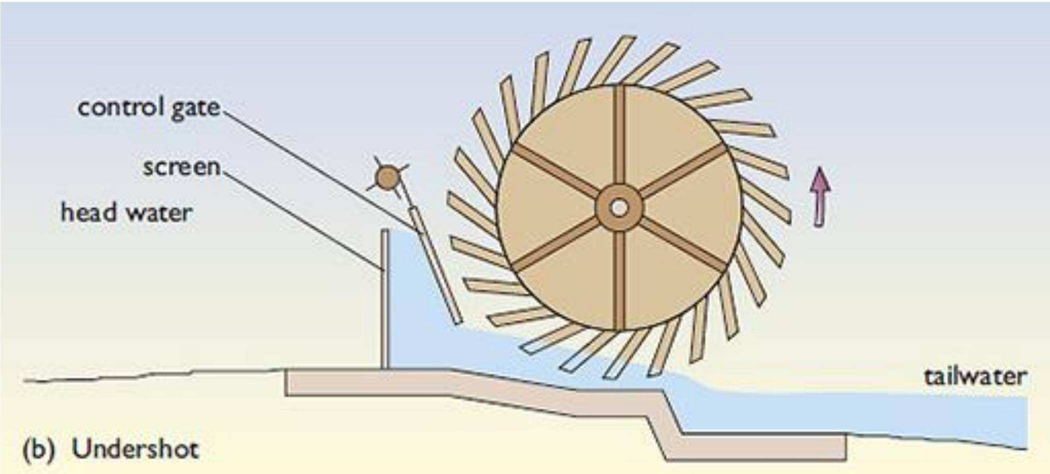


Figure 2 Waterwheel type – undershot – driven by water pressure against lower blades

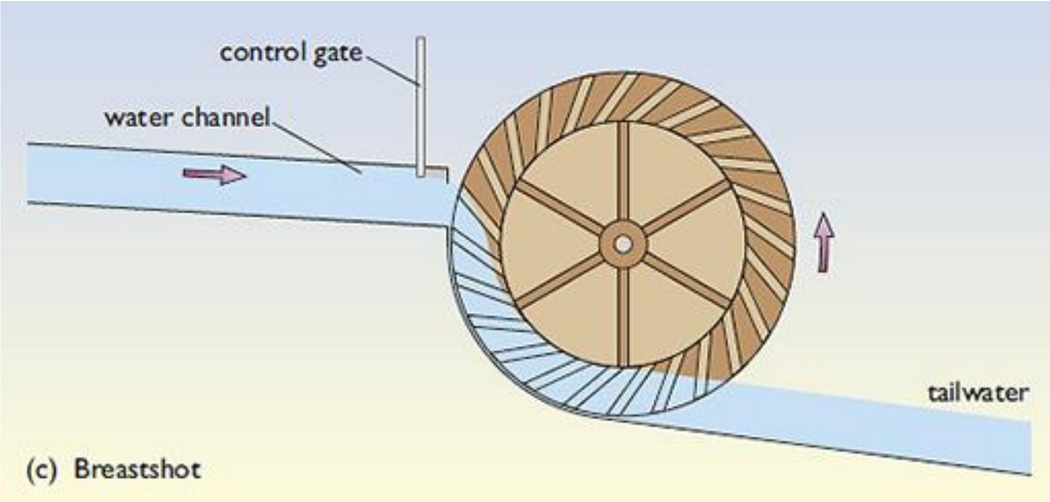


Figure 3 Waterwheel type – breastshot – water strikes paddles at about the level of the wheel axle

What hydropower resources are available? You'll look at that next.

2 Hydropower resources – world, regional, national

As you saw in Week 1, almost a quarter of the 5.4 million EJ (1.5 billion TWh) of solar energy reaching the Earth's atmosphere each year is consumed in the evaporation of water. Water vapour in the atmosphere therefore represents an enormous, constantly replaced, store of energy. Unfortunately most of it is not available to us.

When water vapour condenses into water, most of its stored energy is released into the atmosphere as heat, and ultimately re-radiated into space. But a tiny fraction, (about 200 000 TWh y^{-1}), reaches the Earth as rain or snow, with roughly one fifth of this falling on hills and mountains, descending to sea level in the world's streams and rivers. The 40 000 TWh y^{-1} of energy carried by this flowing water can be regarded as the world's *total hydro resource*.

It is obviously not possible to build hydro plants on every river or stream, so the usable fraction of this flow will be significantly lower, and at the time of writing, the world's *technical* hydro potential is estimated to be about 16 000 TWh y^{-1}, (two-fifths of the above total resource) though the International Energy Agency estimates it at 14 600 TWh y^{-1}(IEA, 2016). This latter figure is equivalent to an installed capacity of around 3 700 GW, approximately three times the current figure.

But how much hydroelectricity is available at a cost competitive with power from other sources? One definition of this *economic potential* suggests that it is the fraction of the total resource that:

> can be exploited within the limits of current technology under present and expected local economic conditions. The figures may or may not exclude economic potential that would be unacceptable for social or environmental reasons.
>
> (WEC, 2010)

Estimates of the *economic* potential for hydropower in different countries or regions are much less reliable than estimates of the *total* or *technical* potential. Here we consider only the total resource and the technical potential, leaving the economic aspects until Section 5.10.

2.1 Regional hydro resources

Looking at the first four columns of Table 1 below shows the estimated total hydro resource and technical potential for different regions of the world, together with their percentage share of the technical potential, with the total here mainly based on national data, which may include small-scale hydro plants.

Table 1 Regional and world hydro potential and output, 2015

	Resources			**Output**		
Region	**Total resource/TWh y^{-1}**	**Technical potential/TWh y^{-1}**	**% of world technical potential**	**Installed capacity/GW**	**Annual output/TWh y^{-1}**	**Percentage of technical potential used**
North America	5500	2420	15%	168	680	28%
South America	7500	2840	18%	132	689	24%
Europe	4900	2760	17%	221	892	32%
Middle East	690	280	1.7%	22	21	7%
Africa	3900	1890	12%	22	114	6%
Asia-Pacific	17300	5820	36%	307	1627	28%
World	39800	16000			4023	

Some sources suggest that world total capacity, including small-scale hydro is close to 1000 GW (source: WEC, 2010a; (British

Petroleum, 2017)), around one-fifth of the technical potential, suggesting that a fourfold increase in output might be possible in future, but this is by no means the case for individual regions.

Hydro resources on a national level are examined next.

2.2 National hydro resources

Data for the 11 countries whose hydro output in 2015 was greater than 50 TWh, together with a few other European countries of interest is shown in Table 2. Several countries appear to have developed more than half their technical potential already; but some may limit their estimates of 'technical potential' to sites that have been studied in detail.

Table 2 National hydro potential and contributions, 2015 (sources: WEA, 2010a, BP, 2010)

Country	Technical potential/TWh y^{-1}	Installed capacity/GW	Annual output/TWh y^{-1}	Average capacity factor	Percentage of nation's electricity
China	2500	171	616	41%	17%
Canada	830	73	399	62%	64%
Brazil	1250	78	391	58%	84%
USA	1340	77	275	41%	7%
Russia	1670	50	176	40%	18%
Norway	240	30	127	49%	96%

India	660	38	106	32%	12%
Venezuela	260	15	86	67%	69%
Japan	136	28	74	30%	7%
Sweden	130	16	76	54%	49%
France	100	21	58	32%	11%
Austria	75	8	37	50%	53%
Italy	65	18	46	28%	16%
Switzerland	43	14	36	31%	52%

The countries with the highest capacity factors tend to be those where hydropower makes a significant contribution but is not the only major source of electricity – a situation that allows the relatively cheap hydropower to be used to its full potential, with an alternative source of electricity available when hydropower cannot meet demand.

In general, if almost all a nation’s electricity comes from hydro plants, annual capacity factors are usually lower, because the installed capacity must be large enough to meet the maximum demand experienced during any day (or year).

Compared with the countries in Table 5.2, the hydro resource of the UK is small. The installed capacity in 2016 was about 1.8 GW including a little over 350 MW small-scale hydro, (BEIS, 2017) with output varying in recent years between about 4.7 and 6.3 TWh – reflecting year-on-year weather variations throughout this relatively small area. However the capacity of and production from small scale hydroelectric plants has shown as significant increase in recent years from 216 MW in 2012 to over 350 MW in 2016 (BEIS, 2017).

Watch this short video, which describes the 152.5MW Loch Sloy hydroelectric power station and gives a brief view of small-scale hydro installation.

Video content is not available in this format.

Next you'll look at hydro output on a world scale.

3 World hydro output

By 1900, after twenty years of commercial hydroelectricity, world annual output had reached an estimated 3.7 TWh from an installed capacity of about 1.3 GW. Despite two world wars and the depression of the 1930s, world capacity then rose at an annual rate of nearly 10% per year throughout the first half of the twentieth century, leading to an output in 1950 that was nearly a hundred times that of 1900. Since then, as shown in Figure 4, fairly constant year-on-year increase of 50 TWh in annual output throughout the second half of the century was maintained, though in 2001 output fell by about 5% despite a further rise in installed capacity – an anomaly attributed to unusually dry conditions in the Americas, the source of about a third of world output.

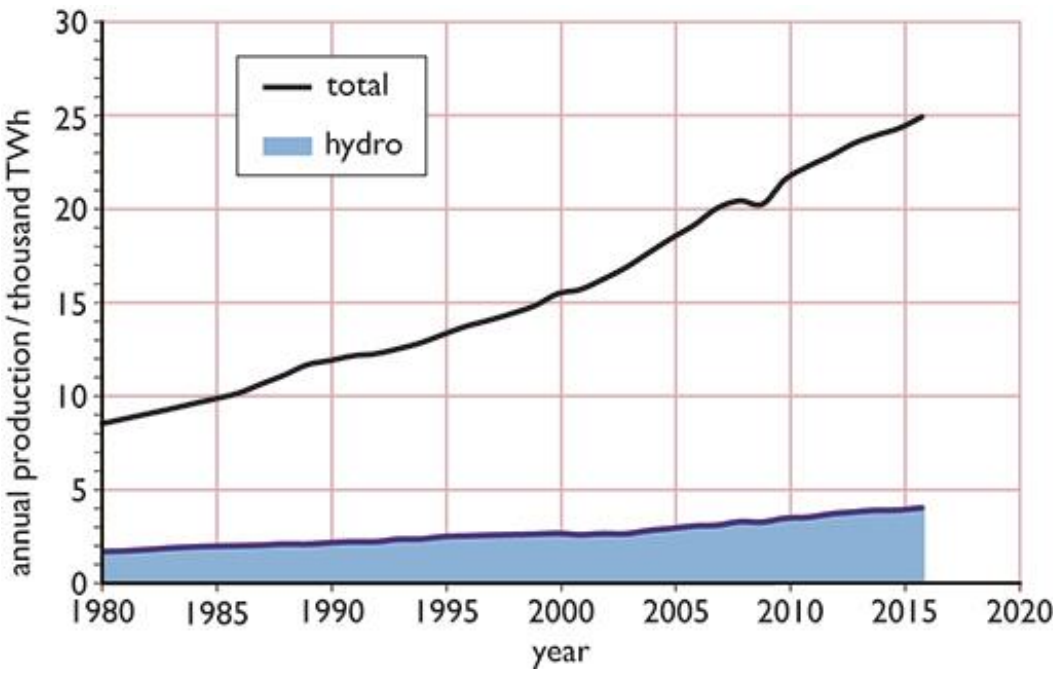


Figure 4 The UK primary energy supply mix 1960 to 2010, alongside two dECC projections (Alpha and Gamma) of possible energy supply mixes in 2050

A fairly constant year-on-year increase of 50 TWh in annual output throughout the second half of the century was maintained, but in 2001 output fell by about 5% for the first time, despite a further rise in installed capacity. The drop was attributed mainly to exceptionally dry conditions in the Americas, the source of about a third of world output. The next year, 2002, was mixed.

The years from 2003 have shown a renewed rapid increase, with world output increasing by a total of 1500 TWh over the twelve years to 2015. Assuming that the average capacity factor remained at about 43%, this implies an increase of about 75 GW in hydro capacity. This period saw growing contributions from the world's two largest hydro plants, Three Gorges in China and Itaipú in Brazil.

But what about hydro on a small scale? You'll move onto that subject next.

4 Small-scale hydro

In the early days of electric power, generators with output ratings between a few kilowatts and a few megawatts were installed on streams or rivers, often using the dams and sluices of old watermills.

Activity 1 Plant output size

What plant output size do you think is now referred to as ‘small-scale’?

View answer - Activity 1 Plant output size

In the industrialised countries, environmental issues have increasingly limited the potential for further major hydro development, whilst small-scale schemes, considered to produce fewer deleterious effects, have received growing encouragement. More recently, a market has begun to emerge for *micro-hydro* plants, generating a few tens of kilowatts for an isolated house or farm. Very small-scale plants are a practicable option for electricity in developing countries without extensive grid systems.

A World Energy Council survey in 2010 (WEC, 2010a) suggests that the global total small-scale (<10 MW) hydro capacity at the end of 2009 was about 60 GW. This is about 6% of the world’s total hydro capacity: a proportion that seems to have remained much the same for several decades. In the UK small scale hydro produced over 1 TWh for the first time in 2016, about 23% of total hydroelectric production. (BEIS, 2017)

You’ll now look at calculating the stored energy and power available in hydro schemes.

5 Stored energy and available power

Box 1: Greek letters

In science and engineering it is common to use Greek letters for certain quantities and we are going to introduce two here:

ρ (pronounced "rho") is used to represent the density of a substance, that is the mass of it that appears in a given volume of that substance. In SI units this is expressed in kilogrammes per metre cubed, kg m-3.

η (pronounced "eta") is used to represent the efficiency of the turbine, that is the fraction of the energy of the flowing water that is converted into electrical energy by the turbine. This is expressed as a number between 0 and 1, and may often be stated as a percentage. For example, an efficiency of 85% is 0.85. (Remember that the "%" symbol means $/_{100}$, so 85% = $^{85}/_{100}$ = 0.85)

Water held at a height represents gravitational potential energy. If m kilograms are raised through H metres, the stored potential energy in joules is given by the following simple equation in Figure 6.

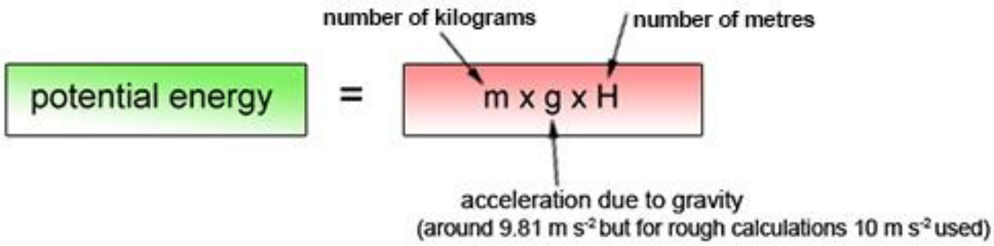


Figure 5 Equation for stored potential energy, in joules

Thus about 10 joules of energy input are needed to lift one kilogram of anything vertically through one metre against the gravitational pull of the Earth, but the capacities of large reservoirs are usually given in cubic metres, rather than kilograms, so we can express the equation for stored energy as shown in Figure 5.6.

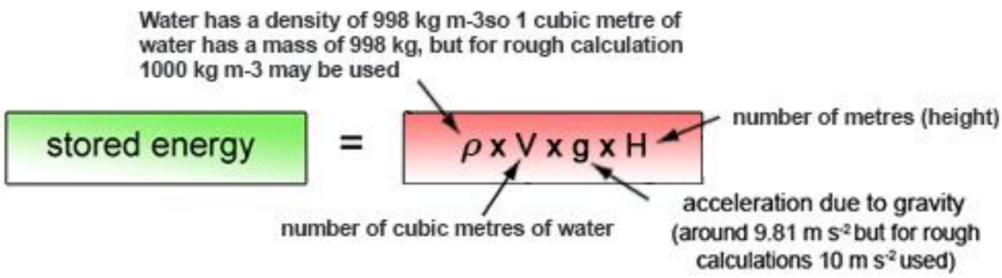


Figure 6 Stored potential energy in a hydro dam depends on height and water volume

This is therefore the energy that will be released when this volume of water *falls* through a vertical distance (H).

Next you will look at pumped storage and how this works to store electrical energy.

5.1 Pumped storage

At present the only practicable and economically viable way to store electrical energy in large quantities is to use it to pump water up a mountain, so pumped storage has become increasingly important, with installed capacity worldwide having grown from 150 GW in 2016 – about a seventh of world total hydro capacity (REN21, 2017).

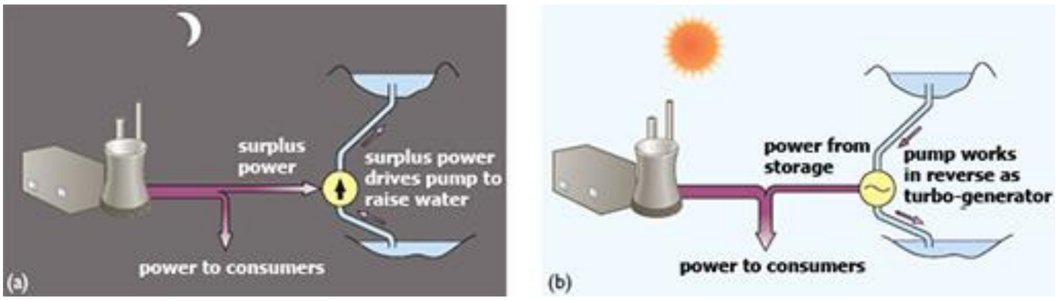


Figure 7 Pumped storage system (a) at time of low demand, (b) at time of high demand

The principle is simple. Electrical energy is converted into gravitational potential energy when the water is pumped from a lower reservoir to an upper one, and the process is reversed when it is released to run back down, driving a turbo-generator on the way (Figure 5.7). The economic viability of the method depends on two nice technological facts:

1. A suitably designed generator can be run ‘backwards’ as an electric motor.
2. A suitably designed turbine can also run in either direction, either extracting energy from the water as a turbine or delivering energy to the water as a pump.

The complete reversal is *turbo-generator* to *electric pump*, with the machines designed for this dual role, but the cost saving is obviously significant. Turbines and generators are very efficient with nearly 80% of the input electrical energy being retrieved as electrical output when needed.

The value of the system is enhanced by its speed of response. Pumped storage is thus particularly useful as back-up in case of sudden changes in demand, or failure elsewhere in a grid system.

The location must of course be suitable, and a low-level reservoir of at least the capacity of the upper one must be available/constructed. Sites such as Cruachan in Scotland, where the mountains rise from a large loch or lake, are obviously ideal.

Figure 8 Cruachan pumped storage plant in Scotland – the dam

The high-level reservoir, behind a large dam, provides an operating head of 365 metres. Running the four 100 MW reversible machines for twenty hours at full capacity, as electric pumps or turbo-generators, raises or lowers the reservoir level by about 15 metres, storing or releasing about 8 million kilowatt-hours (8 GWh) of energy (Cruachan, 2014; Scottish Power, 2010)

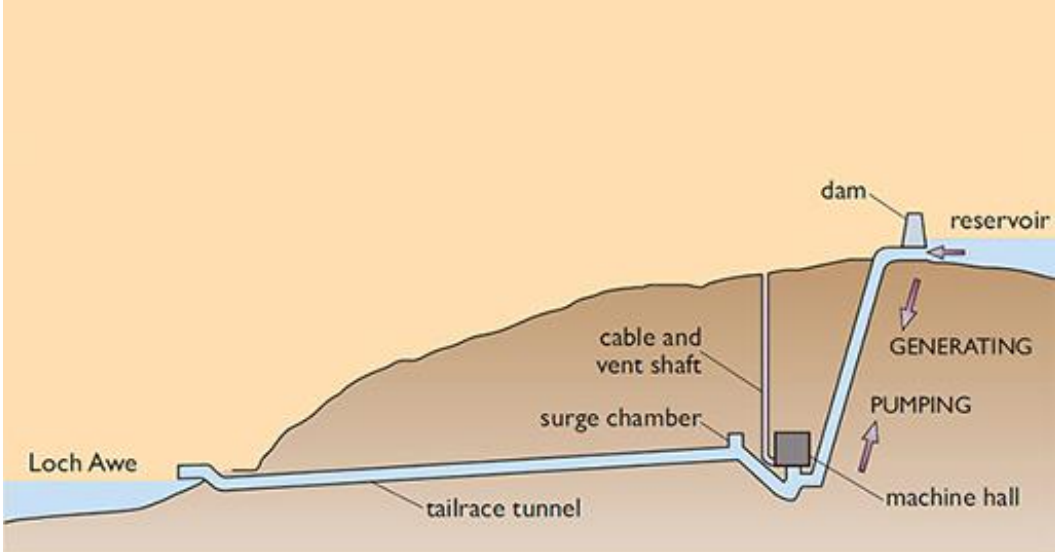


Figure 9 Installation diagram of Cruachan pumped storage plant in Scotland

5.2 Power, head and flow rate

The power supplied by a plant, (the number of *watts*), is the *rate* at which it delivers energy: the number of joules per second. In a hydro plant this will obviously depend on the volume flow rate of the moving water - the number of cubic metres (m^3) per second passing through the plant, usually represented by the symbol Q (think 'Quantity'); g = acceleration due to gravity and H is 'effective head' of water.

It then follows from the equation shown in Figure 10 that this power will be:

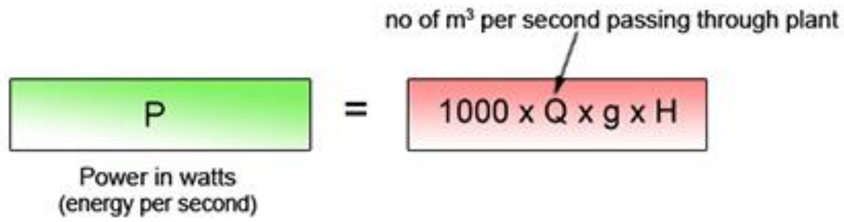


Figure 10 Simple equation for hydro power

However in any real system the water falling through a pipe will lose some energy due to frictional drag and turbulence, and the *effective* head will be less than the actual or gross head. These flow losses vary greatly - in some cases the effective head is no more than 75% of the actual height difference, in others as much as 95%.

Then there are energy losses in the plant itself. Under optimum conditions, a hydroelectric turbo-generator is extremely efficient, converting all but a few percent of the input power into electrical output. Nevertheless, the efficiency (the ratio of the output power to the input power) is always less than 100%. With these factors incorporated, the output power becomes:

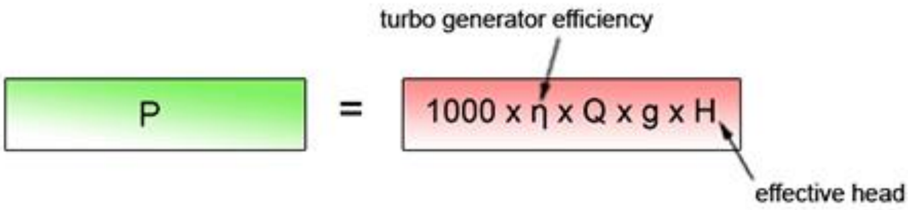


Figure 11 Equation for hydro power, allowing for losses

Box 2: accounting for losses

We’ve seen two ways in which different losses are accounted for: using the *effective* head, $H_{effective}$, rather than the gross head takes care of losses due to friction before the water reaches the turbine while the plant *efficiency*, η, accounts for the losses in the plant itself.

So, moving on, if we now use the approximations g = 10 m s^{-2} and ρ = 1000 kg m^{-3}, we obtain a very useful simple expression:

$$P\,(W) = 1000 \times 10 \times \eta \times Q \times H_{effective}$$

Figure 12 Simplified equation for hydro power, expressed in terms of generator efficiency, water flow rate and effective head

$$P\,(kW) = 10 \times \eta \times Q \times H_{effective}$$

Figure 13 Simplified equation for hydro power in kW, expressed in terms of generator efficiency, water flow rate and effective head

Activity 2 Calculating power output

Use the equation shown in Figure 13 to work out the power output for a site which is a mountain stream with an effective head of 25 metres, turbo-generator efficiency of 0.85 and a modest flow rate of 600 litres a minute, which is 0.010 cubic metres per second.

View answer - Activity 2 Calculating power output

Now you know how to work out how much power a plant can supply, you will now move on in the next section to look at the types of hydroelectric plant.

6 Types of hydroelectric plant

Present-day hydroelectric installations range in capacity from a few hundred watts to more than 10,000 megawatts (10 GW).

We can classify installations by:

- the effective head of water
- the capacity – the rated power output
- the type of turbine used
- the location and type of dam, reservoir, etc.

The available head is an important determinant of the other factors, and the head and capacity together largely determine the type of plant and installation.

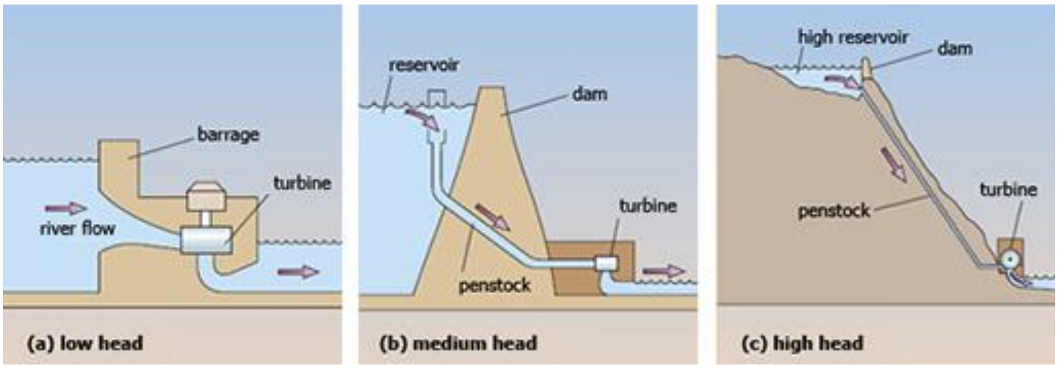


Figure 15 Types of hydroelectric installation: low, medium and high head.

Hydroelectric installations can be classified as *low*, *medium* or *high* head. The boundaries are fuzzy, but *high head* usually implies an effective head of appreciably more than 100 metres and *low head* less than perhaps 10 metres. Figure 14 shows the main features of the three types. Low head 'run-of-river' power stations, having relatively little storage capacity, are dependent on the prevailing flow rate and can present problems of reliability if the flow varies greatly with the time of year or the weather.

Figure 16 The Hoover dam, 1936. This dam on the Colorado River (originally called the Boulder dam) is 220 metres high and its reservoir, Lake mead,

holds 35 billion cubic metres of water. The 2.1 GW power plant is at the foot of the dam.

The ‘medium head’ plant shown in Figure 15(b) and Figure 15 is typical of the very large hydroelectric installations with a dam at a narrow point in a river valley. The large reservoir behind the dam provides sufficient storage to meet demand in all but exceptionally dry conditions. Systems of this type don’t of course have to be on a gigantic scale, and quite small reservoirs can provide power for hydroelectric plant located below their dams.

To call the 220 metre head of the Hoover Dam ‘medium’ may seem surprising, but it illustrates the fact that the distinction between this and high-head systems lies more in the *type of installation*. The *high-head* plant shown in Figure 15(c) shows the difference with the entire reservoir well above the outflow, and the water flows through a long *penstock* (the channel, or pipe, carrying the flow) possibly passing through a mountain to reach the turbine.

With a high head, the flow needed for a given power is much smaller than for a low-head plant, so the turbines, generators and housing are more compact. But the long penstock adds to the cost, and the structure must be able to withstand the extremely high pressures below the great depth of water.

Various different types of turbine are used in hydro schemes, as you'll see in the next section.

7 Types of hydro turbine

Present-day hydro turbines come in a variety of shapes (Figure 17). They also vary considerably in size, with ‘runner’ diameters ranging from as little as a third of a metre to some 20 times this. Here we look at how they work, the factors that determine their efficiency, and the site parameters that determine the most suitable turbine.

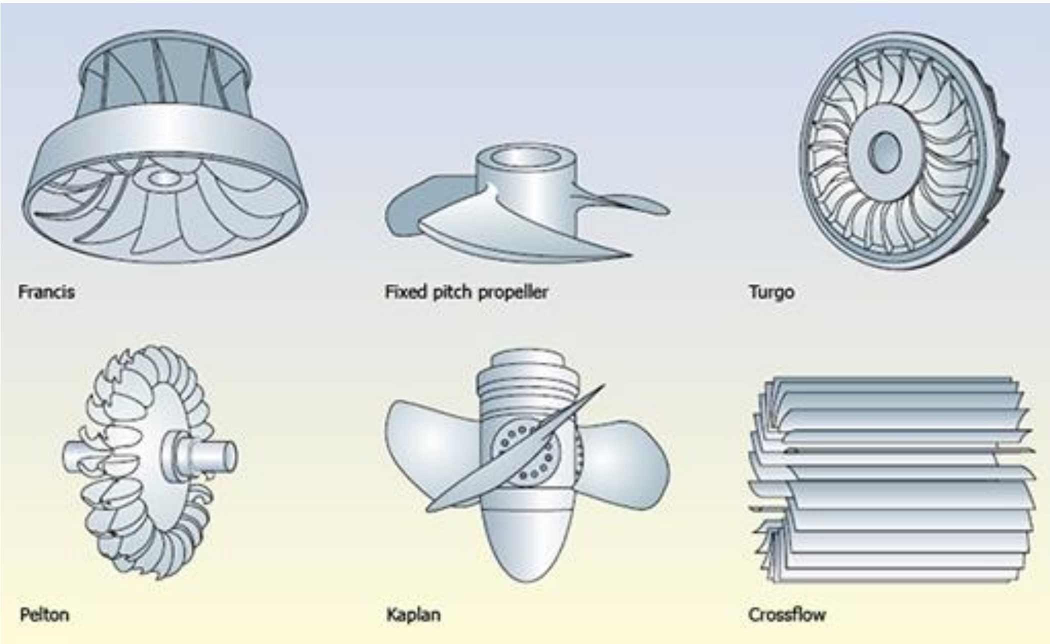


Figure 17 Types of turbine runner

Francis turbines (figure 17, top left) are by far the most common type in present-day medium- or large-scale plants, being used in locations where the head may be as low as 2 m or as high as 200 m. They are radial-flow turbines, which means the water flow is *inwards* towards the centre, and modern turbines can achieve efficiencies as high as 95% – but only under optimum conditions, as maintaining exactly the right speed and direction of the incoming water relative to the runner blades is important.

'Propeller' or axial-flow turbines (figure 17 top centre) sweep their blades through the entire area which the water enters, and are therefore suitable for very large volume flows and have become usual where the head is only a few metres. In such turbines the efficiency can be improved by varying the angle of the blades when the power demand changes. **Kaplan turbines** (figure 17 bottom centre) are axial turbines where the blade angle may be varied to improve efficiency.

Pelton Wheels (figure 17 bottom left) are the preferred turbine for sites of the type shown in Figure 5.14 (c) with heads above 250 metres or so. The pelton is in contrast to the reaction turbines discussed above, it is an *impulse* turbine, operating in air at normal atmospheric pressure, and is basically a wheel with a set of double cups or 'buckets' mounted around the rim. The water passes round the curved bowls, and under optimum conditions gives up almost all its kinetic energy. The power can be varied by adjusting the jet size to change the volume flow rate, or by deflecting the entire jet away from the wheel.

Turgo turbines (figure 17 top right) are a variant on the Pelton wheel, where the double cups are replaced by single, shallower ones, with the water entering on one side and leaving on the other. This is still an impulse turbine, but is able to handle a larger volume of water than a Pelton wheel of the same diameter gives it an advantage for power generation at medium heads.

The **cross-flow turbine** (figure 17 bottom right) is another impulse type. The water enters as a flat sheet rather than a round jet. It is guided on to the blades, travels across the turbine and meets the blades a second time as it leaves.

8 Hydro as a component of a power system

Few large power stations operate in isolation, and the extent to which a proposed plant can form a useful part of a supply system is important with the ideal power station characteristics being:

1. constant availability
2. a reserve energy store to buffer variations in input
3. no correlation in input variations between power stations
4. rapid response to changing demand
5. an input which matches annual variation in demand
6. no sudden or unpredictable changes in input
7. a location which does not require long transmission lines.

Few, if any, sources meet all these criteria, but each compromise with the ideal adds to the effective cost

Almost all hydroelectric plants score well on item 4, and in regions with cold, dark, wet winters, on item 5 as well – unless the water is locked up as ice. Furthermore, sudden unplanned fluctuations in input (item 6) are rare, at least in large plants.

How well hydro performs on items 1, 2 and 3 depends in part on the type of plant. A high-head installation with a large reservoir will normally have little difficulty in maintaining its output over a dry period, whereas the water held behind the low dam of a run-of-river plant may not be sufficient to compensate for periods of reduced flow. A serious drought can of course affect all hydro plant over a wide region, so it cannot be said fully to satisfy the third requirement.

Overall, hydroelectricity ranks reasonably well in terms of the above criteria. And it may also offer a bonus. A hydro plant with a large reservoir not only maintains its own reserve of energy – it might, as we have seen earlier, provide a store for the surplus output of other power stations.

But does hydroelectricity impact the environment? And if so, in what ways? You will look at that next.

9 Environmental impact of hydroelectricity

We might usefully start by briefly summarizing the environmental benefits of hydroelectricity compared with other types of power plant:

- in operation it releases no CO_2, and negligible quantities of the oxides of sulfur and nitrogen that lead to acid rain
- it produces no particulates or chemical compounds such as dioxins that are directly harmful to human health
- it emits no radioactivity
- dams may collapse, but they will not cause major fires
- hydroelectric plant is often associated with positive environmental effects such as flood control or irrigation, and in some cases, its development leads to a valued amenity.

However, during the twentieth century, the construction of large dams has led to the displacement of many millions of people from their homes, and dam failures have killed many thousands. We'll consider these and other deleterious effects under three headings:

1. hydrological effects

2. other physical effects
3. social effects.

These three categories are not of course independent. Any hydrological change will certainly affect the ecology and thus the local community.

9.1 Hydrological effects

Hydrological

A hydroelectric scheme is not basically a consumer of water, but the installation does ‘rearrange’ the resource. Diverting a river into a canal, or a mountain stream into a pipe, may not greatly change the total flow, but it can have a marked effect on the environment. Furthermore, evaporation from the exposed surface of a large reservoir may appreciably reduce the available water supply.

Any structure on the scale of a major hydroelectric dam will affect its environment in many ways in addition to the hydrological changes. The construction process itself can cause widespread disturbance, and the effect on a fragile eco-system can be long-lasting. In the longer term, a large reservoir is bound to bring other significant environmental changes. Whether these are seen as catastrophic, beneficial or neutral will depend on the geographical and biological situation – and on the points of view and interests of those concerned.

More generally the issue of water rights is one of major international significance and, flowing water having little respect for international boundaries, the source of numerous international legal disputes and arguably a few wars. Several of the disputes, across all continents, have concerned hydroelectricity schemes including in recent years the Brahmaputra River crossing from China into India, the "Grand Ethiopîan Renaiisance Dam" on the Nile and the Ilisu Dam on the Tigris River in Turkey. (Johnson, 2014)

With increased demand for fresh water due both to an increasing population and improved living standards the sustainable management of water resources, including their use in power generation, is a priority.

Furthermore climate change is altering hydrological systems in many regions as changing precipitation patterns, snowmelt and melting glaciers affect the quality and quantity of water resources in many regions around the globe (IPCC, 2014).

9.2 Other physical effects

Dam failures

Around 35 major dam failures have occurred since 1960 (defined as those resulting in serious material damage and/or deaths (Wikipedia, 2018), although many dams are for purposes other than hydroelectricity: flood control, water supply, irrigation or recreation. In the U.S. fewer than 2 200 of the country’s more than 87 000 dams (U.S. Department of Energy, 2016) are used to generate electricity so it is not surprising to find only five or six hydroelectric plants in the world list of major dam failures.

However, the safety of hydroelectric dams is a matter of concern (and expense). A notable recent example has been the Oroville hydroelectric dam in California, which during the winter of 2016/7 suffered damage to one of its spillways as a result of heavy rainfall. This required the temporary evacuation of nearly 200 000 people while repair work took place.

The data on dam failures for China is poor. It is known that severe flooding in 1975 led to many dam failures, and estimates of the total fatalities vary between about 70 000 and over a quarter of a million (McKenna, 2011). If the figure is indeed in this range, and hydro plants made up a significant fraction of the destroyed dams, then hydropower must rank high in any list of energy sources in terms of deaths per kWh of useful energy.

Silt

Silt accumulation behind dams has been a known problem for many years. Its build-up reduces the volume of stored water and consequently the hydro potential of a site. The Hoover Dam for instance, lost about one sixth of its useful storage volume in its first thirty years, although the loss rate was reduced when the Glen Canyon dam was built 370 miles upstream.

Fish

France has many dams constructed during the early twentieth century on rivers previously used by Atlantic fish, and as licences became due for renewal in the 1990s, stringent requirements were introduced for the construction of fish ladders or similar passages. One consequence was the decommissioning of dams deemed unsuitable for renewal, on environmental or economic grounds (ERN, 2000).

Methane

It has long been known that vegetable matter that would normally decay in the air to produce carbon dioxide (CO_2) could decay anaerobically under water to produce methane (CH_4). When this was identified as a much more potent greenhouse gas than CO_2, the question arose as to whether hydro schemes that flooded land previously covered in vegetation should join the fossil fuels as significant contributors to global warming.

Detailed studies of individual reservoirs were carried out, the study of a hydroelectric plant on the river Aare in northern Switzerland estimated that each m^2 of the lake surface was releasing about

0.15 grams of methane per day – much more than would be expected for its temperate location, and equivalent to a total annual methane release of about 150 tonnes (EAWAG, 2010), probably due to anaerobic digestion of the particularly large annual quantity of vegetable matter brought down by the river. However, the report also observed that a coal-fired power plant producing the same electrical output would release approximately 40 times more greenhouse gases, expressed in CO_2 equivalent terms.

Currently, the issue of methane emissions seems to play a relatively small role in project assessments. The *2016 Survey of Renewable Energy Resources* of the World Energy Council (WEC, 2016) says that '*The GHG (greenhouse gas) status of freshwater reservoirs is an area of ongoing scientific research and policy responses are still evolving as the state of knowledge progresses'*.

9.3 Social effects of hydroelectricity

The rising water behind China's Three Gorges dam (Figure 18) submerged about 100 towns and displaced over a million people. It is estimated that during the second half of the twentieth century, some 10 million people were displaced by reservoirs in China alone.

But even for the people immediately affected, the building of dams can have very different consequences. For those living in a valley that will become a reservoir it means the loss of their family home, possibly their livelihood, and often their entire community. In contrast, for people living on a river that periodically overflows its banks, the barrage and embankments of a hydroelectric scheme can bring freedom at last from devastating floods.

Figure 18 The Three Gorges dam in the Yangtze in China is one mile long and 181 metres high, with an installed generating capacity of 18,000 Megawatts.

In the next section you look at what can be deduced from both the physical and social effects.

9.4 Considerations and comparisons

The Hydropower Sustainability Assessment Protocol (HSAP, 2017), is the result of a collaboration by representatives of different sectors of the hydro industry, led by the International Hydropower Association (IHA).

Essentially a list of criteria that should be satisfied by any new hydroelectricity project, it is no doubt the response of the industry to many of the environmental issues discussed previously.

Environmental effects

Small-scale systems should have fewer deleterious effects than large systems, and in some respects this is evidently true – few people have been displaced from their homes by the installation of small 5 MW plants, whilst deaths from the collapse of dams across small streams seem rare. However, proponents of large-scale hydro claim dispute this is ‘small is beautiful’ view – arguing that the efficiencies and the capacity factors of small-scale plants tend to be lower, and in some cases the ‘reservoir area’ per unit of output is greater.

Comparisons

It should not be forgotten that the choice may not be hydroelectricity or nothing, but hydroelectricity or some other form of power station. Despite the ‘penalties’ discussed previously, hydroelectricity scores relatively well in terms of many other criteria.

Its overall greenhouse gas emissions, including the construction of dams, are likely to be lower than those of rival fossil-fuelled generating systems. Current issues for hydropower include the question of methane emissions and the costing of long-term compensation for the people displaced by major new hydroelectric installations. Nevertheless, on the criteria discussed above, hydro appears amongst the least harmful sources of electricity.

10 Economics of hydroelectricity

Potential investors in hydroelectricity need to know how much each kWh of output will cost, taking all relevant factors into consideration:

- capital cost
- operation and maintenance costs
- predicted lifetime and capacity factor
- external factors such as the discount rate, which determines the cost of borrowing money over a period of time.

As hydroelectricity is well-established, much of this information is easily available – the water-control systems, turbo-generators and output controls are standard items, covering a power range from a few hundred watts to hundreds of megawatts with the expected lifetime of 20–25 years for the machinery, and 50-100 years for the external structures, but it is difficult to assess the cost combination of the extremely site-specific construction costs and heavy ‘front-end loading’. The dominant factor in determining the cost per unit of hydro output is the initial capital cost, and a major part of this can be the civil engineering costs, which vary greatly from site to site.

An interesting study of hydro potential in the USA (Hall et al., 2003) assessed the costs for over two thousand sites with potential hydro capacities in the range 1–1300 MW. About half of these were ‘green-field’ sites, with no existing dams or hydro plants, and the estimated development costs for these, based on data for similar existing plants, fell mainly in the range $2000–$4000 per kW. (At the time of writing inflation would have increased these initial costs to about $2400–$4800 or approximately £1500–£3000 per kW.)

The civil engineering works typically accounted for 65–75% of this unit cost, whilst meeting the environmental and other criteria necessary for a licence added another 15–20%. In all, 85–95% of the capital cost was ‘site’ cost, with the turbo-generator and control systems accounting for only 10% or so, and with no fuel costs, and relatively low operation and maintenance costs, it is the annual repayments of these initial costs that dominate the cost of the electricity.

However a fairly recent (2014) report from Oxford University (Ansar et al., 2014) suggests that the majority of large hydro dams are not economically viable investments, mainly due to their final capital costs greatly over-running their initially estimated costs. Three quarters of all large dam projects studied had cost overruns and half of all projects were more than 27% over budget. Average costs were nearly twice the estimated cost (Ansar et al., 2014). Although a similar proportion of other large power station projects also suffer cost overruns the average overrun is higher for hydro than for nuclear or thermal (Sovacool et al., 2014). Coupled with the heavy ‘front-end loading’ of costs mentioned above this may have a significant impact on economic viability.

Once built it is a different story. The investors, whether private or public sector, cannot recover their investment by “unbuilding” the dam (the construction cost being at that point which economists describe as a ‘*sunk cost*’) and will only recover any of it by generating electricity.

For the final section this week, you will look at the future prospects for hydro.

11 Future prospects for hydro

World total electricity production in 2016 was nearly 25 000 TWh and hydro power provided 16% of this, about 4000 TWh.

The percentage contribution from hydro has been falling gently for many decades, as the building of new plants has failed to keep up with the rapid growth in total world electricity consumption. As shown in Figure 5.4 most of the increase in world hydro output since 2005 has taken place in China where in 2016 hydro provided 19% of the total electricity demand. Here, electricity consumption has been increasing at about 8% per annum, but this growth rate has been matched by hydro construction whose output has more than doubled in the last decade.

According to the estimate shown in Table 5.2, China would appear to have already developed nearly a half of its hydro technical potential. In 2016, it had 331 GW of hydro installed capacity and, according to the International Hydropower Association, the potential to develop a further 200 GW (IHA, 2017). However most of the hydro resource is located in the mountainous west of the country and will require the construction of long distance high voltage transmission lines to distribute the power to the population centres in the east.

There is also large potential for hydro development in South America, where it already supplies about a half of the electricity. This requires tapping into the flows of large rivers, which may have serious environmental consequences.

There are of course many who would reject the implied acceptance of the construction of new large hydro plants in the less developed regions of the world, whilst not everyone agrees that countries such as the USA, Switzerland and other parts of Europe (including the UK) have no room at all for further hydro development.

Figure 19 The Itaipú hydropower plant on the Parana river between Brazil and Paraguay has a capacity of 14,000 Megawatts, an effective head of 200 metres and a reservoir area of 1350 square kilometres

One form of hydro development that is generally expected to attract support in the coming years is pumped storage. World pumped storage capacity reached 150 GW at the end of 2016 with about 6.4 GW being added in that year (REN21, 2017). China has announced a target of 40 GW of pumped storage by 2020 to help balance the output from the large increase in output from PV and wind power (IHA, 2017).

With rising demand for peak load balancing and the need to accommodate the growing output from intermittent sources such as wind and solar power, the demand for pumped storage is expected to increase by 60% over the next four years (WEC 2010a).

Finally, there is the hydro potential of the many thousands of dams in the world (possibly 30 000) that currently do not support a hydro plant.

That concludes this week. You can now attempt the end of week quiz.

12 Week 5 quiz

Check what you've learned this week by taking the end of week quiz.

Now take the Week 5 quiz.

Open the quiz in a new window or tab then come back here when you've finished.

13 Summary

This week's study may be seen as falling into six main parts:

- a survey of the present situation – the hydro resource and its use on the large and small scale
- a brief account of the physical principles underlying the harnessing of power from flowing and falling water
- an account of the technologies associated with the use of hydropower, including the various types of hydro turbine
- a discussion of the environmental and social benefits and penalties associated with hydroelectricity
- a brief discussion of the economics of hydroelectricity
- a concluding discussion of the future prospects for hydroelectricity.

You can now move on to Week 6.

Week 6: Wind energy

Introduction

Wind energy has been used for thousands of years for milling grain, pumping water and other mechanical power applications. But it is the use of wind energy as a pollution-free means of generating *electricity* on a significant scale that is attracting most current interest in the subject.

This week you will look at modern wind energy technology, at the atmospheric processes that power it, and ways of calculating wind power and energy. You will also look at the environmental impact of turbines, at offshore wind power, and at the economics and future potential of wind technology.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- describe at an introductory level the main aspects of wind energy including the relationship between wind speed frequency distribution and electricity production
- define the terms cut-in wind speed, rated wind speed, shut-down wind speed and rated power
- describe at an introductory level the main current types of wind turbines and how they operate
- understand at an introductory level the environmental and social effects, beneficial and deleterious, of wind energy development.

1 The origins of wind and atmospheric pressure

As mentioned in Week 2, $1m^2$ of the Earth's surface on or near the equator receives more solar radiation per year than $1m^2$ at higher latitudes. The curvature of the Earth means that its surface becomes more oblique to the Sun's rays with increasing latitude. Also, the Sun's rays have further to travel through the atmosphere as latitude increases, so more of the Sun's energy is absorbed en-route before it reaches the surface. As a result, the tropics are warmer than higher latitude regions. This differential solar heating of the Earth's surface causes variations in atmospheric pressure, which in turn give rise to the movements of atmospheric air masses that are the principal cause of the Earth's wind systems.

What is atmospheric pressure?

It's the pressure resulting from the weight of the column of air above a specified surface area. The unit of atmospheric pressure is the *bar*. It is measured using a barometer – a device usually calibrated in *millibars* (mbar), i.e , thousandths of a bar.

The average atmospheric pressure at sea level is about 1013.2 mbar (approximately 1 bar).

On the weather maps featured in television weather forecasts or in newspapers, there are regions marked ‘high’ and ‘low’, surrounded by contours shown in Figure 1.

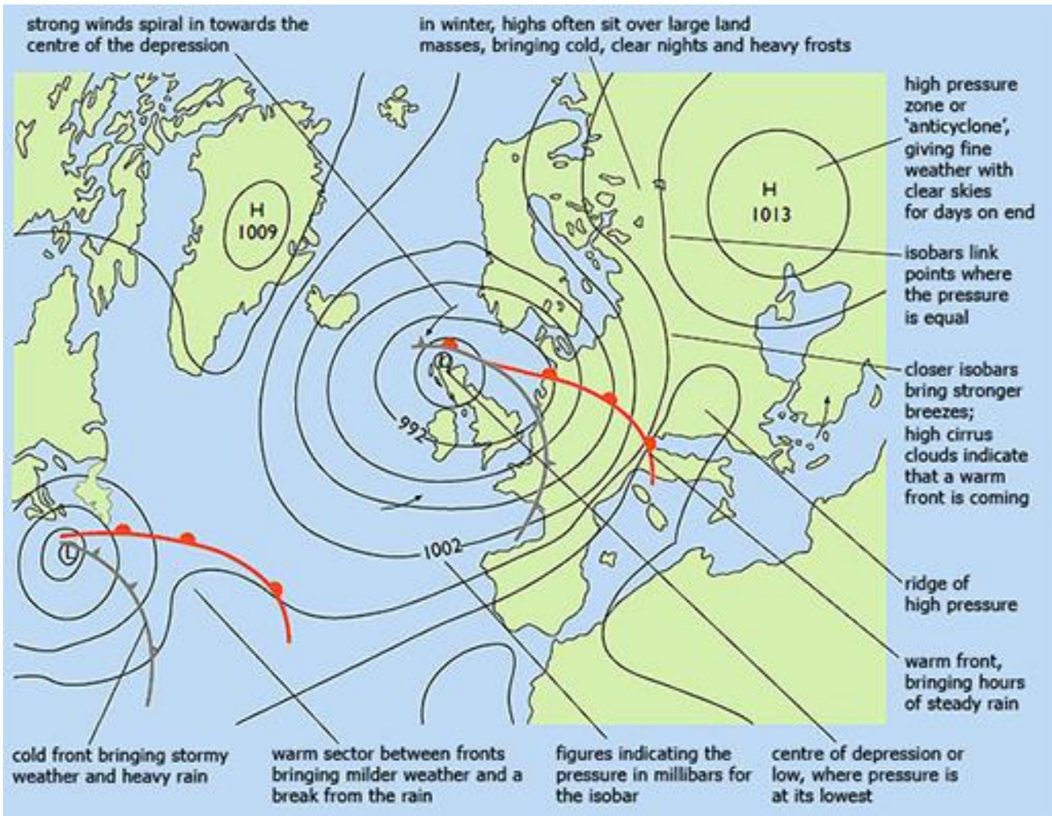


Figure 1 Typical weather map showing regions of high (H) and low (L) pressure

The regions marked ‘high’ and ‘low’ relate to the atmospheric pressure and the contours represent lines of equal pressure called *isobars*. The high-pressure regions tend to indicate fine weather with little wind, whereas the low-pressure regions indicate changeable windy weather and precipitation (rain or snow).

Next you’ll look at how to work out the energy and power in the wind.

2 Energy and power in the wind

The kinetic energy associated with a volume of moving air is equal to half its mass, m, times the square of the velocity,

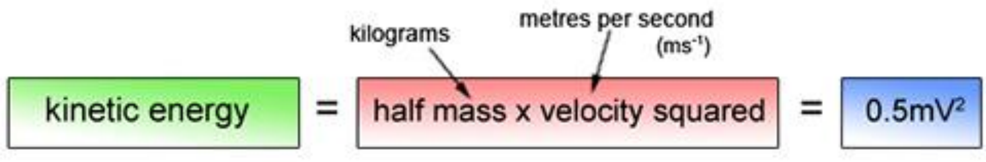


Figure 2 Kinetic energy in moving air equals half mass times velocity squared

Using basic physical principles, the maximum power that could be delivered to a wind turbine by a flow of moving air is proportional to:

1. the density of the air
2. the area of the rotor
3. the *cube* of the wind velocity.

The density of air is lower at higher elevations (e.g. in mountainous regions), and average densities in cold climates may be significantly higher than in hot regions. Also, wind velocity has a very strong influence on power output because of the ‘cube law’.

For example, a wind velocity increase from 6 ms^{-1} to 8 m s^{-1} will increase the power in the wind by a factor of more than two.

The power contained in the wind is not in practice the amount of power that can be extracted by a wind turbine because losses are incurred in the energy extraction/conversion process.

There are many different types of wind turbine, as you'll see in the next section.

3 Wind turbine types

Most modern wind turbines come in one of two basic configurations:

1. Horizontal axis wind turbines (HAWTs). These are predominantly of the 'axial flow' type, i.e. the rotation axis is in line with the wind direction. They range in size from very small machines that produce a few tens or hundreds of watts to very large turbines producing 8 MW or more.

Multi-bladed wind turbines as in figure 3a produce high torque at low rotor speeds and have been used since the nineteenth century for water pumping on farms.

Modern wind turbines as in figure 3b usually have two or three blades and work at much higher rotational speeds, making them attractive for electricity generation in figure 3b. Their rotors superficially resemble aircraft propellers, their design driven mainly by aerodynamic considerations.

Figure 3 a) Multi-bladed wind powered water pump b) Three-bladed HAWT (Vestas V52 850 kW turbine)

2. Vertical axis wind turbines (VAWTs). These are generally of the ‘cross flow’ type, i.e. the rotation axis is perpendicular to the wind direction. They can harness winds from any direction without the need to reposition the rotor when the wind direction changes. Despite this advantage, VAWTs have found little commercial success to date, in part due to issues with power quality, cyclic loads on the tower systems and the lower efficiency of some VAWT designs.

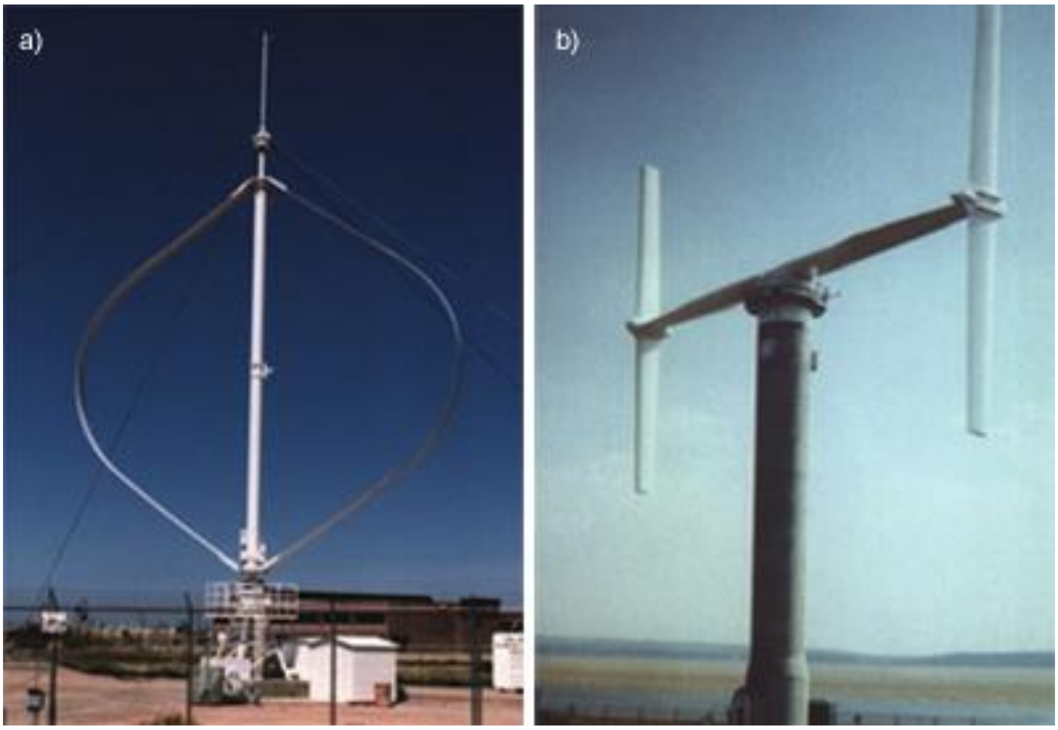


Figure 4 a) Seventeen metre diameter Darrieus-type VAWT at Sandia National Laboratories, New Mexico, USA b) 500 kW ‘H’-type VAWT prototype at Carmarthen Bay, Wales

The modern VAWT evolved from the ideas of the French engineer, Georges Darrieus, whose name describes one type of VAWT he invented in 1925. This device, which resembles a large eggbeater, has curved blades, with a symmetrical aerofoil cross-section, attached to the top and bottom of a vertical shaft in Figure 4a.

However, the curved blades of a Darrieus VAWT can be difficult to manufacture, transport and install, so straight-bladed VAWTs have been developed. These include the ‘H’-type vertical axis wind turbine (H-VAWT) shown in Figure 4b, consisting of a tower capped by a hub to which is attached two or more horizontal cross arms that support the straight, upright, aerofoil blades; and the ‘V’-type vertical axis wind turbine (V-VAWT) shown in figure 5a which has straight aerofoil blades attached at one end to a hub on a vertical shaft. Figure 5b below shows a conceptual design for a multi-megawatt offshore V-VAWT.

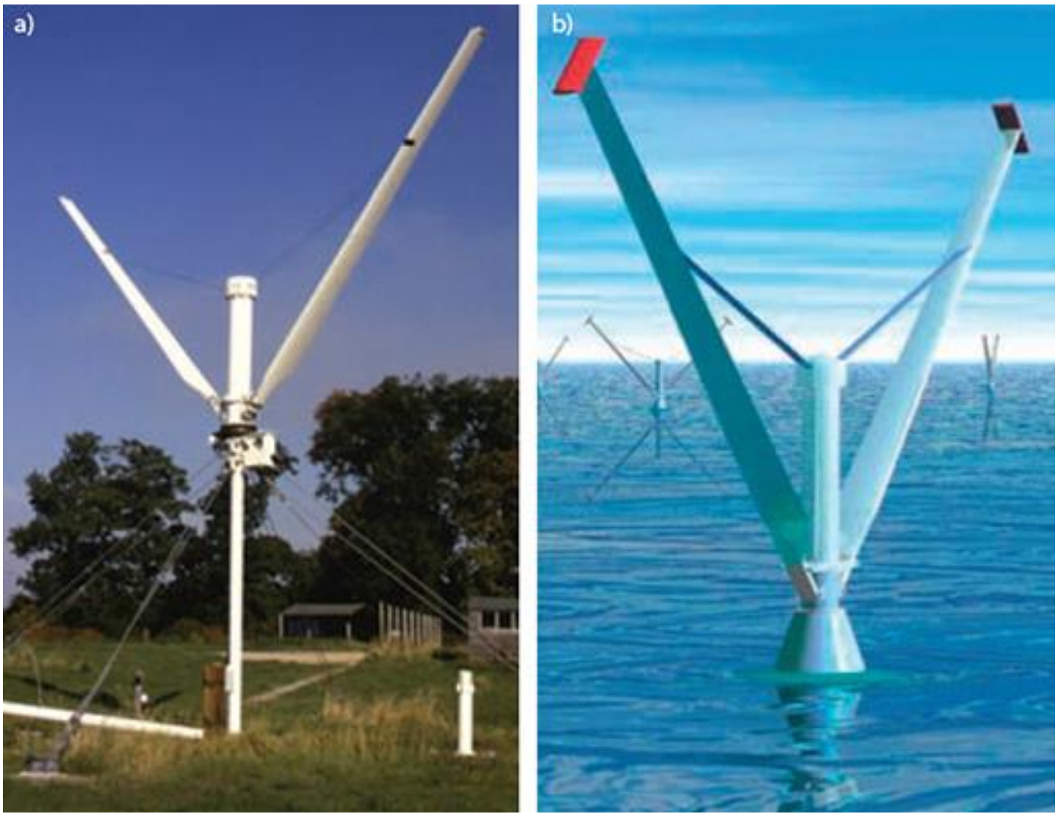


Figure 5 a) V-VAWT prototype developed and tested at the Open University in Milton Keynes in the 1980s b) Multi-megawatt scale V-Turbine concept in offshore configuration

In the next section you'll look in more detail at how wind turbines harness the wind.

4 Aerodynamics of wind turbines

An object in an air stream experiences a force **(F)** imparted from the air stream equivalent to two component forces acting in perpendicular directions, known as the *drag force* **(D)**, and the *lift force* **(L)** (Figure 6).

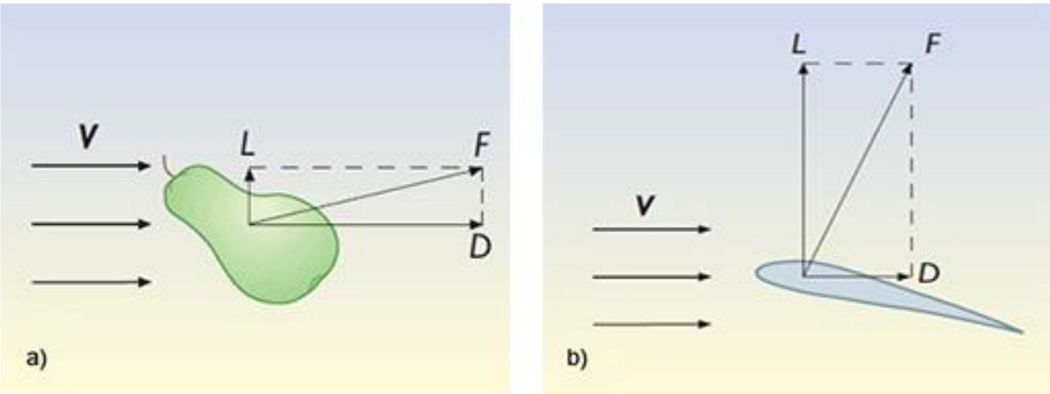


Figure 6 An object in an air stream is subjected to a force F, from the air stream. This is composed of two component forces: the drag force, D, acting in line with the direction of air flow, and the lift force, L, acting at 90° to the direction of air flow.

The magnitude of these forces depends on the shape of the object, its orientation to the air stream, and the air stream velocity. Objects designed to minimize drag forces are described as 'streamlined', because the lines of flow around them follow smooth, stream-like lines, as in the aerofoil section shown in Figure 7.

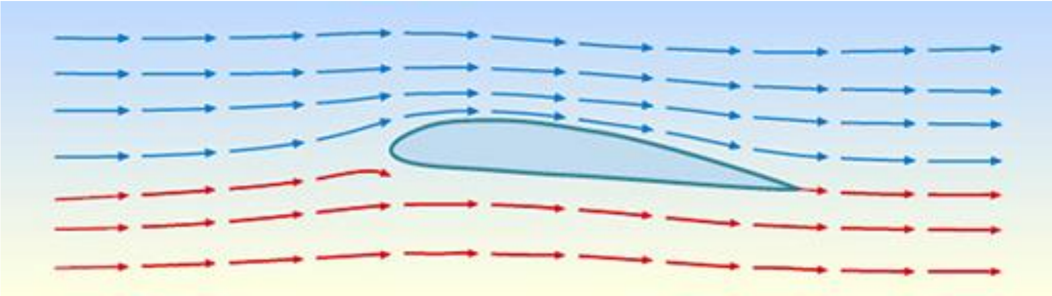


Figure 7 Streamlined flow around an aerofoil section

At small angles relative to the direction of the air stream – that is, when the ‘angle of attack’ is small – a low pressure region is created on the ‘downstream’ side of the aerofoil section as a result of an increase in the air velocity on that side (Figure 8).

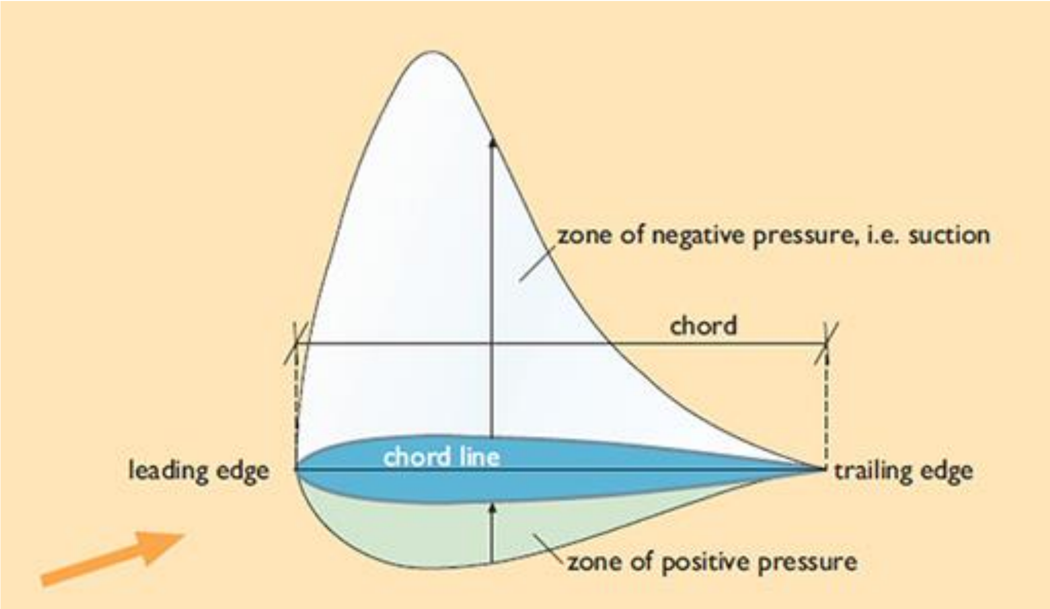


Figure 8 Zones of low and high pressure around an aerofoil section in an air stream

In this situation, the faster the airflow, the lower the pressure (this is known as the 'Bernoulli' effect). The lift force thus acts as a 'suction' or 'pulling' force on the object, in a direction at right angles to the airflow.

You'll look a little bit more at aerofoils in the next section.

4.1 Aerofoils and harnessing aerodynamic forces

There are two main types of aerofoil section:

1. Asymmetrical aerofoils – optimised to produce most lift when the underside of the aerofoil is closest to the direction from which the air is flowing.

2. Symmetrical aerofoils – able to induce lift equally well (although in opposite directions) when the air flow is approaching from either side of the ‘chord line’ (shown in Figure 7).

The angle which an aerofoil (or flat or cambered plate profile) makes with the direction of an airflow, measured against a reference line (usually the chord line), is called the angle of attack α (alpha). When airflow is directed towards the underside of the aerofoil, the angle of attack is positive.

The lift and drag characteristics of many different aerofoil shapes have been determined by measurements in wind tunnels, and catalogued (e.g. in Abbott and von Doenhoff, 1958). The lift and drag characteristics measured at each angle of attack can be described using non-dimensional lift and drag coefficients (C_L and C_D) or as lift to drag ratios (CL/CD). Knowledge of these coefficients is essential when selecting appropriate aerofoil sections in wind turbine blade design. Lift and drag forces are both proportional to the energy in the wind.

Harnessing aerodynamic forces

Modern horizontal and vertical axis wind turbines harness aerodynamic forces in a different ways.

In a HAWT with fixed-pitch blades, with its rotor axis in constant alignment with the wind direction, for a given wind speed and constant rotation speed the angle of attack at a given position on the rotor blade stays constant throughout its rotation cycle.

In most horizontal axis wind turbines the rotation axis is maintained in line with wind direction by a ‘yawing’ mechanism, which constantly realigns the turbine.

In addition to its swept area and rotor diameter, the performance (power output, torque and rotation speed) of a HAWT rotor depends on other factors, including the number and shape of the blades, the choice of aerofoil section, the length of the blade chord,, the blade pitch angle, the angle of attack at positions along the blade, and the amount of blade twist between the hub and tip.

By contrast, in a VAWT with fixed pitch blades, under the same conditions the angle of attack at a given position on the rotor blade constantly varies throughout its rotation cycle. This means that the ‘suction’ side reverses during each cycle, so a symmetrical aerofoil is needed to ensure that power can be produced irrespective of whether the angle of attack is positive or negative.

Let’s now concentrate on the power and energy that wind turbines can deliver.

5 Power and energy from wind turbines

The *power* output of a wind turbine varies with wind speed. Every turbine has a characteristic wind speed–power curve, often simply called the power curve, shown in Figure 9.

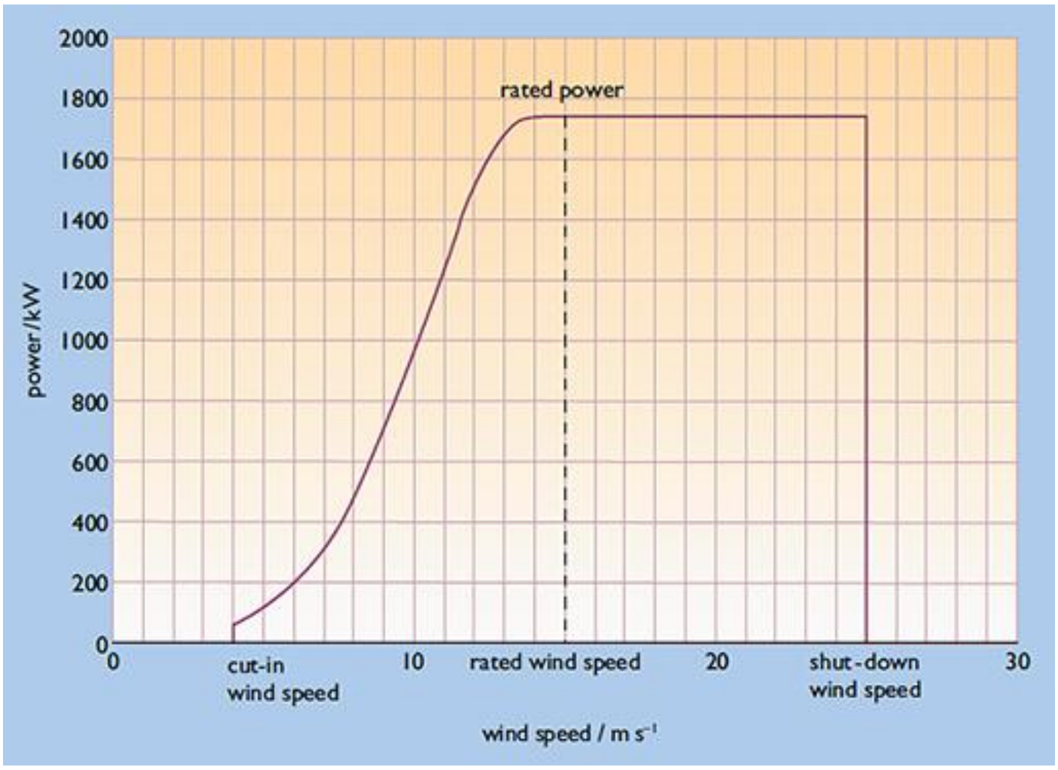


Figure 9 Typical wind turbine wind speed–power curve example

The *energy* a wind turbine will produce depends on both its wind speed–power curve shown in Figure 9 **and** the *wind speed frequency distribution* shown in figure 10 at the site.

The *cut-in wind speed*, shown in figure 9, is the wind speed below which the turbine does not rotate and generate power. Above the cut-in wind speed, the torque generated by air flow overcomes the frictional torques inherent in the mounting assembly of the turbine blades.

The *shut-down wind speed* is the wind speed at which the turbine has to be locked down to avoid damage due to excessive centrifugal forces and other mechanical stresses.

The range of wind speeds between cut-in and shut-down is called the *operating range* of the turbine.

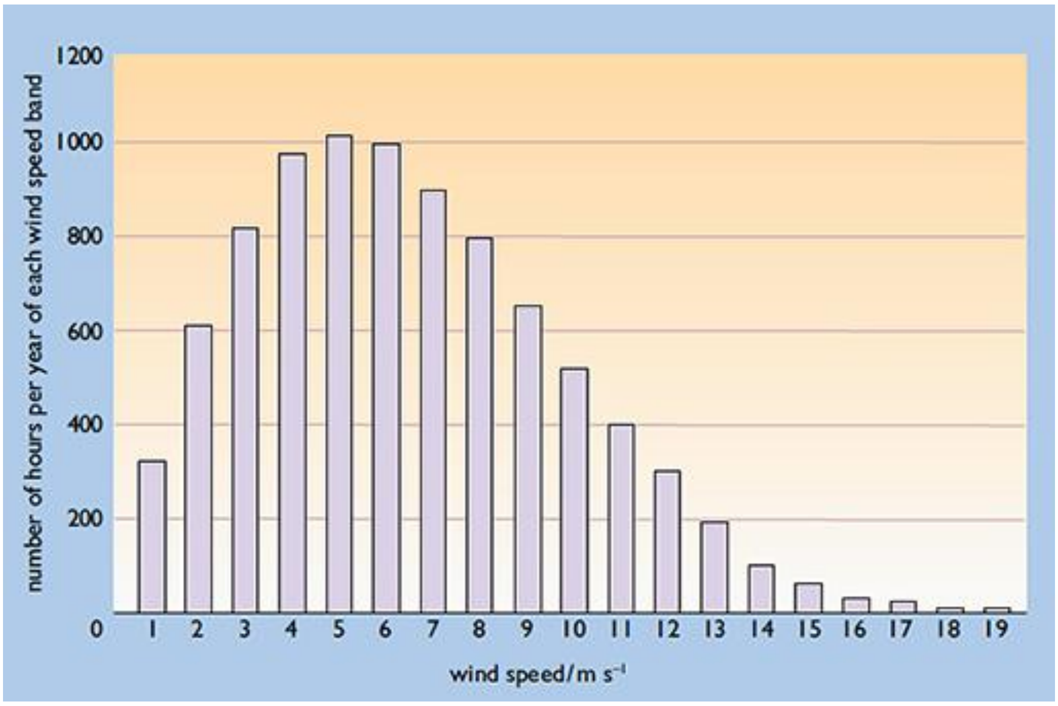


Figure 10 A wind speed frequency distribution example for a typical site, showing the number of hours the wind blows at different speeds during a year

Using the data from these graphs enables us to calculate a wind energy distribution graph, which you'll examine next section.

5.1 Calculating wind energy distribution

For each incremental wind speed between the cut-in wind speed and the shut-down wind speed the energy produced can be obtained by using this equation:

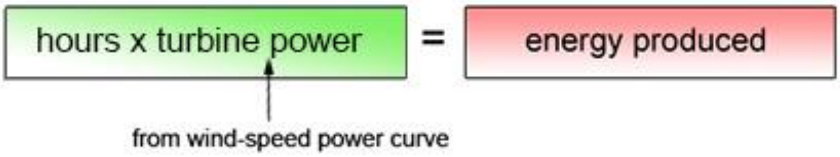


Figure 11 Calculating the energy produced at each given wind speed

This data can then be used to plot a *wind speed – annual output* energy distribution graph, such as that shown in Figure 12 .

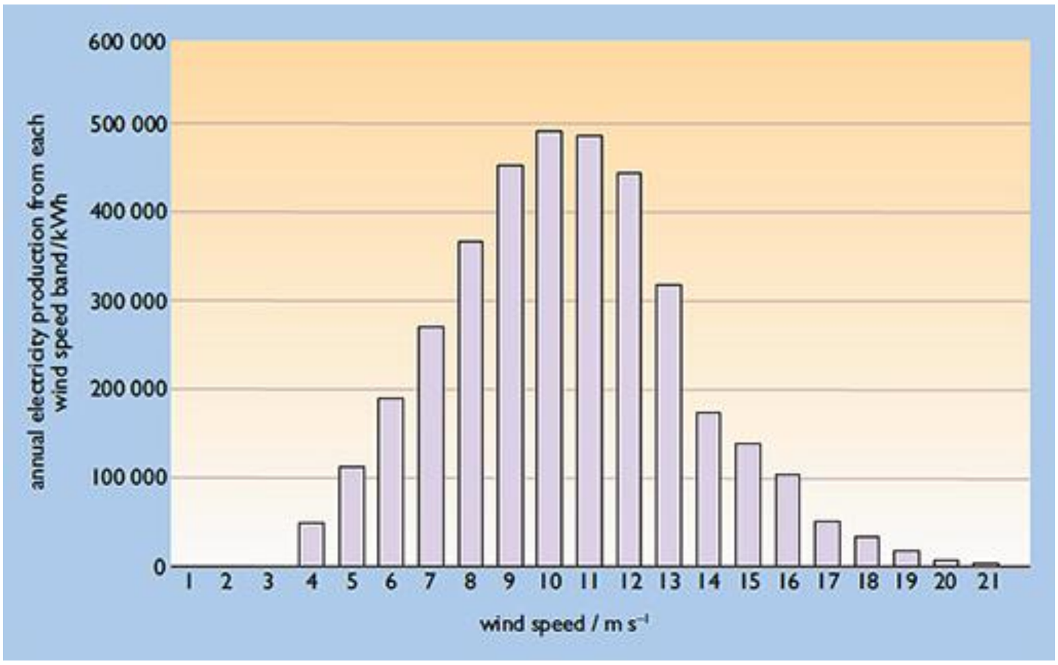


Figure 12 Example of a *wind speed – annual energy output* distribution curve, showing annual electricity production at each wind speed

The total energy produced in a year is then calculated by summing the all the energies produced at each wind speed within the operating range of the turbine.

The wind speed distribution at a site is provided by measuring equipment that records the number of hours for which the wind speed lies within each one metre per second (1 m s^{-1}) wide speed 'band', e.g:

- 0–1 m s^{-1}
- 1–2 m s^{-1}
- 2–3 m s^{-1}, etc.

The longer the period over which measurements are taken, the more accurate is the estimate of the wind speed frequency distribution.

Activity 1 Factors on total energy generated

What other factors could affect the total energy generated?

View answer - Activity 1 Factors on total energy generated

Current commercial wind turbines typically have annual availabilities in excess of 90%, many have operated at over 95% and some are achieving 98%.

Let’s now look at a quick way of making a rough estimate of annual energy production.

5.2 Estimating annual energy production

If the mean annual wind speed at a site is known, or can be estimated, the following formula (Beurskens and Jensen, 2001) can be used to make *a rough initial estimate* of the electricity production (in kilowatt-hours per year) from a number of wind turbines:

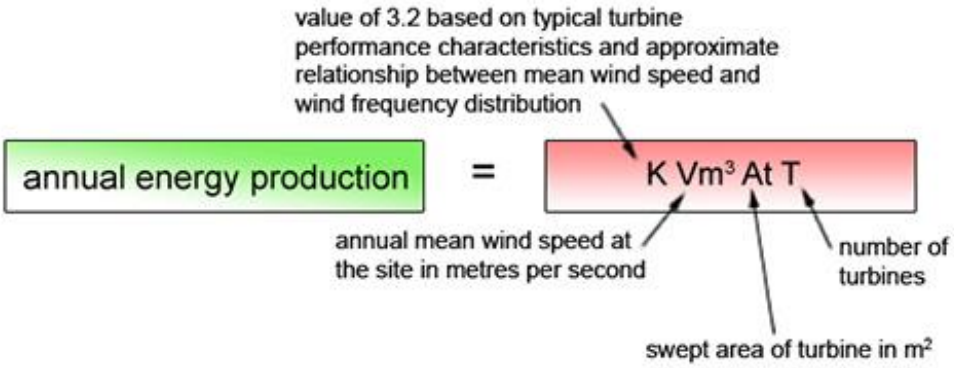


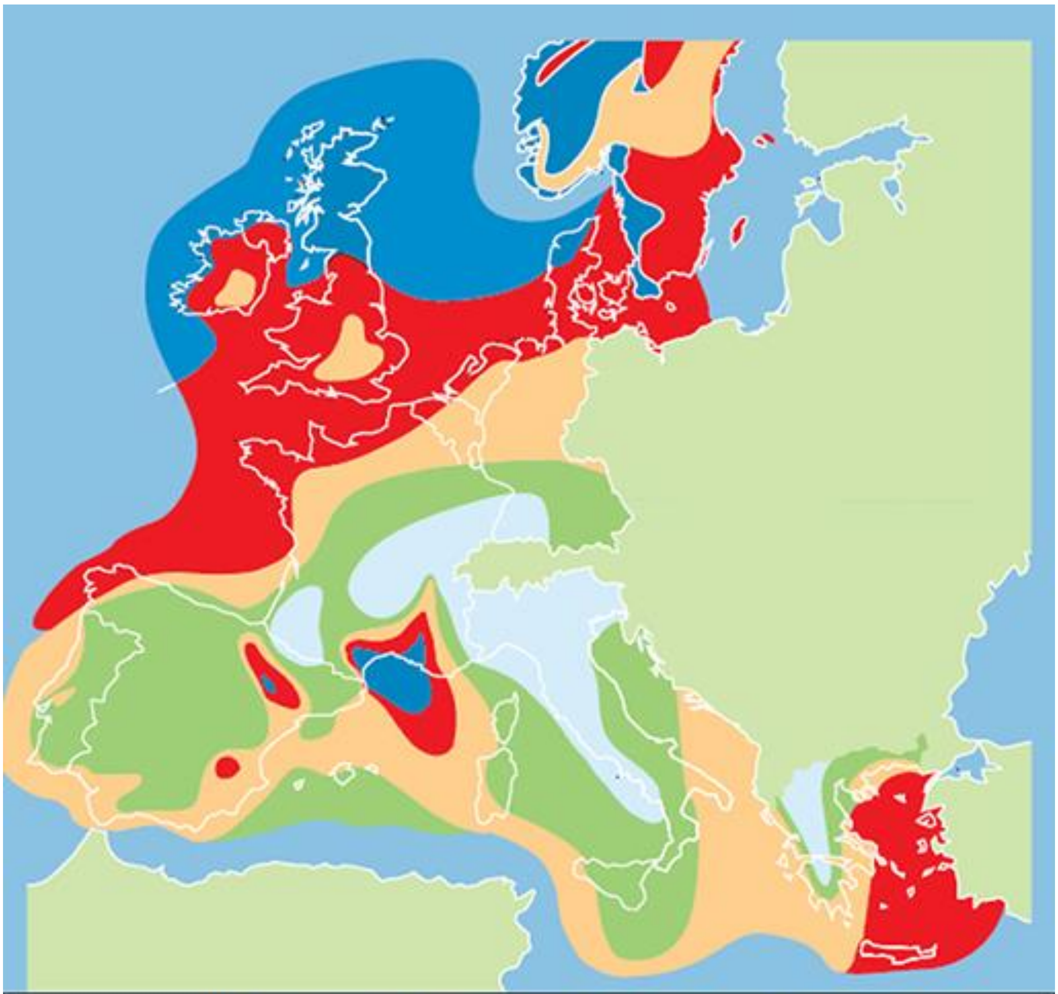
Figure 13 Annual energy production equation

This formula should be used with caution because it is based on an average of the characteristics of the medium- to large-scale wind turbines currently available. It also assumes an approximate relationship between annual mean wind speed (ideally, the mean speed at turbine hub height) and the a frequency distribution of wind speeds that may not be accurate for an individual site. It also does not allow for the different power curves of wind turbines that have been optimized either for low or high wind speed sites.

If it is not possible to carry out wind measurements at a proposed site, or where a preliminary analysis is required prior to installing instrumentation, there are techniques that can give an approximate estimate of the wind speed characteristics of a site. You'll study these in the next section.

5.3 Wind speed maps, atlases and computer models

Maps and atlases specifically for wind energy purposes have been developed for many countries. Using long-term wind measurements and the WAsP computer model, a European Wind Atlas (Troen and Petersen, 1989) has been produced by the Risø Laboratory in Denmark. It includes maps of various areas within the European Union (Troen and Petersen, 1989) has been produced by the Risø Laboratory in Denmark. It includes maps of various areas within the European Union (for example, Figure 14), showing the annual mean wind speed at 50 m above ground level for five different topographic conditions: sheltered terrain, open plain, sea coast, open sea, hills and ridges.



Wind resources at 50 m above ground level for five different topographic conditions

Wind class		Sheltered terrain $m\,s^{-1}$	Sheltered terrain $W\,m^{-2}$	Open plain $m\,s^{-1}$	Open plain $W\,m^{-2}$	At a sea coast $m\,s^{-1}$	At a sea coast $W\,m^{-2}$	Open sea $m\,s^{-1}$	Open sea $W\,m^{-2}$	Hills and ridges $m\,s^{-1}$	Hills and ridges $W\,m^{-2}$
5	(dark blue)	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
4	(red)	5.0–6.0	150–250	6.5–7.5	300–500	7.0–8.5	400–700	8.0–9.0	600–800	10.0–11.5	1200–1800
3	(orange)	4.5–5.0	100–150	5.5–6.5	200–300	6.0–7.0	250–400	7.0–8.0	400–600	8.5–10.0	700–1200
2	(green)	3.5–4.5	50–100	4.5–5.5	100–200	5.0–6.0	150–250	5.5–7.0	200–400	7.0–8.5	400–700
1	(light blue)	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400

Figure 14: Annual mean wind speeds and wind energy resources over Europe (EU Countries) combining land-based and offshore wind atlases (source: Troen and Peterson, 1989)

The atlas includes a series of procedures for taking account of site characteristics to estimate the wind energy likely to be available. These procedures work quite well on sites with a gentle topography but are not so good for very hilly terrain or urban areas. A similar atlas (included in Figure 14) has also been produced to cover the *offshore* wind energy resource in the European Union (Risø, 2009).

6 Environmental impact of wind energy

Wind energy development has both positive and negative environmental impacts. On the positive side, the generation of electricity by wind turbines does not involve:

- the release of carbon dioxide or other greenhouse gases
- pollutants leading to acid rain or smog, causing various diseases
- radioactivity
- contamination of land, sea or water courses
- the consumption of water – unlike many conventional (and some renewable) energy sources. This could be important if water shortages occur with increasing frequency in the future.

Large-scale implementation of wind energy within the UK is turning out to be one of the most economic and rapid means of reducing carbon dioxide emissions. Over its working lifetime, a wind turbine can generate approximately 40 to 80 times the energy required to produce it (Everett et al., 2012).

But wind power is not without negative (or perceived negative) impacts. These include

- noise

- electromagnetic interference
- aviation-related issues
- wildlife
- public attitudes and planning.

6.1 Wind turbine noise

Wind turbines are often described as noisy by opponents of wind energy, but they are not especially noisy compared with other machines of similar power rating – see Figure 15.

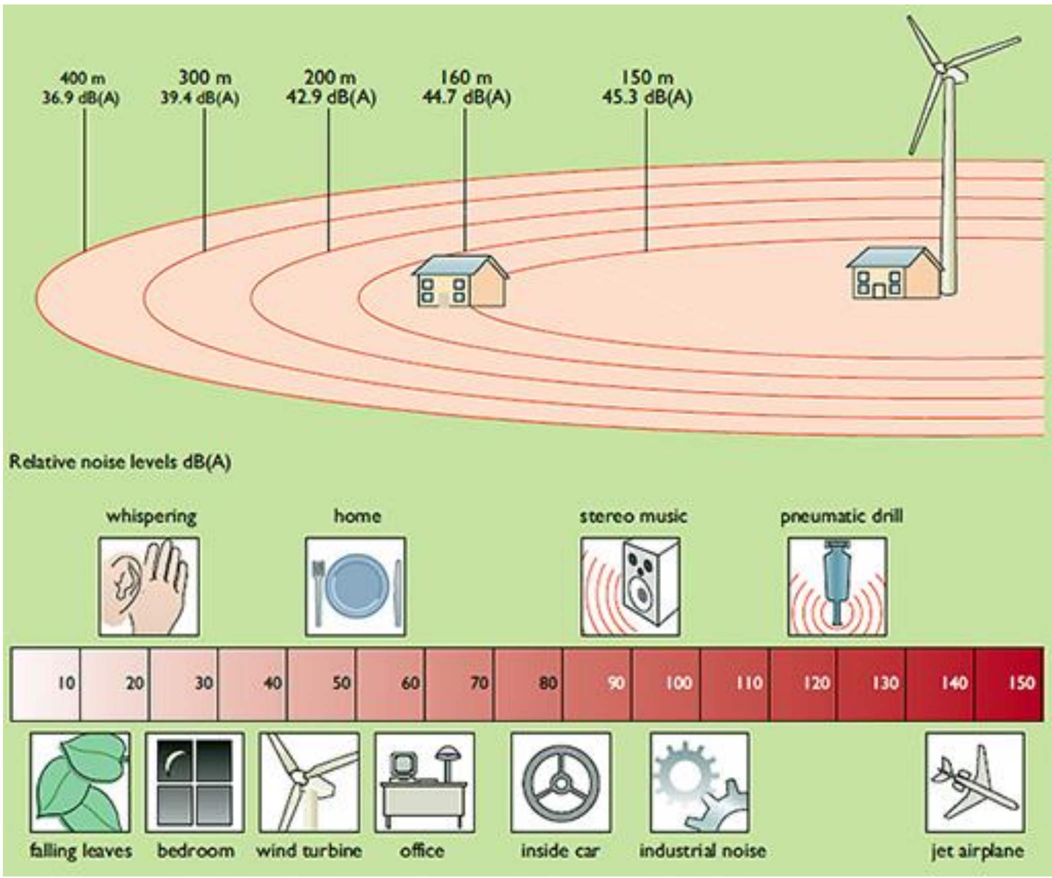


Figure 15 Wind turbine noise pattern from a typical wind turbine (source: EWEA. 1991)

There are two main sources of wind turbine noise:

1. Mechanical noise, produced by equipment such as the gearbox or generator, which can be reduced significantly by the using quieter gears, mounting equipment on resilient mounts, and using acoustic enclosures.

2. Aerodynamic noise, due to the interaction of the airflow with the rotor, which can best be described as a 'swishing' sound. It is affected by the trailing edge of the blades and the interaction of the airflow with the blades and the tower. It tends to increase with the speed of rotation, so some turbines are designed to operate at lower rotation speeds during periods of low wind.

Most commercial wind turbines undergo noise measurement tests and the measured noise levels provide information that enables the turbines to be sited at a sufficient distance from habitations to minimise (or avoid) noise nuisance. In the UK current limits are set at 35 – 40 dB (A) for daytime and 43 dB (A) for night-time.

If noise is not given careful consideration at both turbine design and project planning stages, accounting for the concerns of people who may be affected, opposition to wind energy development is likely.

You'll now look at electromagnetic interference.

6.2 Electromagnetic interference

When a wind turbine is positioned between a radio, television or microwave transmitter and receiver as shown in figure 16 it can sometimes reflect some of the electromagnetic radiation in such a way that the reflected wave interferes with the original signal as it arrives at the receiver. This can cause the received signal to be distorted significantly.

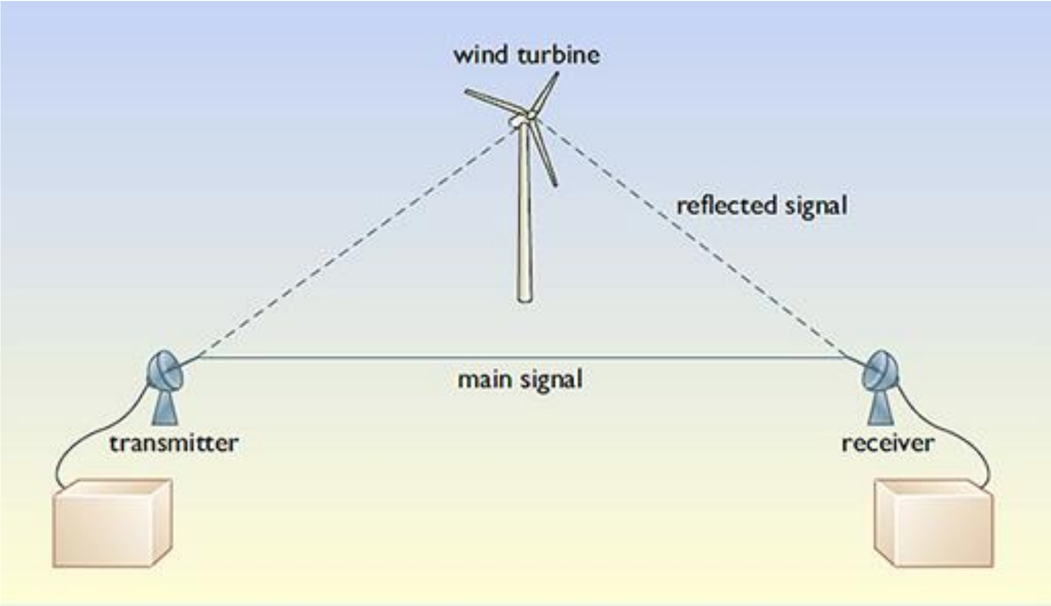


Figure 16 Scattering of radio signals by a wind turbine

The extent of electromagnetic interference caused by a wind turbine depends mainly on the materials used to make the blades and on the surface shape of the tower. In the UK, Ofcom maintains a website that provides guidance on wind farms and electromagnetic interference (Ofcom, 2011).

Can wind turbines interfere with military radar? You'll look at that next.

6.3 Wind turbines and aviation

The UK Ministry of Defence (MOD) has voiced concern about the interference with military radar that could be caused by wind turbines. In addition, it is concerned that wind turbines (particularly those with large diameters and tall towers), when located in certain areas, will penetrate the lower portion of the low flying zones used by military aircraft. MOD intervention has impeded the development of several wind farms in the UK.

Renewable UK maintains a website (Renewable UK, 2011a) giving information about wind turbines and aviation, including a series of maps from NATS (National Air Traffic Services), MOD and RESTATS (RESTATS, 2011) showing the consultation zone areas in the UK for which NATS requires notification of wind turbine planning applications.

One potential solution involves adapting the design of wind turbine blades to include RAMs (radar absorbing materials). In a joint project between QinetiQ and Vestas (Appleton, 2010) a ‘stealth’ turbine equipped with a set of RAM blades has demonstrated a substantially reduced impact on radar.

Another approach is the development of systems that can filter out interference to radar from wind turbines, such as BAE’s ADT (Advanced Digital Tracking) system (Butler, 2007).

Can turbines have an impact on birds and wildlife? You'll cover that next.

6.4 Impact on wildlife

In the UK, English Nature has produced a guidance document (English Nature et al., 2001) for nature conservation organisations and developers when consulting over wind farm proposals in England. Similar documents have been produced for Wales and Scotland.

In the case of offshore wind, there are concerns about the possible impact on fish, crustaceans, marine mammals, marine birds and migratory birds. These are the subject of ongoing research by organizations including Natural England, Scottish Natural Heritage, COWRIE (Collaborative Offshore Wind Research Into the Environment) and CEFAS (Centre for Environment, Fisheries and Aquaculture Science).

The main potential hazard to birds is that they could be killed by flying into turbine blades (Drewitt and Langston, 2006). However the American Bird Conservancy (ABC) reports that 100 000–440 000 bird collisions occur per year with wind turbines, compared with 4–50 million with towers, 10–154 million with power lines, 10.7–380 million with roads/vehicles, over 31 million with urban lights and 100 million–1 billion with glass on buildings (ABC, 2011).

Natural England (2010) suggests that there is little evidence that wind farms in England have a significant impact on birds, but it provides guidance about wind turbines and birds, and post-construction monitoring of bird impacts.

It is possible to install radar systems that automatically detect approaching birds and, if there is a likelihood of collisions, bird deterrent devices can be activated or the turbines shut down until after the birds have passed.

Wind turbines may have an impact on bats – particularly along migration routes. Natural England has produced interim guidance (Natural England, 2009a and 2009b) to help planners and wind turbine operators take account of potential impacts on bats when developing or assessing wind turbine developments.

What are the factors that influence attitudes to wind power among planners and the general public? You'll move onto that now.

6.5 Public attitudes and planning considerations

The visual perception of a wind turbine or a wind farm is determined by a variety of factors including:

- turbine size
- turbine design

- number of blades
- colour
- number of turbines in a wind farm
- layout of the wind farm
- extent to which moving rotor blades attract attention.

Figure 17 compares a wind turbine with other large constructions in the UK.

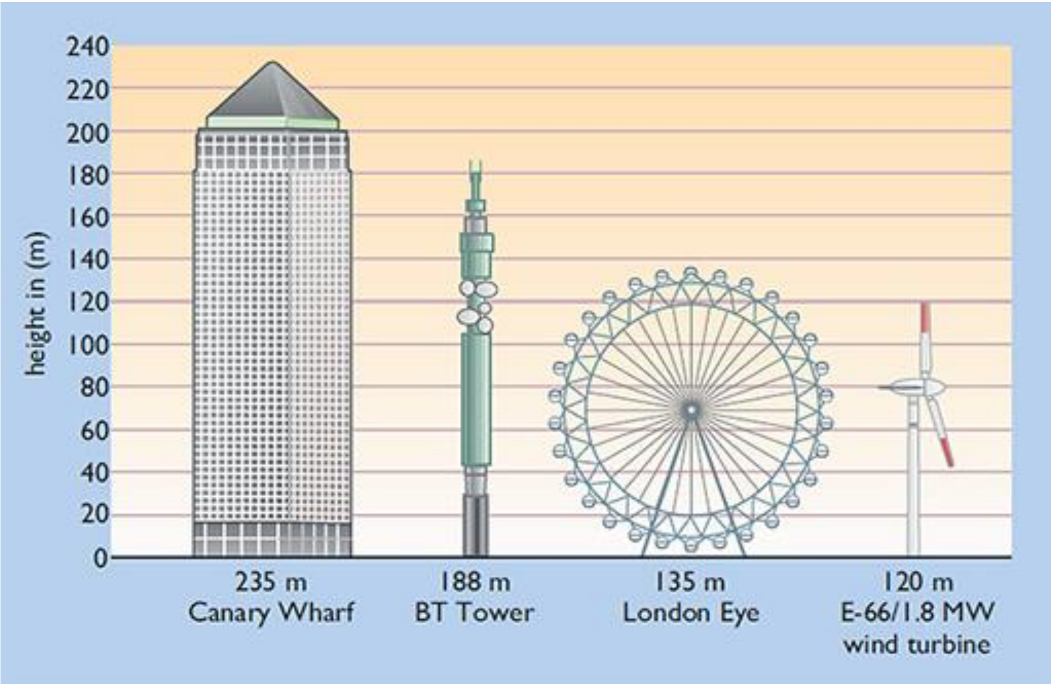


Figure 17 Comparison of wind turbines and other structures in the landscape

An individual's perception of a wind energy project will also depend on a variety of less easily defined psychological and sociological parameters, with much of the controversy due to opposition to changes to the visual appearance of the landscape. Whether this is due to a visual dislike of wind turbines specifically, or simply to a general dislike of changes in the appearance of the landscape is often unclear.

Since the 1990s surveys of public attitudes have consistently shown that on average 70% to 80% support the development of wind farms in the UK (see for example NOP, 2005 and YouGov, 2010). However, there is still opposition to change and it is important for projects to be well designed and planned. Developers should engage with local communities to provide trusted and reliable information, together with meaningful community benefits.

Planning considerations and controls have a major influence on the deployment of wind turbines.

The UK Government includes planning guidance for wind energy in its *National Planning Policy Framework*, (DCLG, 2011). Guidelines for developers and planners have also been prepared by Natural England, Scottish Natural Heritage and the Countryside Council for Wales. Some UK local authorities have also developed policy guidelines on planning aspects of wind energy.

7 Calculating the costs of wind energy

The costs of electricity from wind depend principally on:

- the annual energy production from the wind turbine installation
- the capital cost of the installation
- the discount rate being applied to the capital cost of the project
- the length of the contract with the purchaser of the electricity being produced
- the number of years over which the investment in the project is to be recovered (or any loan repaid)
- the operation and maintenance costs, including maintenance of the wind turbines, insurance, land leasing, offshore leasing etc.

Taking all these factors into consideration, the UK Government as part of its 2013 Energy Bill set up a system called ‘Contracts for Difference’ which introduced ‘strike prices’ for various renewable and non-renewable electricity generators from 2015, see Figure 18.

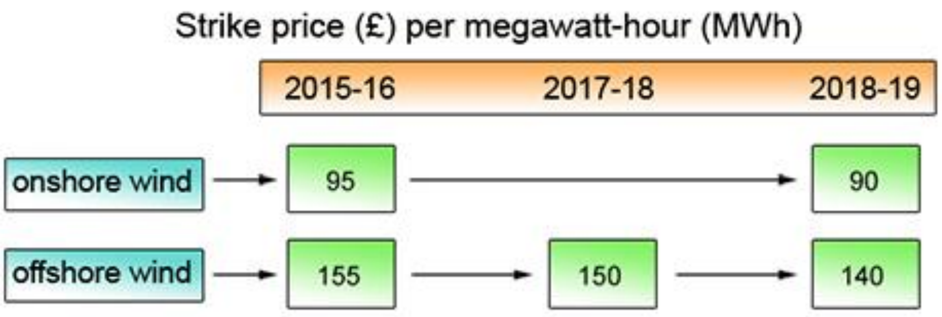


Figure 18 Strike prices for onshore and offshore wind in £ per megawatt-hour as set from 2015

If the prevailing market price for electricity is lower than the strike price, the generator will be paid the difference; and if higher, the generator will have to refund the difference.

In the next section you will take a look at offshore wind energy.

8 Offshore wind energy

The capital costs of energy from offshore wind farms, such as the one shown in Box 2, are currently higher than those of onshore installations because of the extra costs of civil engineering for substructure, higher electrical connection costs and the higher specification materials needed to resist the corrosive marine environment.

Box 2: Thanet offshore wind farm

One of the world's largest wind farms is in the estuary of the river Thames. It began operating in September 2010 at a site 12 km off Foreness Point in Kent. It forms the second wind farm in the Thames Estuary after the Kentish Flats Wind Farm.

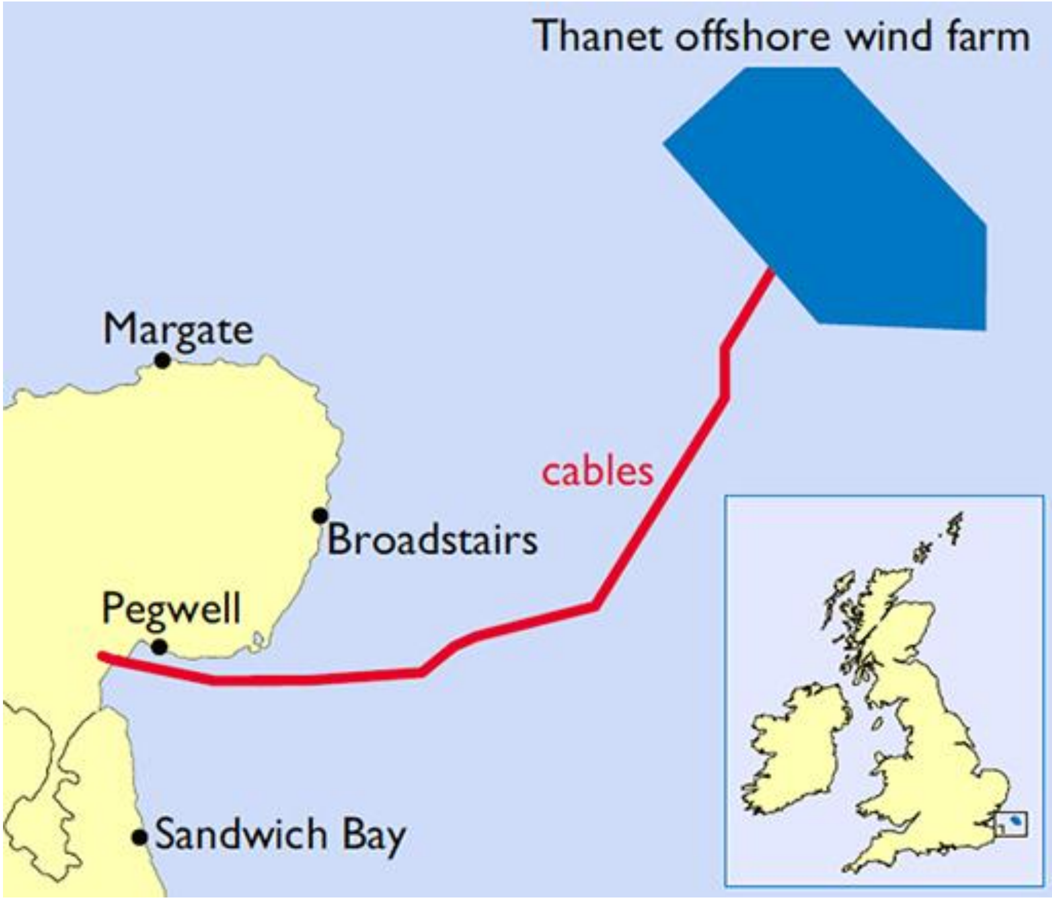


Figure 19 The Thanet offshore wind farm location

The Thanet wind farm cost £780 million, took two years to construct and was completed in June 2010.

The project consists of 100 Vestas V90-3 turbines each rated at 3 MW, giving a total installed capacity of 300 MW.

Figure 20 The Thanet Offshore Wind Farm

The 90 metre diameter turbines are spaced 500m apart in one direction and 800m apart in the other, over an area of 35 km2, in a water depth of 20-25m. Each turbine has a hub height above sea level of approximately 70m. The wind farm is estimated to generate an electricity output equivalent to the consumption of more than 200,000 UK homes.

In general offshore wind speeds are higher and more consistent than on land. Test results from the Tunø Knob offshore wind farm in Denmark indicate that actual output is 20–30% higher than that estimated from wind speed prediction models. Availability was also higher than expected with an average of 98% being achieved. These characteristics, together with likely reductions in offshore costs as experience is gained, are expected to make offshore wind energy costs competitive in the medium to long term.

Very large-scale wind turbines can capture more energy from a single platform and this can have benefits in terms of reduced maintenance costs. Although the initial capital investment is higher, the falling price of wind energy in the UK has been dramatic. In September 2017, a competitive tender resulted in a price of £57.50 per MWh, far cheaper than the government-backed price of £92.50 awarded in 2016 to the Hinkley Point nuclear power station project (The Guardian, 2017).

The main driver for lower wind energy prices is the ever-increasing length of the turbine blades being manufactured. A turbine commissioned in 2002 swept a diameter of 80 m; in 2005, this increased to 90 m; in 2011 it was 120 m. as in Figure 21. By 2020, 180 m swept diameter is expected on new installations.

Figure 21 E126 7.5MW 126m diameter wind turbine, an example of a very large turbine (source: Enercon, 2011)

An interesting recent development involves floating offshore turbines, such as Norway's Hywind, an innovative wind turbine, as in Figure 22, that has been successfully demonstrated in a water depth of 220 m. Floating wind turbines have significant implications for expanding the potential offshore wind energy beyond the shallow continental shelf sites so far developed. Development of the world's first floating wind farm, 25 km offshore from Peterhead in Scotland, is aiming at generating 30MW starting in late 2017 (BBC News, 2017)

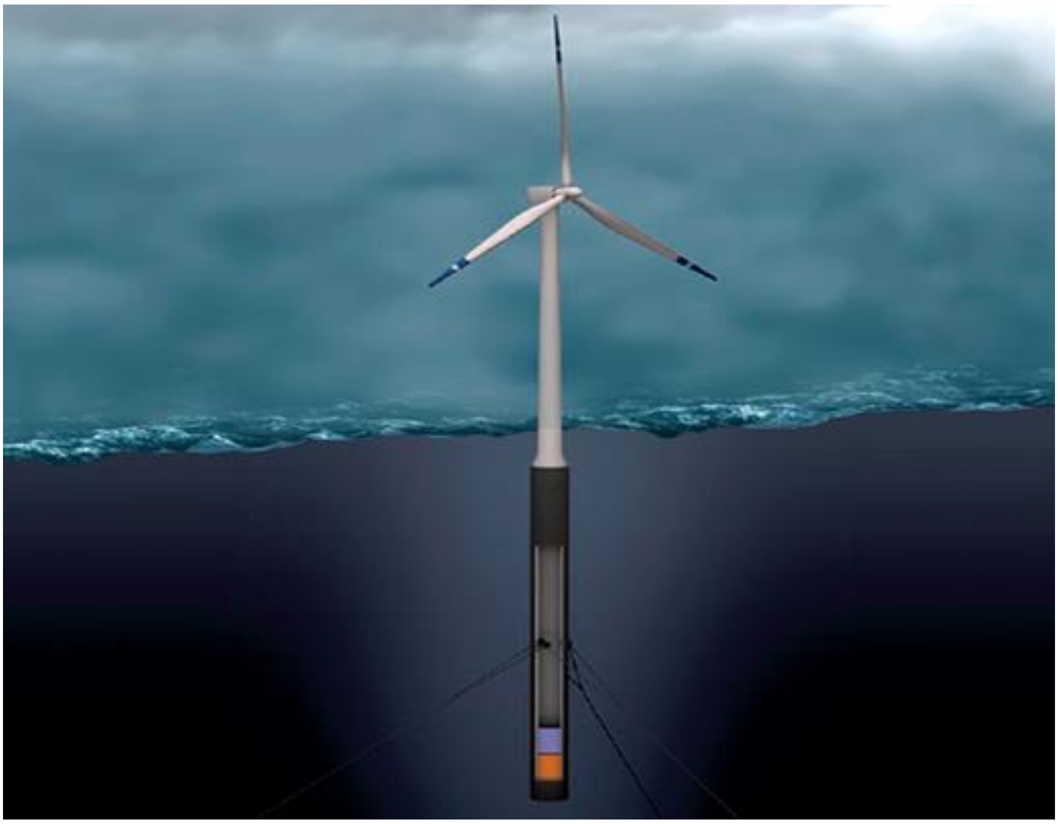


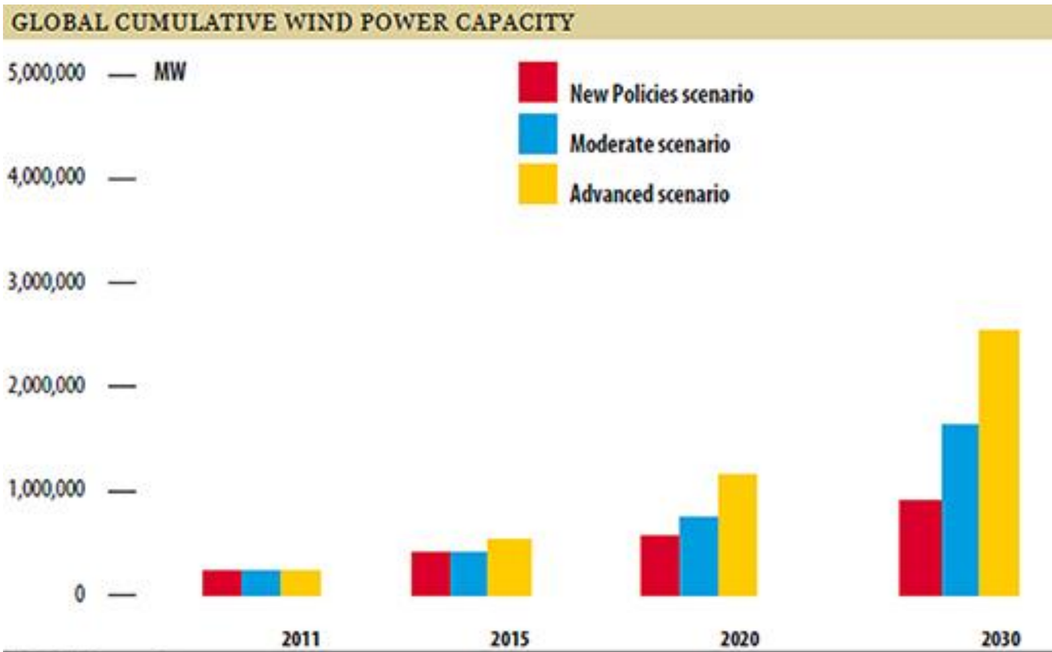
Figure 22 The Hywind floating 2.3 MW wind turbine

In late 2017, with 5,355 MW of offshore operational wind energy capacity installed from 1,500 offshore turbines, the UK has the world’s largest offshore wind energy capacity at the time of writing (RenewableUK, 2017.)

9 Future prospects for wind energy

In 2016 the GWEC (Global Wind Energy Council) produced a series of global wind energy outlook scenarios (GWEC, 2016) to examine the future potential for wind energy up to 2020, 2030 and 2050. These were based on three scenario assumptions:

1. a New Policies *Scenario* (NPS) based on the projections by the International Energy Agencys 2009 (IEA).
2. An *IEA 450 Scenario* based on an optimistic interpretation of the implementation agreements in the Paris Climate Agreement.
3. GWEC's Moderate *Scenario* (MS) reflects a world which carries on more or less the way it has for the past decade.
4. GWEC's Advanced *Scenario* (AS) which uses more ambitious assumptions about the ability of wind energy to produce more than a third of global electricity demand by 2050.



	2011	2015	2020	2030
New Policies scenario				
[MW]	237,699	397,859	586,729	917,798
[TWh/a]	583	976	1,439	2,412
Moderate scenario				
[MW]	237,699	425,155	759,349	1,617,444
[TWh/a]	583	1,043	1,863	4,251
Advanced scenario				
[MW]	237,699	530,945	1,149,919	2,541,135
[TWh/a]	583	1,302	2,821	6,678

Figure 23 Global cumulative wind power capacity to 2030 (source: GWEC, 2016)

Figure 23 shows the predicted increases in global cumulative wind power capacity based on these four scenarios up to 2050 (GWEC,2016).

Wind energy looks set to become a major generator of electricity throughout the world. Particularly in Europe, the offshore exploitation of wind energy is likely to become one of the most important means of reducing carbon dioxide emissions from the electricity sector. But achieving the levels of generation seen in the scenarios will require considerable investment in electricity grids, interconnection and in other infrastructure.

However, it appears that there is strong motivation from many governments and industries to facilitate this expansion.

Next you can attempt the Week 6 quiz.

10 Week 6 quiz

Check what you've learned this week by taking the end of week quiz.

Week 6 quiz.

Open the quiz in a new window or tab then come back here when you've finished.

11 Summary

This week you have:

- described the atmospheric processes that give rise to winds on the planet and the power they contain
- described the principal wind turbine types, the aerodynamic principles governing their operation, and various ways of calculating their power and energy production
- discussed the environmental impacts of wind turbines: noise; electromagnetic interference; aviation-related issues; wildlife impacts; public attitudes; and planning considerations
- looked at the economics of wind energy, and its projected future costs
- discussed offshore wind power, likely to be an important area of progress in coming decades
- concluded with a discussion of recent developments in wind energy and some projections of wind energy's future potential, world-wide and in the EU.

Week 7: Wave energy

Introduction

The possibility of extracting energy from ocean waves has intrigued people for centuries, but it was only in the latter half of the twentieth century that viable schemes began to emerge.

This week we will be looking at the physical processes involved in wave energy, what resources are available, and what technologies can be used to harness this energy. We'll also cover its economics and how wave power could be integrated into electricity grids.

You'll start by looking at the physical principles of wave energy.

Video content is not available in this format.

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By the end of this week, you will be able to:

- describe at an introductory level the physical characteristics of ocean waves and the basic physical principles underlying the conversion of energy from waves into useful power
- compare the essential features of various fixed, tethered and floating devices that have been developed or proposed for harnessing power from ocean waves

- understand at a basic level the order of magnitude of the natural wave energy resource available to Britain and elsewhere
- describe at an introductory level the potential economic and environmental costs and benefits of wave power.

1 The physical principles of wave energy

Ocean waves are generated by wind passing over long stretches of water known as ‘fetches’. Three main processes are involved:

1. Air flowing over the sea exerts a tangential stress on the water surface, resulting in the formation and growth of waves.
2. Turbulent air flow close to the water surface creates rapidly varying shear stresses and pressure fluctuations. Where these oscillations are in phase with existing waves, further wave development occurs.
3. Finally, when waves have reached a certain size, the wind can exert a stronger force on the upwind face of the wave, causing additional wave growth.

Because, as we saw in Week 6, the wind is originally derived from solar energy we may consider the energy in ocean waves to be a stored, moderately high-density form of solar energy. Solar power levels, typically of the order of 100 W m^{-2} (mean value) can be eventually transformed into waves with power levels of up to 30 kW per metre of **crest length**.

This measure of wave power is used because the nature of waves makes it impossible to refer to power per unit area: we have to consider that the wave action takes place throughout the depth of water, and so we consider the power passing through a one metre wide slice of water.

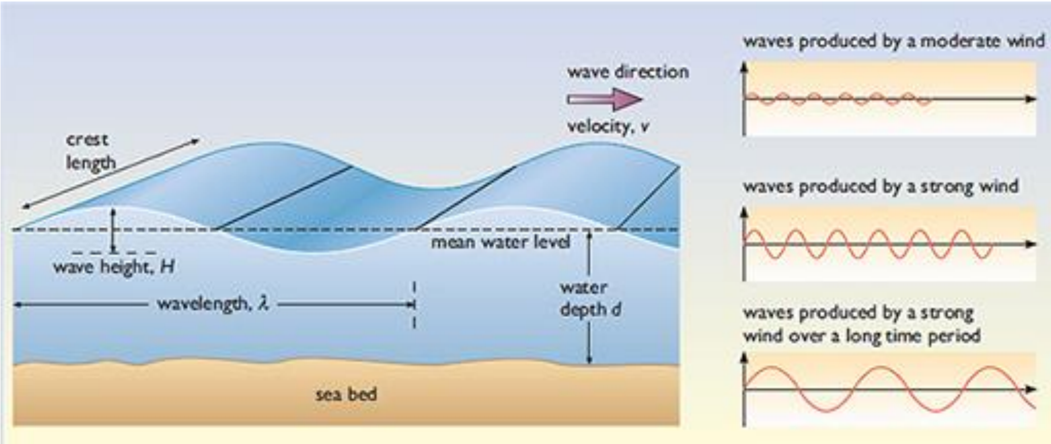

Figure 1 Characteristics of an idealised wave

Let’s start by looking at an idealised wave as shown in Figure 1.

This simple, ‘regular’ wave can be characterised by:

- its wavelength (λ) – the distance between successive peaks (or troughs) of the wave,
- its height (H) – the difference in height between peaks and troughs, and

- its period (t) – the time in seconds taken for successive peaks (or troughs) to pass a given fixed point.

The peaks and troughs of the wave move across the sea surface with a **velocity (v)** and a **frequency (f)** – the number of peak-to-peak (or trough-to-trough) oscillations of the wave surface per second. Mathematically, the frequency f is the reciprocal of the period, as shown in Figure 2.

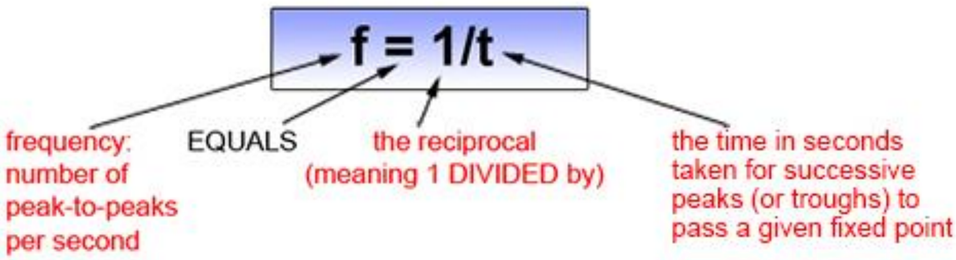

Figure 2 The frequency of a wave is equal to the reciprocal of its period

So if a wave is travelling at velocity v past a given fixed point, it will travel a distance equal to its wavelength in a time equal to the wave period t. This can be expressed in the equation in Figure 3.

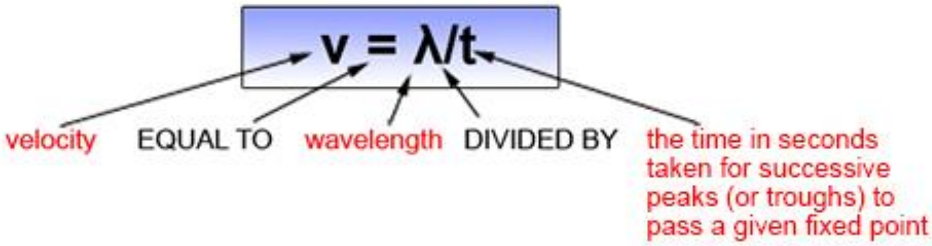

Figure 3 Wave velocity equals wavelength divided by its period

It can be shown that the power, P, of an idealised ocean wave is approximately equal to the square of its height, H (in metres), multiplied by the wave period, t (in seconds). P can be expressed (approximately) in kW per metre of wave front, in the equation shown in Figure 4.

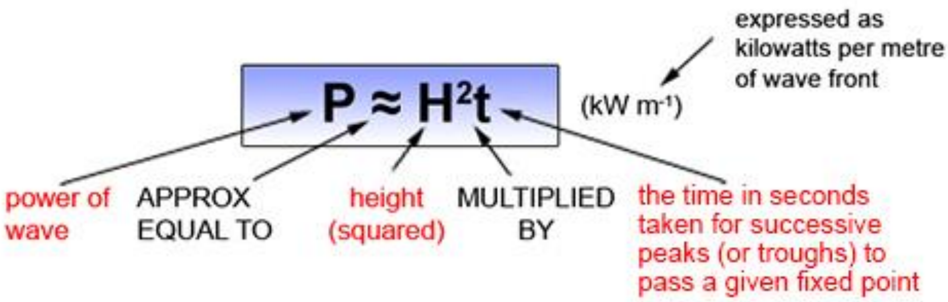

Figure 4 Wave power approximately equals height squared times period

There are differences between waves in deep and shallow water, which you will look at next.

1.1 Deep and shallow water waves

Deep water waves – In terms of wave propagation, water is considered ‘deep’ when the water depth is greater than about half the wavelength. The velocity of a deep-water ocean wave can be shown to be proportional to its period, as expressed in the equation in Figure 5:

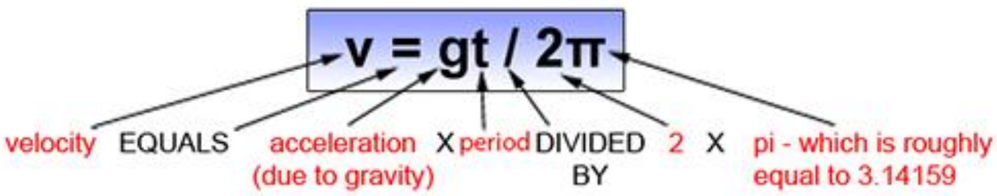

Figure 5 Velocity of deep water wave is proportional to its period

When simplified, this equation leads to the useful approximation that:

the velocity of deep water wave in metres per second is about 1.5 times the wave period in seconds

Activity 1 Long waves and short waves

Which waves travel faster – long waves or short waves?

View answer - Activity 1 Long waves and short waves

Shallow water waves – As waves approach the shore, the seabed starts to have an effect on their velocity, and it can be shown that if the water depth is less than a quarter of the wavelength then:

the velocity under these conditions is equal to roughly three times the square root of the water depth – it no longer depends on the wave period

The height and steepness of the waves generated by any wind field depends upon three factors:

- the wind speed
- its duration
- and the ‘fetch’, i.e. the distance over which wind energy is transferred into the ocean to form waves.

When a steady wind has blown for a sufficient time over a long enough fetch, the waves are referred to as constituting a ‘fully developed’ sea.

The UK is well situated to make use of wave energy because it lies at the end of a long fetch (the Atlantic Ocean) with the prevailing wind blowing towards it. The UK’s western approaches have therefore been of most interest to wave energy engineers and developers.

It’s important to know what goes on under the water to understand how to capture wave energy efficiently. You’ll look at that in the next section.

1.2 What happens beneath the surface?

The surface profile of the ocean is the obvious evidence for the existence of waves, but we also need to understand the sub-surface nature of waves if we are wto design schemes to capture energy from them.

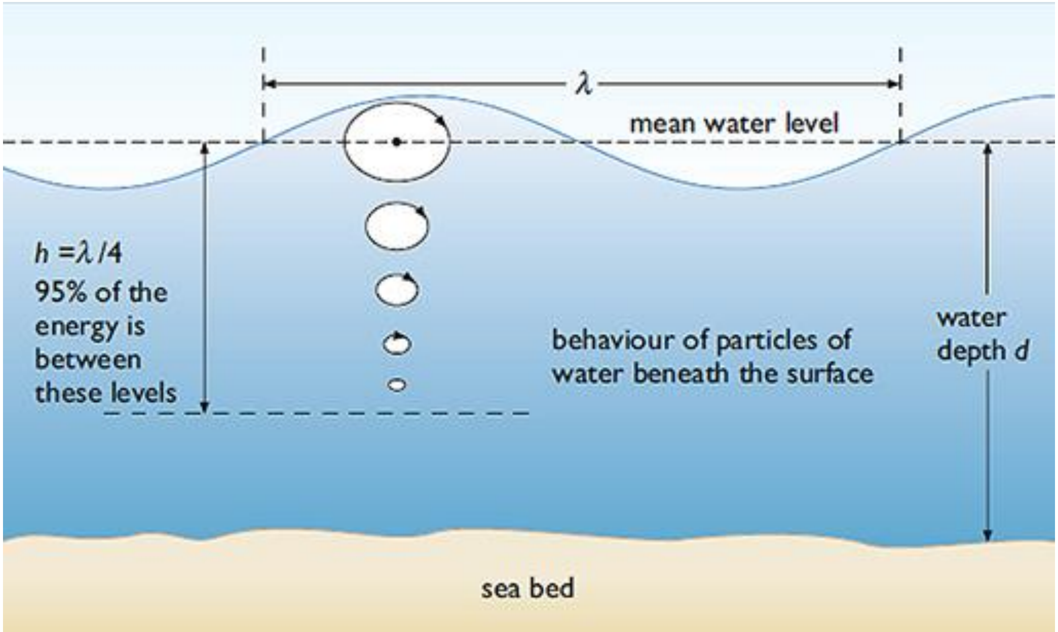

Figure 6 Behaviour of particles of water beneath the surface

As Figure 6 shows, waves are composed of orbiting particles of water. Near the surface, these orbits are the same size as the wave height, but the orbits decrease in size as we go deeper below the surface. The size of orbits decreases exponentially with depth. 95% of the wave energy is contained in the layer between the surface and a depth equal to a quarter of the wavelength.

There are a few areas in the world where the shoreline is formed by a steep cliff that drops into reasonably deep water. These are the most suitable for shore-mounted wave energy converters because the incident waves have a high power density. But, for most coastlines around the world the near-shore water is quite shallow. Due to the frictional coupling between the water particles at the greatest depths with the seabed, deep water waves gradually give up their energy as they move into shallower water and eventually run up the shore to the beach.

This power loss obviously reduces the total wave energy resource. Typically, waves with a power density of 50 kW m^{-1} in deep water might contain 20 kW m^{-1} or less when they are closer to shore in shallow water.

A further mechanism for energy loss as waves run up a beach is the formation of breaking waves, which are turbulent and energy-dissipating.

2 Wave energy resources

Figure 7 shows estimates of the average wave power density at various locations around the world. The areas that are subjected to regular wind fluxes are those with the largest wave energy resource. South-westerly winds are common in the Atlantic Ocean, and often travel substantial distances, transferring energy into the water to form the large waves that arrive off the European coastline.

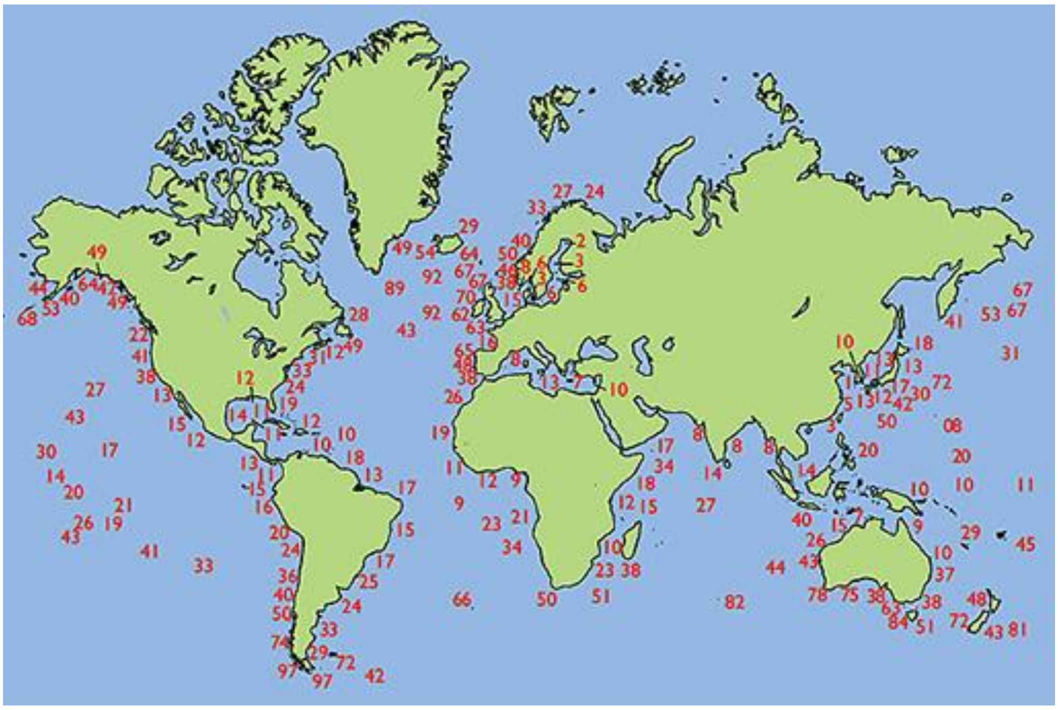

Figure 7 Annual average wave power in kilowatts per metre (kW m^{-1}) of crest length, for various locations around the world (source: adapted from Claeson, 1987)

Regarding the UK, Thorpe (2003) estimated that the total annual average wave energy along the north and west side of the United Kingdom ranges from 100 to 140 TWh per year at the near shore, to about 600 to 700 TWh per year in deep water. The proportion of this resource that could actually be harnessed to produce electrical power depends, of course, on various practical, technical and economic constraints.

Thorpe (1992) estimated that the technical resource (i.e. the resource technically available regardless of cost) is between 7 GW and 10 GW annual average power, equivalent to 61 to 87 TWh per year, depending on the water depth. In comparison, total UK annual electricity production in 2010 was approximately 360 TWh. Table 1 gives a breakdown of the resource at different water depths.

Table 1 The natural and technical wave energy resource for the north and west side of the UK

Water depth/m	Average natural resource		Average technical resource	
	GW	TWh per year	GW	TWh per year
100	80	700	10	87
40	45	394	10	87

20	36	315	7	61
Shoreline	30	262	0.2[1]	1.75

[1] The technical shoreline resource is very dependent on details of the local shoreline structure, for example the nature and shape of the rock formations and of gullies and beaches.

Source: Thorpe (1992) and (2001)

3 Wave energy technologies

To capture energy from sea waves it’s necessary to intercept the waves with a structure that will react in an appropriate manner to the forces applied to it by the waves. In a shore-mounted device the structure is firmly fixed to the seabed and the waves make water move in a useful way.

For other types of device some part of the structure may be fixed, perhaps anchored to the seabed, but another part may be a float that moves in response to the waves by pulling against the anchor. In this case the relative motion between the anchor and the float provides the opportunity to extract energy.

Very loosely tethered floating structures can also be employed, but a stable frame of reference must still be established so that the ‘active’ part of the device moves relative to the main structure. This can be achieved by taking advantage of inertia, or by making the main structure large enough to span several wave crests, hence remaining reasonably stable in most sea states.

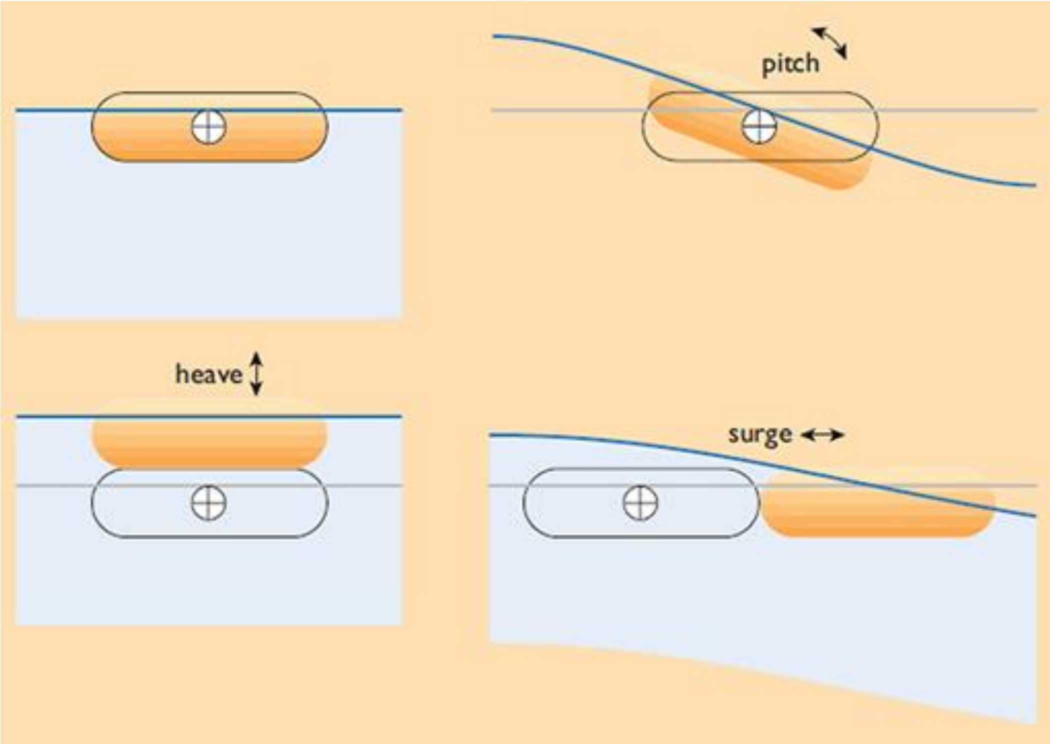

Figure 8 The pitch, heave and surge responses of a floating object to incident waves

A body in the sea subject to waves can respond to six types of movement. These are **sway**, **roll** and **yaw**, not generally harnessed in wave energy conversion technology. Three more, harnessed to varying degrees in most wave energy converters, are:

1. **pitch** – waves cause the device, or part of it, to rotate about its axis.

2. **heave** – waves cause the device to rise and fall vertically, though these devices have too high a natural frequency to be particularly effective.
1. **surge** – waves cause the device to move horizontally backwards and forwards, Theoretically, surging motions are twice as energetic as heaving ones, making it preferable to harness this component of waves.

Economics demands that a device should survive at sea for at least five years. During that time some of its components will have to execute 15 to 30 million cycles, placing severe constraints on material selection and strain levels. A structure designed to operate at a particular wave power density will also have to endure storms with power densities ten to thirty times higher than the operating value.

The physical size of the structure of a wave energy converter is a critical factor in determining its performance. The appropriate size can be estimated by considering the volume of water involved in the upper particle orbits in a wave. In most circumstances a wave energy converter will have to have a swept volume similar to this volume of water in order to capture all of the energy contained in the wave. The precise physical size and shape of each device will be governed by its mode of operation, but as a rough guide the swept volume must be of the order of several tens of cubic metres per metre of device width.

There are many different configurations of wave energy converter. Several ways of classifying them have been proposed:

1. Classified by mode of operation (Figure 9)

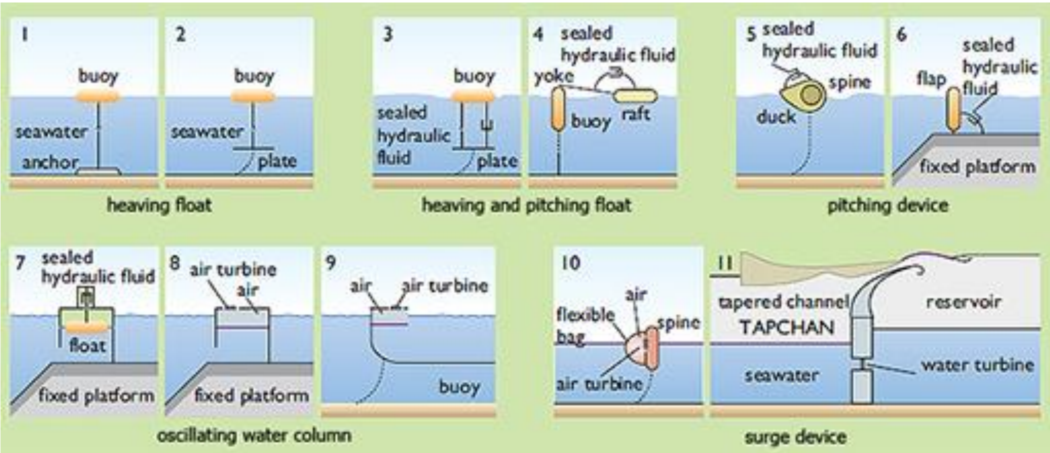

Figure 9 Schematic representation of various types of wave energy converter classified by mode of operation (source: based on Falnes and Løvseth, 1991)

2. Classified by device location – usually in three general classifications (shown in Figure 9):

1. fixed to the seabed, generally in shallow water (eg TAPCHAN)

2. tethered in intermediate depths (eg Oyster)
3. floating offshore in deep water (eg AWS-III).

These three named devices are described in the next section.

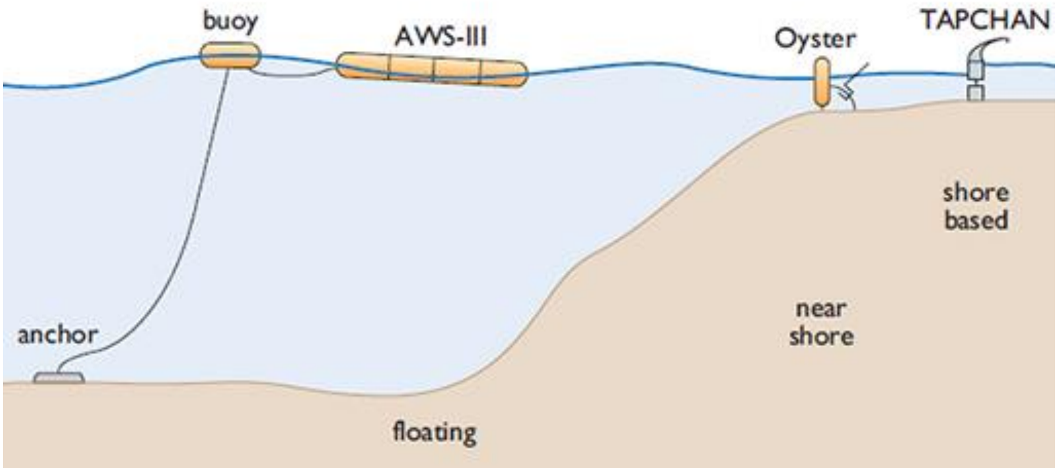

Figure 10 Classification of wave energy converters according to location

3. Classified by geometry and orientation (see Figure 11). Here the options are:

1. terminators
2. attenuators
3. point absorbers.

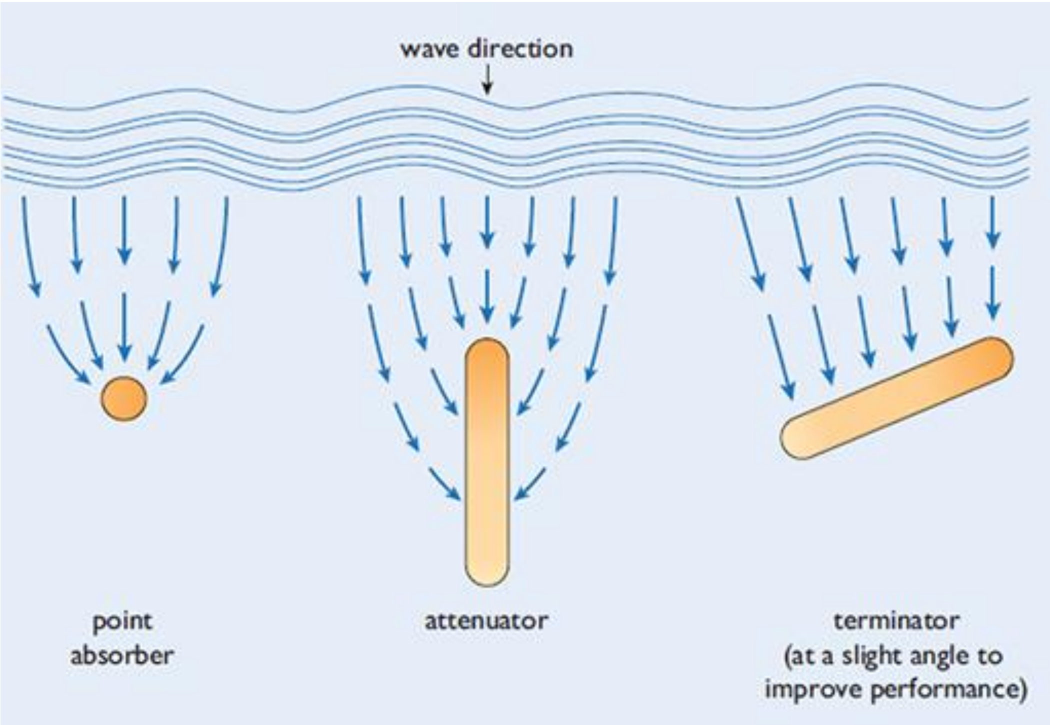

Figure 11 Classification of wave energy converters according to size and orientation

We'll take a closer look at fixed devices in the next section, and for brevity the various wave energy devices described are those developed or installed in or around the British Isles.

3.1 Fixed devices

Fixed seabed and shore-mounted devices are usually terminators. These have been the most common types of wave energy converter tested as prototypes at sea.

Activity 2 Pros and cons of fixed and shore mounted devices over floating devices

What advantages and disadvantages do you think apply to fixed and shore mounted devices over floating ones?

View answer - Activity 2 Pros and cons of fixed and shore mounted devices over floating device ...

The majority of fixed devices tested and planned are of the oscillating water column (OWC) type. In these, an air chamber pierces the surface of the water and the contained air is forced out of, and then into, the chamber by the approaching wave crests and troughs. On its passage from and to the chamber, the air passes through an air turbine – usually of the Wells type shown in Box 3.

Box 3: Wells Turbine

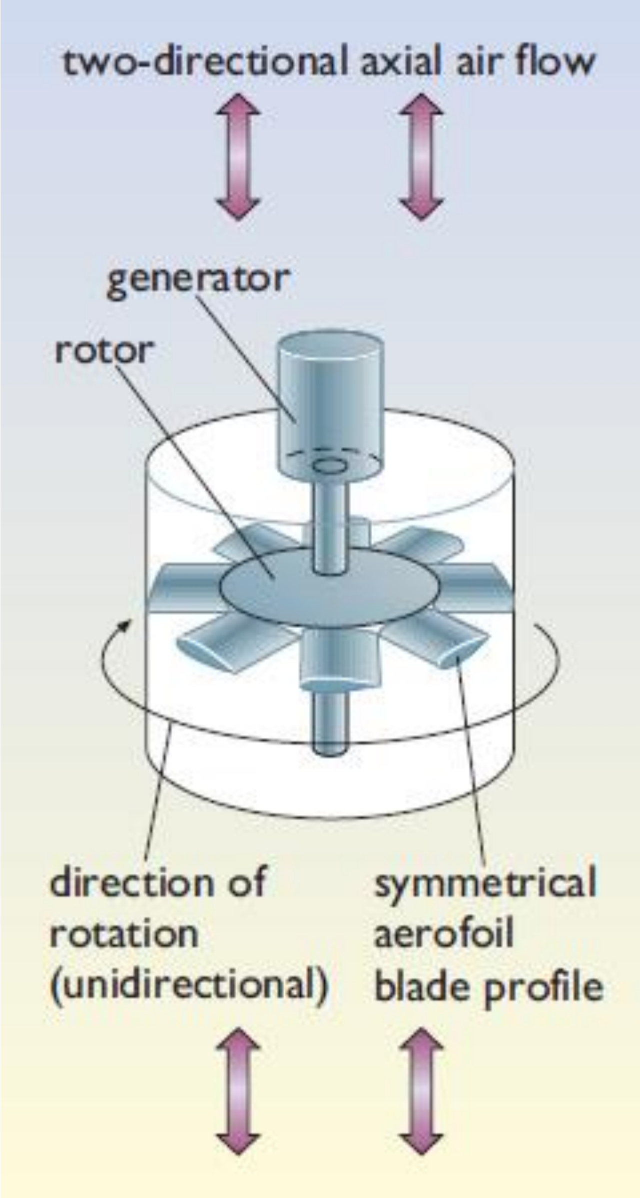

Figure 12 The Wells turbine

A Wells turbine is an axial flow device that drives a generator and so produces electricity.

It rotates in the same direction irrespective of the direction of airflow, and has aerodynamic characteristics particularly suitable for wave applications.

A very attractive feature of its use in OWCs is that the cross-sectional area of the air turbine can be much smaller than the area of the moving water surface. This acts like gearing to increase the air velocity through the turbine so that it can operate at high speed.

In the next section we'll look at some examples of OWC devices.

3.2 TAPCHAN and other fixed devices

The TAPCHAN ('TAPered CHANnel') concept is simple. The first, and so far only, example was built on a small Norwegian island. It has a channel with a 40 metre wide horn-shaped collector. Waves entering the collector were fed into the wide end of the tapered, upward sloping channel, where they then propagated towards the narrow end with increasing wave height.

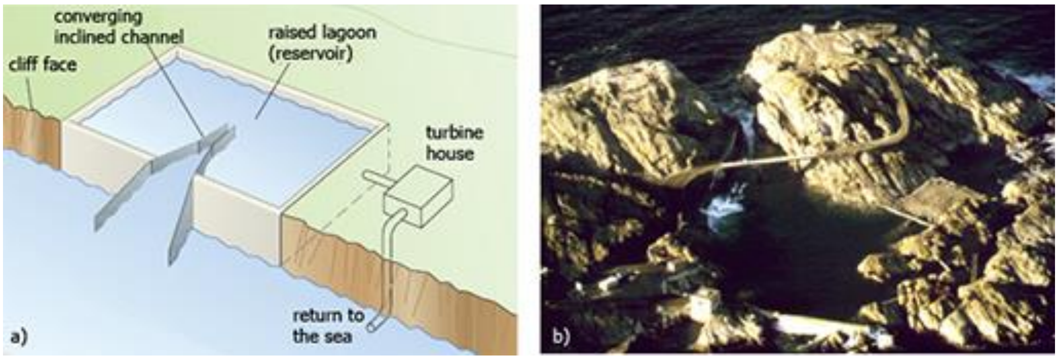

Figure 13 (a) The tapered channel (TAPCHAN) wave energy conversion device (b) Aerial photograph of the Norwegian TAPCHAN : water is entering the reservoir in the centre of the image, where the channel device can just be seen between the cliff walls

The kinetic energy in the waves was thus converted into potential energy, and this was subsequently converted into electricity by allowing the water in the reservoir to return to the sea via a low-head Kaplan turbine system. This powered a 350 kW generator that delivered electricity into the Norwegian grid.

With very few moving parts, The TAPCHAN's maintenance costs should be low and its reliability high. The storage reservoir also helps to smooth the electrical output.

Fixed OWC devices have been investigated in a number of locations, with slight variations to the basic concept.

In the mid-1980s Queen's University, Belfast (QUB) worked on the development of a shoreline oscillating water column (OWC) device on the island of Islay in Scotland. It supplied the local grid with electricity on an intermittent basis from a 75 kW generator from 1991 until it was decommissioned in 1999. The QUB approach was to develop a device that could be built cheaply on islands using locally available technology and plant.

To overcome some of the limitations of its first prototype, the QUB team went on to develop a second design called **LIMPET** (Land Installed Marine Powered Energy Transformer).

The 'designer gully' where it was installed was excavated in order to improve the flow of water into and out of the oscillating chamber, and the main part of the gully chamber was built at a slope so as to efficiently change the water motion from horizontal to vertical and vice versa (Figure 15).

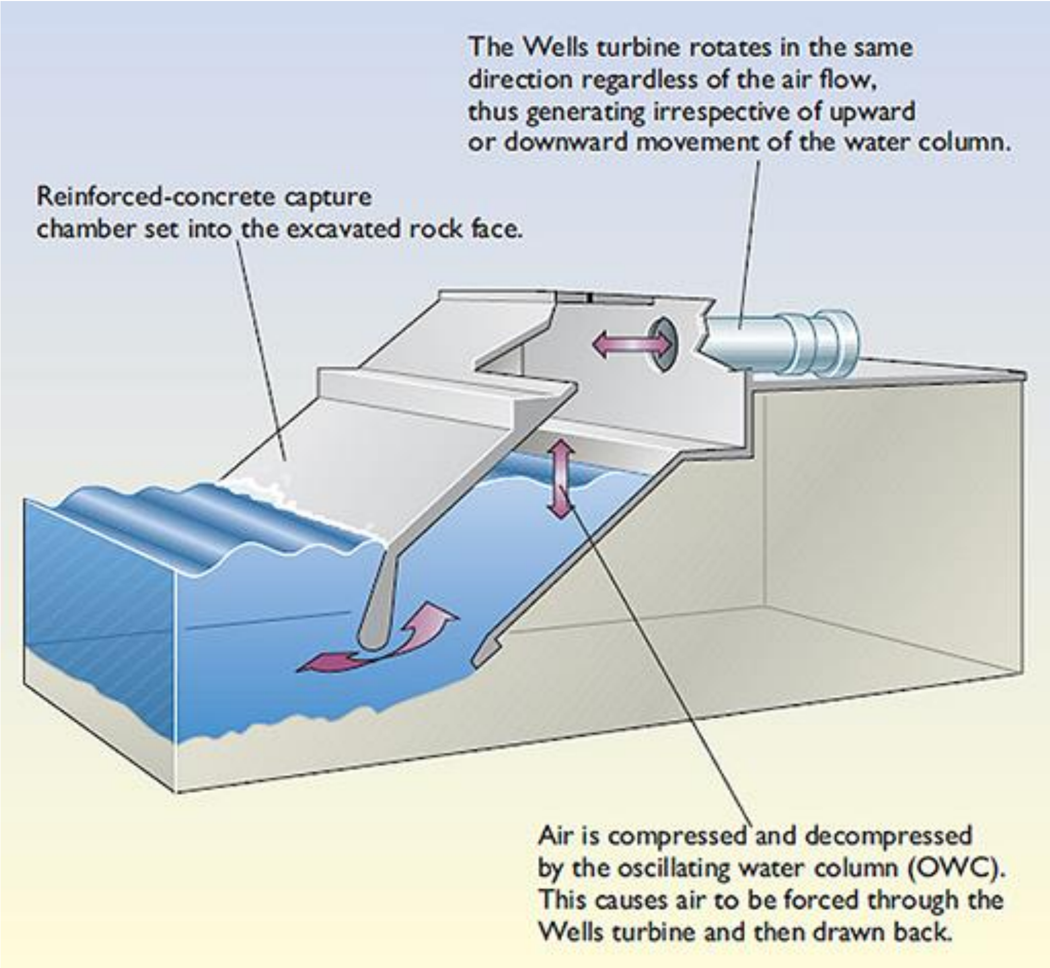

Figure 14 Outline of the LIMPET device on island of Islay

Construction of LIMPET was completed in September 2000. It has a 500 kW maximum power output, has accumulated many thousands of hours of operation in more than ten years, and is used as a test bed for air turbines.

Other, **non-OWC fixed device** prototypes have also been tested in Japan and Scotland. A number have used a mechanical linkage between a moving component, such as a hinged flap, and the fixed part of the device. In Scotland, a device called Oyster, capable of delivering 315kW was installed at the European Marine Energy Centre in 2009. A second generation Oyster, capable of delivering 800 kW, was commissioned in 2012. Unfortunately, after an investment of £3 million, the project was abandoned in 2015.

Figure 15 The 315 kW Oyster I in the factory

You'll look at floating devices in the next section.

3.3 Floating devices

Floating wave energy conversion devices should be able to harvest more energy than fixed, on-shore devices, since the wave power density is greater offshore than in shallow water and there is little restriction to the deployment of large arrays of such devices.

One such device is the Backward Bent Duct Buoy (see Figure 16).

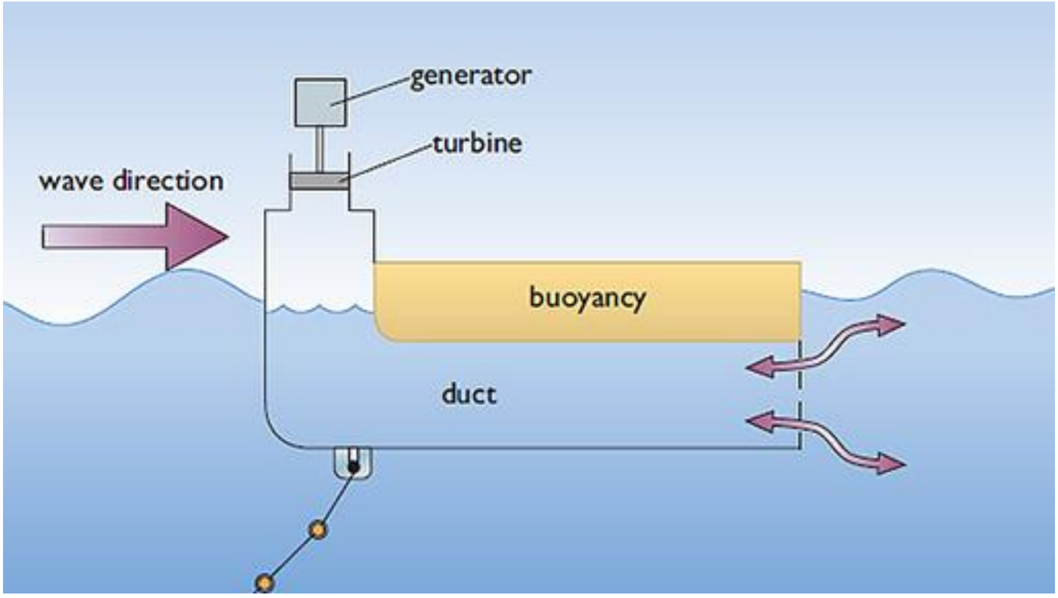

Figure 16 The Backward Bent Duct Buoy (BBDB)

A quarter scale hull achieved over 20 000 hours of operation in live sea trials at the wave energy test site at Spiddal in Ireland. A multi-cell version of the BBDB is under development by Offshore Wave Energy Limited (OWEL), which aims to test a 45 m long 500 kW prototype at the Wave Hub site in Cornwall.

The **Edinburgh 'Duck'** concept (Figure 7.17) was originally envisaged as many cam-shaped bodies linked together on a long flexible floating spine, spanning several kilometres of sea and oriented almost parallel to the principal wave front. The Duck was designed to extract energy by pitching to match the orbital motion of the water particles, as discussed earlier.

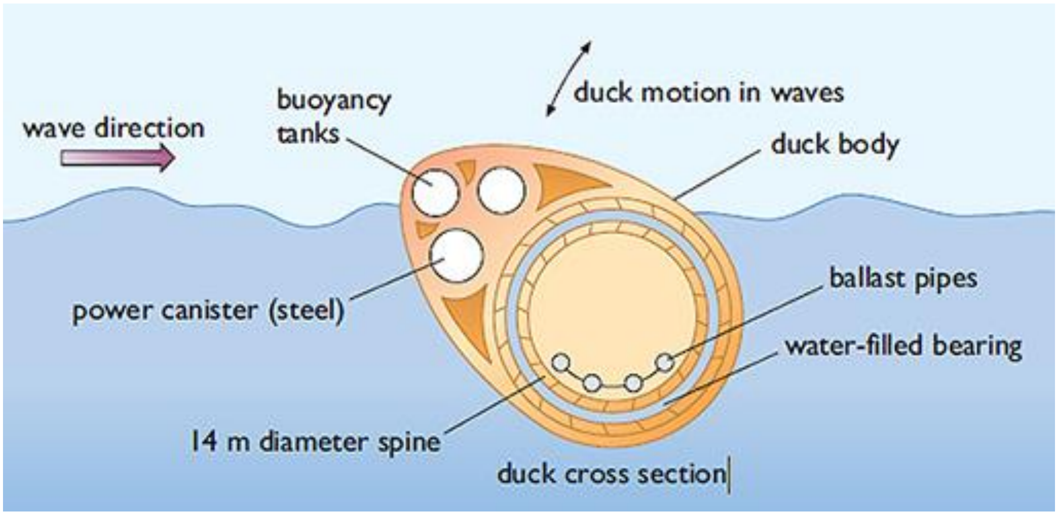

Figure 17 The Edinburgh Duck wave energy converter

To generate power, each cam-shaped body – or ‘duck’ – either moves relative to the spine, producing high pressure in a hydraulic system, or drives a set of gyroscopes mounted in the noses of the ‘ducks’. Matching to the waves can be nearly perfect at one wave frequency, and the efficiency in long waves can be improved by control of the flexure of the spine through its joints. The concept is theoretically one of the most efficient of all wave energy schemes, but it is likely to take a very long time to develop fully the engineering necessary to utilize the concept at full scale.

We will now move on to look at point absorber devices.

3.4 Point absorbers: the AWS-III/Clam

Developed at Coventry University, the AWS-III/Clam (see Figure 7.18). consists of twelve interconnected air chambers, or cells, arranged around the circumference of a toroid, with Wells turbines in each cell. At full scale this would be 60 m or so in diameter, deployed in deep water (40–100 m). Each cell is sealed against the sea by a flexible reinforced rubber diaphragm.

Figure 18 AWS-III in 1:9 scale test on Loch Ness, Scotland

Waves cause the movement of air between cells. Air, pushed from one cell by the incident wave, passes through at least one of the twelve Wells turbines on its way to fill other cells. As the air system is sealed, this flow of air will be reversed as the positions of wave crest and trough on the circle change. The important points about AWS-III are its omni-directional energy absorption and the highly sensitive diaphragms that accept energy from the surge motion of the waves. As pointed out earlier, the surge component of waves can be twice as energetic as the heave.

Now you'll look at attenuator devices.

3.5 Attenuator devices

The Pelamis, or 'sea snake', consists of a number of floating cylindrical tubes, connected to each other by active joints (see Figure 19). The tubes are arranged at a slight angle to the down wave direction and so act as attenuator devices. The wave-induced heaving and swaying of the tubes is resisted by hydraulic rams that pump high pressure oil through hydraulic motors via smoothing accumulators, and the hydraulic motors drive electrical generators to produce electricity.

The ability to withstand high wave power densities has been a key goal of the designers. The Pelamis is capable of inherent load shedding, i.e. the spine is not subjected to the full structural loadings that would otherwise be imposed on it during a storm. It sits down the waves rather than across them and so becomes 'detuned' in long storm waves, where the waves are much longer than the device.

Figure 19 The Pelamis P2

At the time or writing, Pelamis Wave Power, a privately-owned company which is designing, manufacturing and operating Pelamis devices, has raised £45 million from a variety of financial and industrial backers. Development projects are underway off the coast of the Orkney Islands, the Shetland islands, Lewis, the Sutherland Coast and northern Portugal.

The European Marine Energy Centre (EMEC) is hosting a three-year programme testing two second-generation Pelamis wave energy converters sold to two different UK utility companies. The companies have a working agreement to maximise the learning from operating and maintaining the machines in a small-scale wave farm.A further phase of development is foreseen, with a 50MW wave farm consisting of 66 Pelamis wave machines and a UK grid connection on the drawing board (Pelamis (2017).

You'll now look at the economics of wave energy – our topic for the next section.

4 Wave energy economics

The capital cost per kW of establishing a wave-energy power station is likely to be at least twice that of a conventional station running on fossil fuels; and the capacity factor is likely to be lower than that of a conventional station due to the variability of the wave climate. Therefore wave energy costs can only be competitive if the running costs are significantly below those for a conventional station.

Naturally the ‘fuel’ costs are zero, leaving the operation and maintenance costs as the determining factor. Schemes will therefore have to be reliable in their energy conversion and robust enough to survive the wave climate for many years, so they will need to be designed for long lifetimes and with small numbers of moving parts (to minimise failures). The oscillating water columns and TAPCHAN schemes are good examples of what is required.

The UK Committee on Climate Change (CCC, 2011) has calculated the cost of electricity from a possible future (2030) 50 MW array of shoreline wave energy converters, with a capital cost of £2200 per kW and a life expectancy of 40 years. Using a 10% discount rate and expressed in £ (2010):

1. for a low capacity factor (15%) the cost of electricity would be 29.1p kWh^{-1}

2. for a high capacity factor (22%) the cost of electricity would be 19.9p kWh^{-1}.

These cost figures are relatively high and reflect the fact that the fixed devices cannot usually benefit from mass production as they would be purpose-built for a specific location. Also, such devices would generally operate in shallow water where there is a much reduced wave energy climate. The total capital investment required for wave energy schemes is therefore dependent on location and overall average energy conversion efficiencies. Many of the devices detailed above have average efficiencies of around 30%.

At the time of writing, the capital cost is typically around £3000–£4500 per installed kW, although the cost of particular schemes may vary markedly from this.

Large offshore schemes are technically demanding because of the high structural loads imposed by the north Atlantic wave climate. Over time there have been improvements in design, performance and construction techniques, together with rationalisation of some of the problems and a move to smaller schemes. Smaller schemes are technically simpler and less financially risky, hence the capital and insurance costs are reduced, with commensurate reduction in produced energy costs.

Wave energy technology is moving into the commercial world. Several developers are already deploying prototypes and, in some cases, executing schemes generating electricity or desalinating seawater at favourable prices. Coupled with incentives for avoided carbon dioxide emissions, the economic prospects for commercial wave energy exploitation appear good in the longer term.

As wave energy is considered to be environmentally benign (discussed in the next section), if the technology can be successfully further developed it should become an attractive commercial and political proposition, which should result in an extensive installation programme, with wave farms deployed in many locations. Refinement to designs should the cost of such installations from current levels, making them more efficient, and creating lower production costs when they are (where possible) mass-produced.

What are the environmental impacts of wave energy technology? You'll investigate that next.

5 Environmental impact of wave energy technology

Wave energy converters should be among the most environmentally benign of energy technologies for the following reasons:

1. They have little potential for chemical pollution. At most, they may contain some lubricating or hydraulic oil, which will be carefully sealed from the environment.
2. They have little visual impact, except where shore-mounted.
3. Noise generation is likely to be low – generally lower than the noise of crashing waves
4. They should present a small (though not insignificant) hazard to shipping.
5. They should present no difficulties to migrating fish.
6. Floating schemes are incapable of extracting more than a small fraction of the energy of storms so will not significantly influence the coastal environment. A scheme such as a new breakwater **incorporating** a wave energy device will provide coastal protection but may result in changes to the coastline. And concrete

structures will need to be removed at the end of their operating life.

7. It is estimated that near-shore wave energy schemes will release (e.g. from, construction and material transport) some 11 g of CO_2, 0.03 g of SO_2 and 0.05 g of NO_x for each kWh of electricity generated (Thorpe, 1992). This makes them very attractive in comparison to conventional UK coal, gas and nuclear plants. Thus wave energy could make a significant contribution in meeting climate change and acid rain targets.

6 Grid integration of wave energy

The electrical output from a wave energy scheme can be used locally, but it is much more likely that the electricity will be fed into a grid.

When the electrical outputs of several wave energy units are added together, the total output will be generally smoother than for a single unit. If we extend this to an array of several hundred floating devices, then the summed output will be smoother still. In addition, any fluctuations in output will be less important if the electricity is to be delivered to large national systems like those of the UK, where in most locations the grid is ‘strong’ enough to absorb contributions from a fluctuating source.

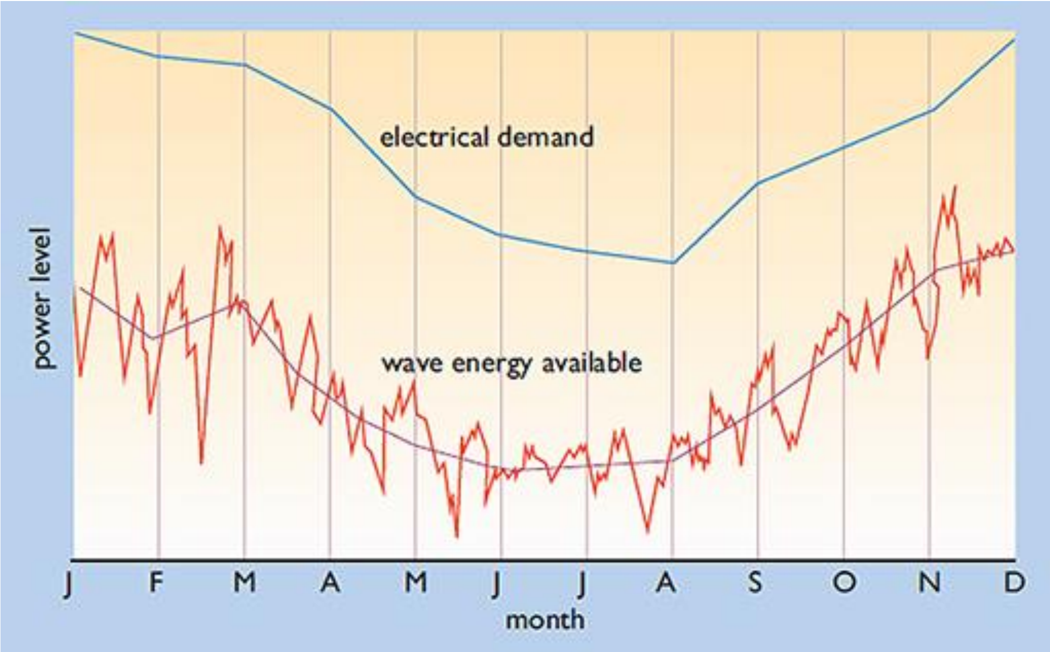

Figure 20 Seasonal availability of wave energy and electrical demand for the UK (Rugbjerg et al 2000 and Petroncini and Yemm, 2000)

Although there are short-term fluctuations on second or minute scales, the wave resource also varies on a day-to-day and season-by season basis. For countries in the north-east Atlantic such as the UK, Ireland, Spain and Norway, the seasonal variation shown in Figure 20 demonstrates that wave power output reaches a maximum in the bad weather of winter when the electrical demand is greatest.

That's about it for this week. You'll finish with a quick summary of what you've learned.

7 Conclusions

The world wave energy resource is extremely large. If only a small proportion could be harnessed it would make a major contribution to meeting the world's energy requirements.

The waves in deep water are very energy rich, but the conditions are difficult, so wave energy converters here must be highly robust. As waves move towards the shore they lose some of their energy, and while the operating conditions are less strenuous, different technological challenges are raised in designing economic devices for capturing the energy.

In the UK the wave climate is conducive to wave power developments, but the political climate has not always been so favourable. In the 1970s and 1980s the UK government's brief to wave energy teams was to design huge 2 GW schemes. This was like expecting someone to design a Boeing 747 in the early days of aviation without going through the evolution of the biplane, single seat monoplane and jet engine.

Attitudes are changing very quickly, however, prompted by the need to address global climate change, by the issue of long-term resource security of fossil fuel supplies and by the increasingly competitive economics of wave energy.

UK teams conducted much of the early work in the development of wave energy systems. New schemes and concepts are emerging from countries such as Norway, Australia, Sweden, Denmark and the USA, as well as the UK.

The generation of electricity is not the only option for the delivered energy. Desalination, coastal protection, water pumping, mariculture, mineral recovery from seawater, and hydrogen generation are among the benefits being investigated.

The cost of energy from the current generation of wave energy converters is high, but wave energy developers are confident that time, experience and technological improvements will result in an environmentally attractive and sustainable wave energy industry.

The development of wave energy technologies has been a long process, but the economics of many current designs are potentially attractive. Proving the long-term survival and cost effectiveness of devices as technologies mature should make the prospect of wave power stations on a large scale a realistic possibility.

8 Week 7 quiz

Check what you’ve learned this week by taking the end of week quiz.

Week 7 quiz.

Open the quiz in a new window or tab then come back here when you’ve finished.

9 Summary

This week you have:

- described the physical principles of wave energy
- looked at the various wave energy resources available
- introduced different wave energy technologies and how they are implemented
- studied wave energy economics
- discussed the environmental impact of wave energy
- examined the potential for grid integration of wave energy.

Week 8: Towards a renewable future

Introduction

In the preceding seven weeks of the course, you've looked in turn at the principal renewable energy sources and described the individual contributions they might make to the energy needs of the UK, Europe and the world, under various conditions.

This final week draws the threads together. It examines a number of future energy scenarios showing how combinations of renewable sources could provide all, or most, of the energy needs of the United Kingdom, of other European countries and the World as a whole, during the first few decades of the 21st century, starting with the UK.

Video content is not available in this format.

View transcript - Uncaptioned interactive content

By the end of this week, you will be able to:

- assess at a basic level the contribution that renewable energy technologies can make to the overall sustainability of energy systems at different scales
- discuss the difficulties created by the time-varying nature of some renewable energy supplies
- describe the importance of energy storage and demand management
- compare and contrast at a basic level British, other European and global approaches to renewable energy

development and its importance in global sustainable development.

1 UK renewable energy futures

Firstly we'll discuss renewable energy futures, starting with the prospects for deployment of renewables in the UK.

How much of the UK's energy needs could renewables supply in the coming decades? Figure 13 in Week 1 illustrated how the UK's independent Committee on Climate Change (CC) envisages the potential contribution of renewables growing from 2020 to 2030.

Its analysis suggests that by 2030 renewables could be providing between:

1. 28 and 46% of UK *delivered* energy
2. 30 and 65% of *electricity* supplies
3. 35 and 50% of *heat*
4. 11 and 25% of *transport energy* (CCC, 2011).

The prospects for UK renewables deployment on a shorter timescale, to 2020, were published in 2011 by the Department of Energy and Climate Change (DECC) in its *Renewable Energy Roadmap* (DECC, 2011e). The UK is committed under the EU Renewable Energy directive (European Commission, 2009) to produce some 15% of its gross final energy from renewables by 2020, and the *Roadmap* sets out in some detail how the UK government proposes to achieve this.

Table 1 DECC Renewable Energy Roadmap's central view of the deployment potential of renewable energy technologies by 2020

Technology	**Central range for deployment in 2020/TWh y^{-1}**
Onshore wind	24-32
Offshore wind	33-58
Biomass electricity	32-50
Marine	1
Biomass heat (non-domestic)	36-50
Air-source and ground-source heat pumps (non-domestic)	16-22
Renewable transport	Up to 48
Others (including hydro, geothermal, solar and domestic heat)	14
Estimated 15% target	234

Source: DECC, 2011e

Table 1, summarises the ranges of annual energy contributions of the eight technologies DECC considers likely to make the most significant contributions to achieving the 15% goal in its 'central view' of their deployment potential.

Watch this video, which looks at EU and UK Renewable energy targets for 2020 and 2030, at fossil fuel supplies, and the factors involved in a transition to low-density renewable sources. The potential resource available from solar power in the UK is discussed, along with the case for major investments in renewables.

Video content is not available in this format.

1.1 UK electricity scenarios

In 2011 the World Wide Fund for Nature (WWF), published *Positive Energy* (WWF, 2011a), describing a range of UK *electricity* scenarios for 2030 based on detailed analysis by the specialist consultancy Germanischer Lloyd Garrad Hassan (GLGH). The report demonstrated that renewables could contribute some 60–80% of the UK's electricity by 2030. GLGH created six scenarios for the UK electricity sector in 2030, with the first three 'Central' scenarios assuming only modest attempts to reduce UK electricity demand, whereas the second three involve more ambitious energy conservation measures.

The report comments:

> In all cases, the scenarios make full provision for ambitious increases in electric vehicles (EVs) and electric heating. Energy efficiency and behavioral change lead to the reductions in demand in the ambitious demand scenarios.
>
> The volume of renewable capacity installed by 2020 in all scenarios is similar to that set out in the government's Renewable Energy Roadmap in July 2011. However, critically, the scenarios envisage installation continuing at a similar rate during the 2020s. This will avoid the risk of 'boom and bust' in the UK renewables sector [...] and mean renewables provide at least 60% of the UK's electricity by 2030.

> The amount of renewable capacity the UK can and should build is determined by economic constraints – not available resources or how fast infrastructure can be built. GLGH assumes that it is economic to supply around 60% of demand from renewables. Going beyond 60% depends on whether there's a market in other countries for the excess electricity the UK would generate at times of high renewable energy production.

An even more ambitious scenario, envisaging the UK making a transition to a 'Zero Carbon Britain' (ZCB) powered entirely by renewables by 2030, was published by the environmental charity the Centre for Alternative Technology (CAT) in 2013 and 2018. This transition would be achieved through 'Powering Down' – reducing energy demand without reducing quality of life; and 'Powering Up' – deploying renewable energy on a large scale and very fast. (Zero Carbon Britain, 2018).

Figure 1 summarises how the ZCB scenario envisages energy flowing in 2030 from a variety of renewable energy sources, via various energy conversion processes, to supplying energy for heating, cooking, lighting & appliances, industry and transport.

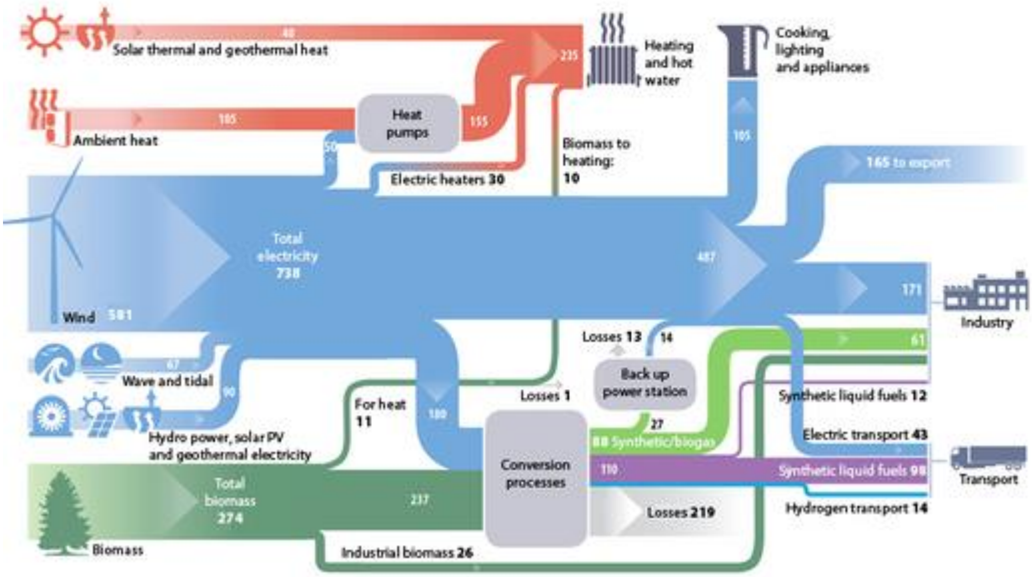

Figure 1 ZCB scenario showing energy flows from renewable energy sources to supply energy demands in 2030

The ZCB scenario is based on a detailed hourly model of UK energy supply and demand. In it, the majority of renewable electricity comes from a very large capacity of on-shore and offshore wind power, and there will be many occasions when this supply exceeds electricity demand. The ZCB researchers propose a ‘power to gas’ process in which surplus renewable electricity is converted into hydrogen by electrolysis. This is then combined with carbon dioxide from biomass to produce methane, which can be distributed and stored in the existing UK gas grid and burned in the

UK's conventional backup power stations (which normally burn fossil methane) when there is a deficit of renewable electricity.

In addition, some of the hydrogen and carbon dioxide are instead converted to a synthetic *liquid* fuel, methanol, which can be used as a substitute for gasoline in many vehicles.

Watch the following video, which gives more information on the thinking behind the ZCB scenario.

Video content is not available in this format.

These proposals are extremely radical and ambitious, but the UK's offshore renewable energy resource, from wind, wave and tidal sources, is huge. In 2010 the Offshore Valuation study (Offshore Valuation Group, 2010), backed by the Crown Estate, UK and Scottish government departments and some major companies, concluded that it is equivalent in size to the UK's offshore oil and gas resources – but unlike these fossil resources, the renewable resources do not suffer from depletion and should be available for an indefinite period.

The study also showed that the majority of the wind resource is located far offshore, and could be harnessed using floating turbines moored in very deep waters. As shown in Week 6, a number of companies including the Norwegian company Statoil are developing floating wind turbines.

But what's involved in balancing supply and demand? You'll look at that in the next section.

2 Balancing renewable supply and demand

There are plenty of problems, as well as solutions, involved in a future of balancing energy supply and demand with increasing amounts of renewables.

Watch the following video, in which the need for flexibility in demand, storage and backup supplies from conventional power stations are discussed. It also describes the very large magnitude of renewable resources and the desirability of grid links to other European countries and perhaps North Africa, in the DESERTEC proposals.

The existing grid links in Northern Europe are shown, together with the plans to expand these greatly by 2030 – including a proposed 'offshore supergrid' with nodes in the North Sea, the Baltic and Bay of Biscay.

The UK Government's offshore grid initiative is also discussed. Creating an offshore grid would be a challenge, but one that is achievable, depending on the time scale.

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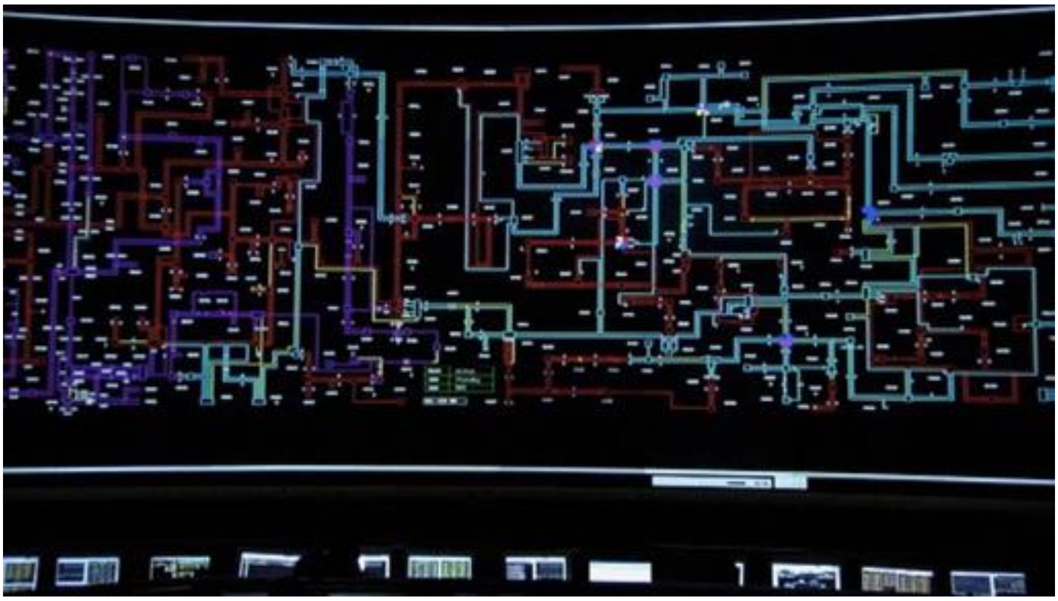

What are the various energy supply pathways that UK could follow to reduce carbon emissions by 80% by 2050? You'll move on to that next.

3 Pathways to 2050

Looking much further ahead, to 2050, DECC produced in 2010 a Pathways Analysis (DECC, 2010c) illustrating a number of different primary energy supply and demand 'pathways' that the UK could choose to pursue between 2010 and 2050 in order to achieve the government's goal of reducing UK greenhouse gas emissions by 80%.

There are six of these 'illustrative' pathways, labelled A to Z, plus a Reference pathway, labelled R.

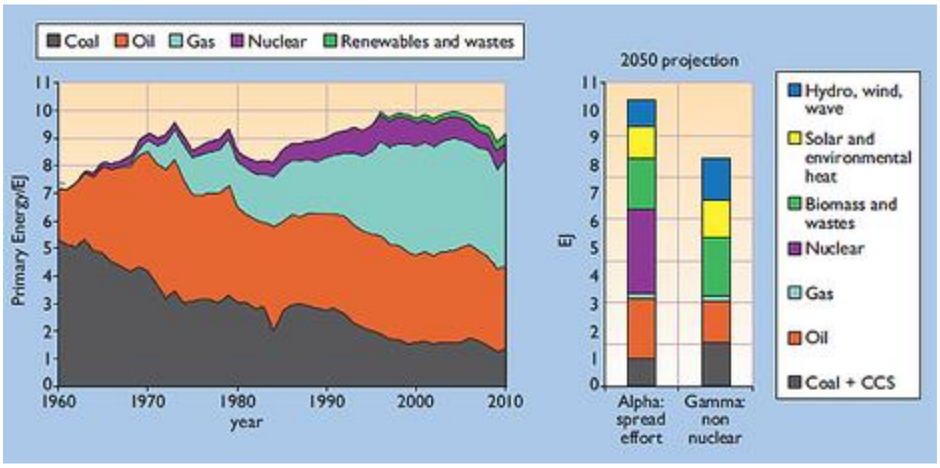

Figure 2 The UK primary energy supply mix 1960 to 2010, alongside two DECC projections (Alpha and Gamma) of possible energy supply mixes in 2050

Figure 2 shows the historic mix of UK primary energy use over the five decades from 1960 to 2010, and two different projected *future* mixes of energy supply and demand by 2050 - those described in DECC pathways Alpha and Gamma. Pathway **Alpha** ('balanced effort') envisages renewables contributing around one third of UK primary energy by 2050. In the renewables-intensive pathway **Gamma** the total renewable energy contribution (including renewables from waste) rises to approximately 60% by 2050.

Having looked at renewable energy futures for the UK, we now turn to two EU nations that have taken the lead in renewable energy deployment: Denmark and Germany.

4 Renewable energy futures for Denmark

Denmark is a good example of a country that started promoting renewable energy back in the 1980s. During the 1960s, Denmark's energy use expanded rapidly in an era of cheap oil (see Figure 3). By 1972 it had become almost totally reliant on imported oil and was badly hit by the ten-fold oil price rises in 1973 and 1979.

The situation encouraged energy researchers from Danish universities to produce in 1983 an 'alternative energy scenario' (AE83). This outlined a programme aimed at cutting oil and coal imports to zero by 2030, to be achieved by an increase in the proportion of renewables (wind, solar and biofuels) and sharply reducting total energy demand. The plan did not include nuclear power, which was unpopular in Denmark at the time.

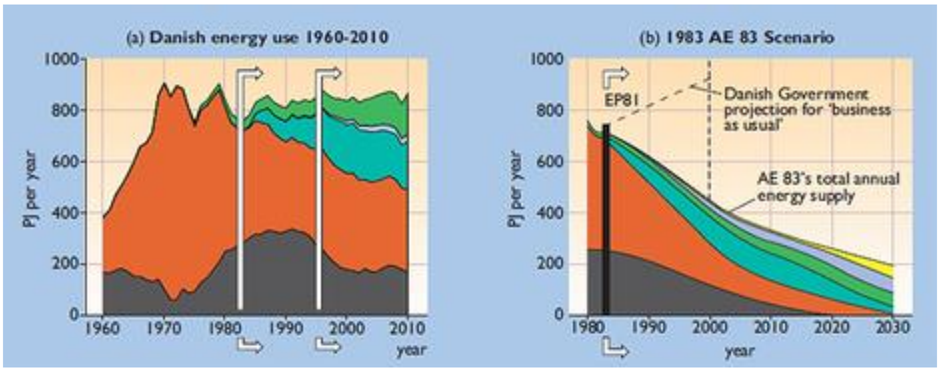

Figure 3: (3a) Primary energy consumption in Denmark, 1960–2010; (3b) Denmark's 1983 Alternative Energy scenario (AE83), and the Danish Government's 1981 'business as usual' projection (EP81). (sources: Norgaard and Meyer; 1989, Eurostat 1993, MEE, 1996, DEA, 2010, DEA, 2011a, Danish Government, 2011)

The AE83 projection, shown on the right of Figure 3b above, is in strong contrast with the official 1981 Danish government 'Business as usual' projection EP81 (shown in the dotted line in Figure 4b, which suggested a continued growth in energy demand.

In practice, the Danish government solved its immediate energy security problems in several ways:

1. It pursued a policy of energy conservation, imposing high energy taxes and new regulations to encourage the insulation of buildings and promote the use of Combined Heat and Power (CHP). The results were impressive. Between 1972 and 1985, the total heated building floor area increased by 30%, but the amount of energy used to heat it decreased by 30% (Dal and Jensen, 2000).
2. It switched power stations from oil-firing to coal-firing. National reliance on oil dropped from 93% in 1972 to only 43% in 1992. It developed its own oil and gas

resources in the North Sea. The results started to appear in the early 1980s and by 1997 Denmark had become a net energy exporter.

3. It made considerable efforts to start building up its renewable resources, particularly biomass and wind power. Denmark is now a major exporter of wind turbines, technology and know-how.

Actual Danish energy consumption up to 2015 has not followed either the AE83 projection or the government EP81 projection -- which confirms that scenarios are only pictures of what *could* happen rather than what *will* happen.

By the mid-1990s, the focus of energy policy had shifted from self sufficiency to climate change. Denmark is a low-lying country and any future sea level rises would have serious consequences. The switch from oil to coal and natural gas meant that national CO_2 emissions had remained at their 1970s level.

In 1996, the centre-left government adopted a policy of cutting emissions by 20% from their 1988 levels by 2005 and by 50% by 2030, as set out in their *Energy 21* plan (MEE, 1996). In this scenario, total primary energy use would fall only slightly and the use of coal would be replaced by increased use of natural gas and renewable energy, as shown at the bottom left of Figure 8.3. It was suggested that by 2030 half of Denmark's electricity could come from renewable sources.

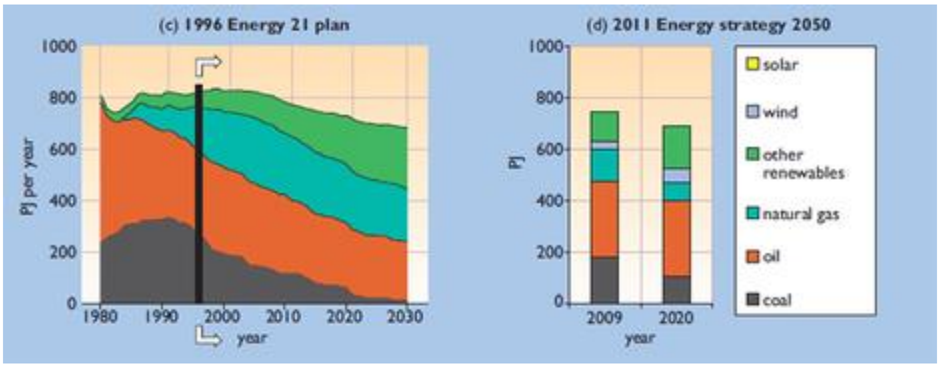

Figure 3 (3c) 1996 Energy 21 scenario; (3d) Projected energy use in 2020 in the Energy Strategy 2050 scenario. Notes: in Figure (3c) 'other renewables' includes wind. Figure (3d) excludes energy use in the oil and gas industries. (sources: Norgaard and Meyer; 1989, Eurostat 1993, MEE, 1996, DEA, 2010, DEA, 2011a, Danish Government, 2011)

To implement this policy there were continued high energy taxes and support for renewable energy through a Feed in Tariff (FIT) scheme.

However, in 2001, a new right-wing government was elected which was committed to tax reform. It took the attitude that the country's environmental initiative was 'ahead of schedule', resulting in the Energy 21 plan being dropped, orders for three offshore wind farms cancelled and many tax incentives for energy efficiency scrapped.

In May 2011, the Danish government produced a new ‘Energy Strategy 2050’ stating a long-term goal of a complete transition away from the use of fossil fuels by that date (Danish Government, 2011), as shown on the right of Figure 4. This is essentially the same goal as the 1983 AE83 scenario but with the target date delayed by 20 years. It involves:

1. a continuing reduction in overall energy demand
2. a reduction in the use of coal in electricity generation, to be replaced by renewables
3. a continued expansion of the use of renewable energy, particularly solid biomass and wind power.

In 2010 renewables supplied 33% of the country’s electricity, nearly 21% from wind power.

There is an intermediate target that renewables will contribute over 30% of final (delivered) energy use by 2020 (around 200 PJ per year), with a 10% contribution to the transport sector. In the electricity sector it is suggested that 60% should come from renewables, 40% being from wind power.

A comparison of projected 2020 energy use with that of 2009 is shown on the right of Figure 8.4. This scenario is more ambitious in terms of renewable energy deployment and less reliant on natural gas than the now ‘abandoned’ Energy 21 Plan.

Looking much further ahead, Denmark’s Climate Change Committee (2011) sees the country’s energy future as 100% renewable powered by 2050, from a mixture of onshore and offshore wind, solar PV and thermal panels, biomass fuels (some imported), electric heat pumps, geothermal energy, CHP plants and large heat stores. International electricity links also enable Denmark to export and import electricity when there are surpluses or deficits.

This vision has been backed up by an earlier study from the Danish Society of Engineers (2010). All fossil fuel use has been phased out, and the country runs on 100% renewable power, from a mixture of onshore and offshore wind, solar PV and thermal panels, biomass fuels (some imported), electric heat pumps, geothermal energy, CHP plants and large heat stores. International electricity links enable Denmark to export and import electricity when there are surpluses or deficits.

What are Germany’s renewable energy plans? You’ll discover in the next section.

5 Renewable energy futures for Germany

In Germany, following the 2011 Fukushima nuclear accident in Japan, the government decided to adopt a revised ‘Energy Concept’ for the country over the coming four decades. According to the Federal Environment Ministry (BMU, 2011):

> The objectives are a rapid transition to the age of renewable energies and the phasing out of nuclear energy by the end of 2022. The intention is for renewable energies’ share of power generation to rise from the current 17 percent of power consumption to at least 35 percent in 2020. The German government will strive to ensure this share is 50 percent by 2030, a figure that should rise to 60 percent by 2040, then 80 percent by 2050. [...] However, promoting energy efficiency will be important too if the demand for energy is to fall.
>
> To begin with, conventional (i.e. gas and coal-fired) power plants will still play a central role in ensuring security of supply; they are able to provide power at any time. The expansion of grids, the application of load management, the improvement of power feed-in forecasts for wind and

> solar energy, and the development of storage technologies will allow a power system overwhelmingly based on renewable energies to secure our supply [...] The measures planned will allow CO_2 emissions to be cut at least 80 percent by 2050.

Germany's independent advisory council on the environment (SRU) also published in 2011 a study suggesting that an even more ambitious target of a 100% renewable *electricity* system for Germany is feasible and economic. As its report (SRU, 2011) states:

> Our scenario computations show that Germany could readily achieve a wholly renewable electricity supply that is both reliable and affordable. Providing that the relevant storage facilities and grids are implemented, the renewable energy potential in Germany and Europe would allow for the satisfaction of maximum posited electricity demand at all times throughout the year, using wind turbines, solar collectors, and other currently available technologies and despite fluctuations in the availability of renewable electricity.

As the lowest cost energy resource in the run-up to 2050, wind energy, particularly from offshore wind turbines, plays a pivotal role in all of the scenarios discussed in the present report. On the other hand, the level of solar energy use in the various scenarios varies according to electricity demand and the amount of electricity that is imported. Biomass use in the scenarios involving transnational energy supply networks accounts for no more than 7% of electricity demand, largely owing to land use conflicts and the relatively high cost of this energy resource.

In the view of the SRU, instituting a wholly renewable electricity supply in Germany by 2050 would entail economic advantages in addition to promoting climate protection, whereby the aggregate costs of such a system would be largely determined by the extent to which a network comprising other European countries is established.

Inflation adjusted, a wholly renewable electricity supply using German resources only would be relatively cost intensive, ranging from 9 to 12 euro-cents per kWh, depending on demand. On the other hand, an inter-regional smaller-scale German Danish-Norwegian, or larger-scale Europe-North Africa network, would provide electricity at a cost of only 6 to 7 euro-cents per kWh, including the cost of international grid and storage capacity expansion. Our rough estimates indicate that expanding the German grid would entail additional costs amounting to approximately 1 to 2 euro-cents per kWh. Over the long term, renewable electricity will prove to be less cost intensive than conventional low carbon technologies such as CCS power plants and new nuclear power plants, whose costs will rise owing respectively to limited uranium resources and storage facilities.

(SRU, 2011)

The eight SRU scenarios mentioned in the report are summarised in Table 2 below.

Table 2 Eight scenarios for a wholly renewable electricity supply for Germany in 2050.

Assumptions	**German electricity demand in 2050: 500TWh**	**German electricity demand in 2050: 700TWh**
Self sufficiency	Scenario 1.a: DE 100% SV-500	Scenario 1.b: DE 100% SV-700
Net self-sufficiency, interchange	Scenario 2.1.a: DE-	Scenario 2.1.b: DE-

with Denmark and Norway	DK-NO 100% SV-500	DK-NO 100% SV-700
Maximum 15% net import from Denmark and Norway	Scenario 2.2.a: DE-DK-NO 85% SV-500	Scenario 2.2.b: DE-DK-NO 85% SV-700
Maximum 15% net import from the Europe-North Africa region (EUNA)	Scenario 3.a: DE-DK-NO 85% SV-500	Scenario 3.b: DE-DK-NO 85% SV-700

In the first four scenarios, German energy demand is some 500 TWh per year (SV500). In the second four scenarios, electricity demand rises to 700 TWh per year (SV700). The four variants involve different assumptions about the extent of self-sufficiency in Germany and the strength of interconnections to neighbouring countries.

The next section discusses whether some of the measures that Germany is implementing could be used as a model for other countries, including the UK.

5.1 Germany as a role model?

Is the UK in danger of being left behind? Should it follow the lead of countries like Germany and give greater commitment to deploying renewable energy?

Watch the following video, which describes the feed-in tariffs and other measures that have led Germany to accelerate the deployment of renewables, accompanied by a phase-out of nuclear power.

It also points out that, out that as part of Germany’s energy transition, the railway operator Deutsche Bahn, is proposing to run the country’s rail system entirely on renewables. The concept of a transition to renewables providing much-needed meaningful work among young people concerned about future climate change is also discussed.

The video interviewees agree that the UK should be doing much more to develop its enormous renewable resources. It should look at what other countries have done, and not just at EU countries like Germany but other major nations. China is heavily committed to developing renewables and wants to take the lead in developing and marketing the technologies world-wide. If China can see the opportunities, then maybe UK should do so too?

Video content is not available in this format.

6 Renewable energy scenarios for Europe

Can renewable energies provide all, or most, of Europe's electricity? That this is possible is the conclusion of a 2010 study by the European Climate Foundation (ECF), based on analysis by the consultancy McKinsey, Imperial College London and Oxford Economics, among others (ECF, 2010). It illustrates various pathways to a 'Prosperous, Low Carbon Europe', in which the renewable electricity contributions range from 40% to 100%.

Figure 5 describes one such pathway, ECF's 80% renewable electricity scenario, with hydro, solar, wind, biomass and geothermal energy growing to provide 80% of Europe's electricity by 2050.

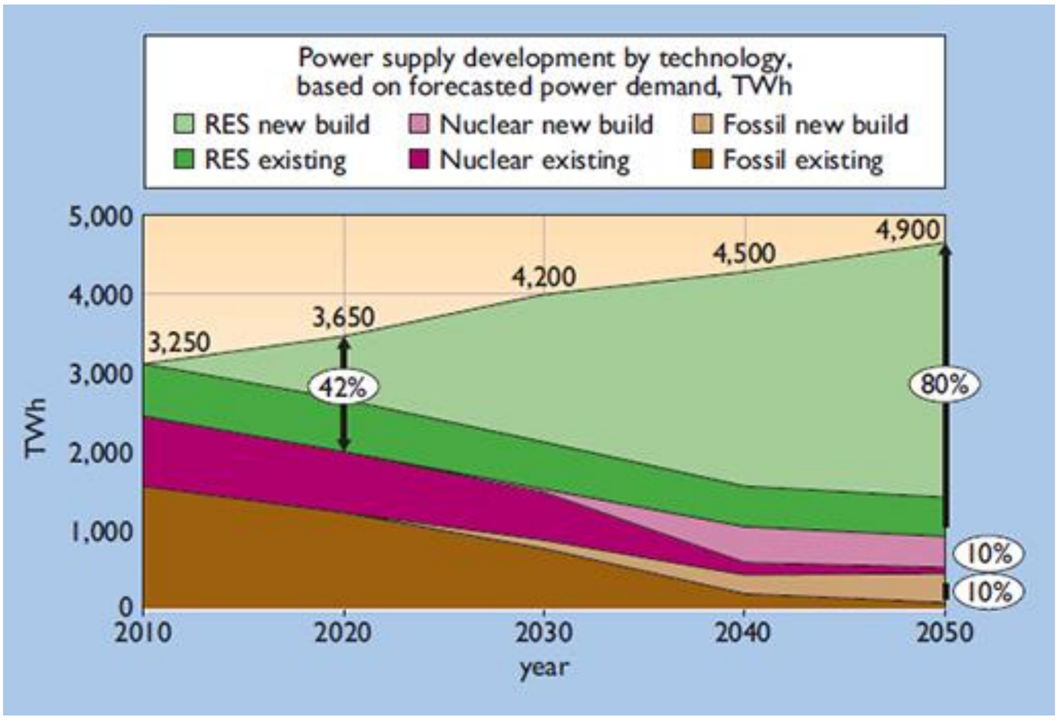

Figure 4 European Climate Foundation Roadmap 2050 projection, showing how renewables could supply 80% of Europe's electricity by 2050. 'Existing' plant includes new builds up to 2010.

Unlike some of the scenarios we've been discussing, the ECF scenario envisages a continuing role in Europe for nuclear power, alongside a major contribution from renewables, with new reactors replacing the existing fleet.

Watch the following video where the interviewee discusses the track record of the United Kingdom on nuclear power, and whether it would be preferable for the UK to invest in energy efficiency and renewables instead of building new nuclear plants.

Video content is not available in this format.

If you would like to explore the pros and cons of nuclear power in more detail, have a look at the arguments for and against in the OpenLearn free course *Nuclear power: friend or foe?*.

So what are the implications for renewable energy of the proposed European supergrids and DESERTEC? You‘ll look at this in the next section.

7 European supergrids and DESERTEC

In the video activity in Section 2, on balancing renewable energy demand and supply, Dr Alistair Martin described how the UK, Denmark, Germany and several other European countries envisage an important future role for additional electricity connections between countries.

Activity 1 Variable weather conditions

Given the varying weather conditions across the continent, how would additional electricity connections help countries cope with variable renewable electricity supplies?

View answer - Activity 1 Variable weather conditions

In the same video, Niall Stuart of Scottish Renewables described the even more ambitious DESERTEC-EUMENA proposal for electricity grid enlargement made by the DESERTEC Industrial Initiative, a consortium of large and mainly German companies.

Activity 2 Electricity grid enlargement

As the video shows, it envisages strong high voltage direct current (HVDC) electricity grid links between Europe and the Middle East and North African (MENA) countries.

What would these grid links enable?

View answer - Activity 2 Electricity grid enlargement

Now, returning to the question posed at the start of the course – could renewable energy sources power the world?

8 Can renewables power the world?

Can renewable energy provide enough energy to power the world?

One study demonstrating that this is possible was published in popular form in *Scientific American* in 2009 by two scientists from Stanford University in California (Jacobson and Delucchi, 2009).

In the following year they backed up their arguments in two detailed papers in the refereed journal *Energy Policy* (Jacobson and Delucchi, 2010a and 2010b), Their research suggests that the world's total power demand for electricity and other purposes, which they estimate will reach between 11.5 and 16.9 TW by 2030, could be supplied by large numbers of wind turbines, solar power plants, water wave, hydro and geothermal installations, as detailed in Table 3 below.

Table 3 Number of wind, wave and solar (WWS) power plants or devices needed to supply world final energy power demand in 2030 (11.5 TW)

Energy technology	Rated power of one plant or device/MW	Per cent of 2030 power demand met by plant/device %	Number of plants or devices needed for world energy	Footprint area (% of global land area)	Spacing area (% of

			demand		**global land area)**
Wind Turbine	5	50	3.8 million	0.000033	1.17
Wave device	0.75	1	720 000	0.00026	0.013
Geothermal plant	100	4	5350	0.0013	0
Hydroelectric plant	1300	4	900[a]	0.407[a]	0
Tidal turbine	1	1	490 000	0.000098	0.0013
Roof PV system	0.003	6	1.7 billion	0.042[b]	0
Solar PV plant	300	14	40 000	0.097	0
CSP plant	300	20	49 000	0.192	0
Total		100		0.74	1.18
Total new land				0.41[c]	0.59[c]

[a] About 70% of the hydroelectric plants are already in place

[b] The footprint area for rooftop PV does not represent an increase in land since the rooftops already exist and are not used for other purposes

[c] Assumes 50% of the wind is over water, wave and tidal are in water, 70% of hydroelectric is already in place, and rooftop solar does not require new land.

Source: Derived from Jacobson and Delucchi, 2010a.

The figures shown above assume a given partitioning of the demand among plants or devices. They also show the footprint and spacing areas required to meet the world demand, as percentages of the total global land area (1.446 x 10^8 $km^{2)}$.

Jacobson and Delucchi acknowledge that the numbers in Table 3 above may seem daunting, but as they point out, installation would be spread over two decades, and since the world currently produces some 73 million cars and light trucks every year, for example, this could suggest that the world's industrial production capacity is probably sufficient – if we chose to harness it in this way.

You'll now look at another study, showing how the world could supply nearly all of its *energy* from renewables by 2050, if combined with major energy saving measures.

8.1 95% of global energy from renewables by 2050

A study was published by the World-Wide Fund for Nature (WWF) in its 2011 *Energy Report* (WWF, 2011b), based on analysis by the Dutch energy consultancy Ecofys. It shows how, in the decades to 2050, the world could implement major energy saving measures, reducing the massive waste that is present in our current energy systems. Simultaneously it could phase in a mixture of wind, solar, geothermal, hydro and biomass energy sources to provide 95% of the world's final energy demand, as shown in Figure 6.

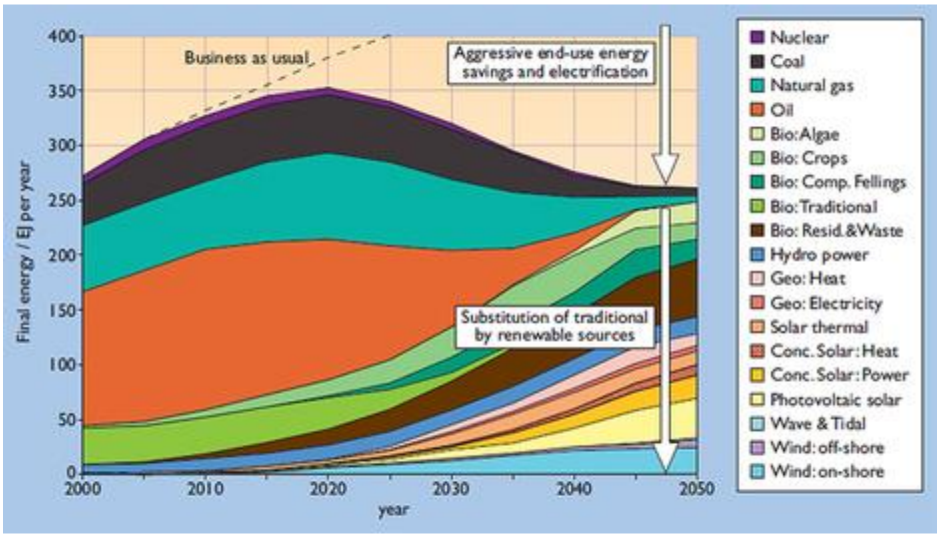

Figure 5 WWF Energy Report scenario – energy efficiency measures reducing final energy demand combined with phasing-in renewable energy sources by 2050

A series of renewable-intensive future world energy scenarios has also been produced over the past decade by the environmental group Greenpeace. Early versions were initially dismissed by sceptics as over-optimistic in their projections for the growth of solar or wind power. But these early projections have in fact proved pessimistic, given the high growth rates that have been achieved in recent years.

Figure 6 shows the growth of world primary energy use between 1960 and 2010. It also shows projections for 2050 from Greenpeace's Advanced Energy (r) Evolution scenario (Greenpeace, 2010) and from the IEA 'Blue Map' scenario (see below). As in the WWF scenario, energy demand in the Greenpeace scenario is reduced by implementing energy efficiency improvements. By 2050 more than 80% of the world's (reduced) energy consumption would be supplied by a mixture of hydro, wind, biomass, geothermal, solar and ocean energy sources.

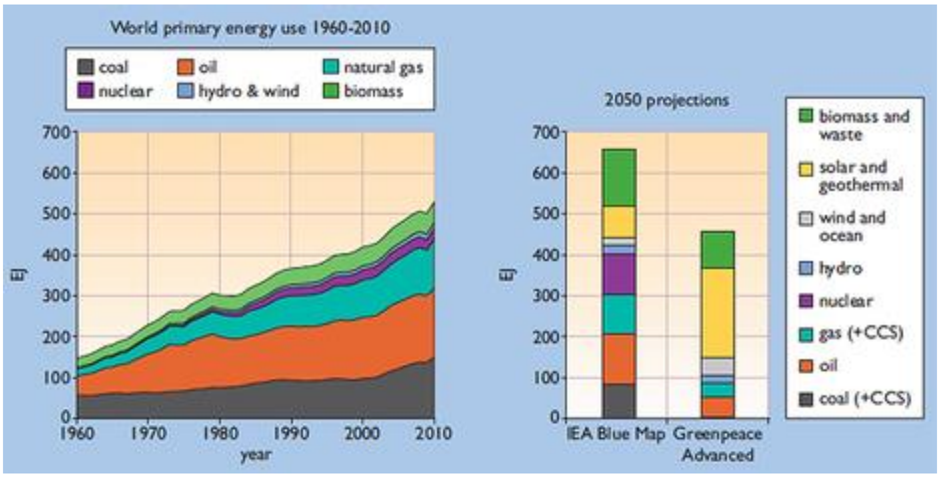

Figure 6 World energy use 1960–2010 and in IEA Blue Map and Greenpeace Advanced scenarios for 2050

Watch the following video, in which the optimistic projections in Greenpeace's 'Advanced Energy Revolution' scenario, are compared with the much more pessimistic projections of the oil company BP. Further studies are discussed, showing that the world could be entirely powered by renewables without fossil or nuclear fuels by around 2040. However, a dissenting note is sounded by one of the interviewees, who believes the idea of achieving 100% renewables by 2050 is 'ridiculous'.

The video then goes on to suggest that an all-renewable world is not only possible but desirable, given the need for a transition to zero carbon energy sources to mitigate the serious impending consequences of global climate change.

Video content is not available in this format.

8.2 Comparing International Energy Agency and Greenpeace scenarios

Energy scenarios are published regularly by the International Energy Agency in its *Energy Technology Perspectives Reports*, which outline the Agency's view of the future prospects for various energy technologies. In the 2010 report (IEA, 2010) it produced a 'Blue Map' scenario to illustrate how world CO_2 emissions could be halved by 2050, compared to current levels, in order to enable atmospheric concentrations to be kept below 450 ppm and global temperature rises to below 2 ˚C – a threshold that many experts believe should be an upper limit. In the IEA's Blue Map scenario, world primary energy use continues to grow, and renewable energy by 2050 contributes almost 40% of primary energy supply (see Figure 7).

The IEA has also published several variants on its 2010 Blue Map scenario, including a ‘Blue High Renewables scenario’, in which the renewable share of world electricity rises from 48% to 75% by 2050. In Figure 7 this is shown along with the electricity projection for 2050 from Greenpeace’s ‘Advanced Energy (r) Evolution scenario’. Both the IEA and Greenpeace expect a doubling of world electricity demand by 2050. The IEA envisages ‘spread effort’, including some fossil and nuclear fuels but with plenty of scope for the expansion of renewables. Greenpeace sees even more room for expansion of biomass, wind, solar and geothermal energy (but not hydro), though it rules out nuclear power.

The IEA’s 2014 *Energy Technology Perspectives* report was more optimistic about the future prospects for renewable energy, and in particular solar power. In included a ‘2DS’ Energy scenario for the world energy system to 2050, which’…describes an energy system consistent with an emissions trajectory that recent climate science research indicates would give at least a 50% chance of limiting average global temperature increase to 2oC’ (IEA, 2014). And as mentioned in Week 3 Photovoltaics, it also produced a ‘2DS High Renewables’ (2DS hiRen) scenario, a variant which ‘illustrates an expanded role of renewables in the power sector, based on a decreased or delayed deployment of nuclear technologies and CCS'.

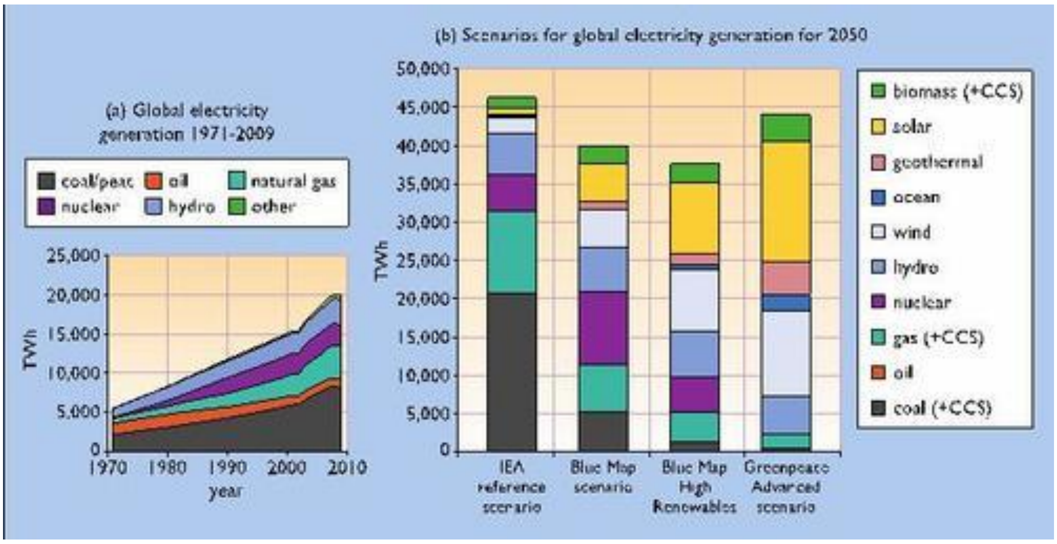

Figure 7 (a) World electricity generation by fuel 1971–2009. (b) Electricity projections in the IEA Reference scenario for 2050; in the IEA Blue map scenario 2050; in the IEA Blue Map High renewables scenario 2050; and in the Greenpeace Advanced Energy (r) Evolution scenario 2050.

As Figure 7 illustrates, in the 40 years between 1970 and 2010, world electricity generation more than tripled. In the next 40 years it seems likely to double in all the scenarios shown. The task of building and installing new clean electricity generation capacity, and the associated networks, will be a major world challenge in coming decades, and these scenarios suggest that renewables are likely to play a major role.

9 Summary and conclusions

This week you looked at the conditions under which the various renewable energy sources can continue to make increasingly significant contributions to the energy needs of the UK. We also looked briefly at the problem of meeting energy demand from *variable* renewable supplies, and at some possible solutions.

We then described scenarios in which renewables in future could meet a major fraction of the energy needs of Denmark and Germany, countries with very ambitious targets for renewable energy's contribution in coming decades. We then looked briefly at the potential for renewables to supply the electricity needs of Europe as a whole.

Finally we looked at studies suggesting that renewables could supply all, or nearly all, of the world's energy, or its electricity, perhaps as early as 2030 – if their rapid deployment were given sufficient political and economic priority.

The technical, social and political challenges involved in phasing-out fossil and nuclear fuels and replacing them largely, or entirely, with renewables are formidable. But there is little doubt that world population, and the world economy, will continue to grow very substantially during the 21st century. An accompanying rise in global primary energy use seems extremely difficult (even if not technically impossible) to avoid. And if a substantial share of this additional energy is not to be supplied by renewables, it will have to come from fossil or nuclear fuels, with all the familiar environmental, social and resource depletion concerns that the use of these sources entails.

The extent to which renewables can increase their share of world-wide energy supplies will depend on many factors including:

- the extent to which investment in research and development and large-scale production can bring about efficiency improvements and cost reductions
- the outcome of debates about the environmental and social costs of conventional sources and the extent to which these costs are reflected in energy prices
- the future patterns of world economic and population growth, and their effect on the level of demand for various forms of energy
- the impact of these considerations on the priorities of governments
- the environmental and social acceptability of renewables to the public.

It seems difficult to avoid the overall conclusion that renewables are likely to play a greatly increased role in future energy supplies. As we have seen, the relatively conservative International Energy

Agency suggests that renewables by 2050 could be supplying some 40% of world primary energy, and between 48% and 75% of world electricity demand. And if history should prove the more optimistic projections of Jacobson and Delucci, WWF and Greenpeace to be correct, by mid-century renewables could be supplying virtually all of the world's energy, or nearly all of its electricity needs, as countries progress towards a more sustainable world economy.

10 End of course quiz

Now try the End of course quiz and earn yourself a digital badge.

11 End of course summary

In this final week of the course you examined some future energy scenarios showing how combinations of renewable sources could provide all, or most, of the energy needs of the United Kingdom, of other European countries, and of the world as a whole, during the first few decades of the 21st century.

In the preceding seven weeks, you looked in turn at the principal renewable energy sources, describing their underlying technologies, their economics, their environmental impact, and the contributions each might make to the energy needs of the UK, Europe and the world, under various conditions.

The technical, social and political challenges involved in phasing-out conventional fuels and replacing them largely, or entirely, with renewables seem formidable. it seems difficult to avoid the conclusion that renewables are likely to play a greatly increased role in future energy supplies. And if the optimists are correct, with sufficient support and encouragement from governments, industry and the public, renewable energy *could* power the world.

Well done for completing *Can renewable energy sources power the world?* If you have studied the full course and completed all the quizzes you will receive a Statement of Participation certificate as a record of your achievement. You can access and print it from your MyOpenLearn profile.

Now you’ve completed the course we would again appreciate a few minutes of your time to tell us a bit about your experience of studying it and what you plan to do next. We will use this information to provide better online experiences for all our learners and to share our findings with others. If you’d like to help, please fill in this optional survey

You can now return to the Course progress page.

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Activity 1

Answer

One year = 365 days x 24 hours = 8760 hours in a year or so, the annual capacity factor = 8760 MWh / 8760 MWh = 1 or 100%

Back to Unit 2 Session 3 Activity 1

Activity 2

Answer

We have already worked out that there are 8760 hours in a year, so: annual capacity factor = 3000 MWh / 8760 MWh = 0.342 or 34.2%

Back to Unit 2 Session 3 Activity 2

Activity 3

Answer

The average North American consumes some 250 GJ per year; whereas most Europeans use roughly half this amount; and many of those in the poorer countries of the world less than one fifth – much of it in the form of traditional ‘biofuels’

Back to Unit 2 Session 5 Activity 1

Activity 4

Answer

They are:

- water vapour
- carbon dioxide
- methane.

These act like the panes of a greenhouse, allowing solar radiation to enter, but inhibiting the outflow of long-wave infrared heat radiation.

Back to Unit 2 Session 6 Activity 1

Activity 1 Collection of solar energy

Answer

Low-temperature solar energy collection mainly depends on using glass and other surfaces with selective properties that allow solar radiation to pass through but block the re-radiation of long-wave infrared. Glass is transparent to visible light and short-wave infrared radiation, but is opaque to long-wave infrared re-radiated from a solar collector or building behind it.

Over recent decades enormous effort has been put into improving the performance of glazing, both to increase its transparency to visible radiation, and to prevent heat escaping through it.

Gathering solar energy for *high-temperature* applications, such as driving steam engines to power electricity generators, mainly involves concentrating the Sun's energy using complex mirrors, as you will see in Section 2.9

You will now go on to discuss direct and diffuse solar radiation.

Back to Unit 3 Session 2 Activity 1

Activity 2 Energy output of the sun

Answer

This is because the Earth circles the Sun with its polar axis tilted towards the plane of rotation, as shown in Figure 2. In June, the North Pole is tilted towards the Sun therefore its rays strike the northern hemisphere more perpendicularly and the Sun appears higher in the sky, as you can see by looking at Figure 3 In the northern hemisphere in December the North Pole is tilted away from the Sun and its rays strike more obliquely, resulting in fewer kilowatt-hours reaching each square metre of ground per day.

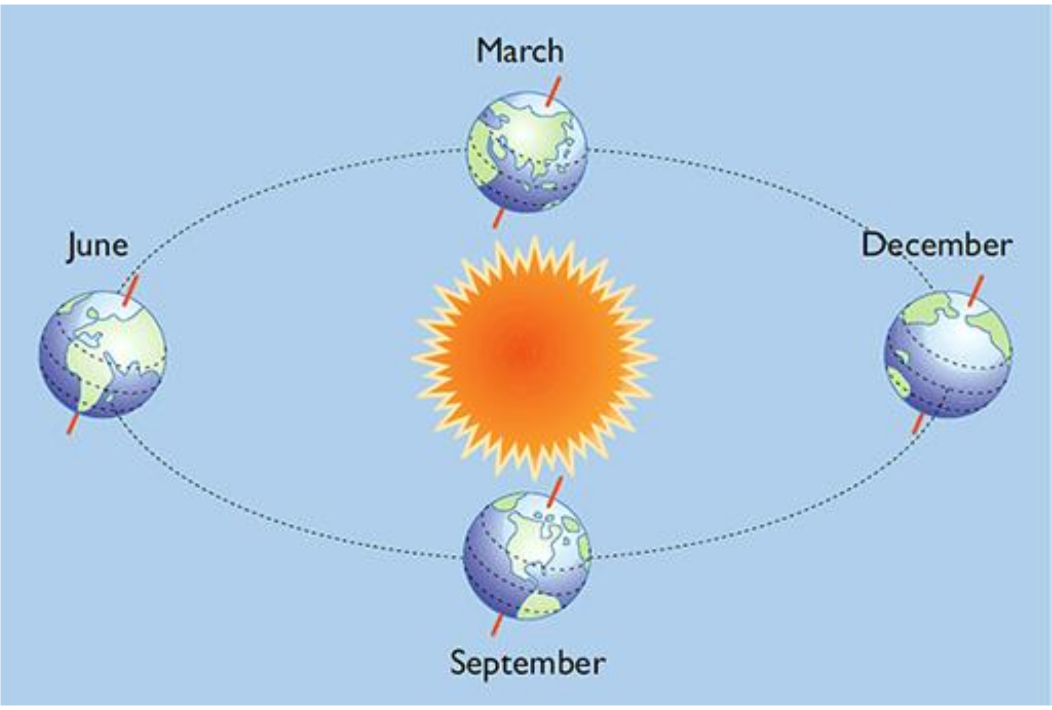

Figure 2 The Earth revolves around the Sun with its axis tilted at an angle of 23.5 ° to the plane of rotation

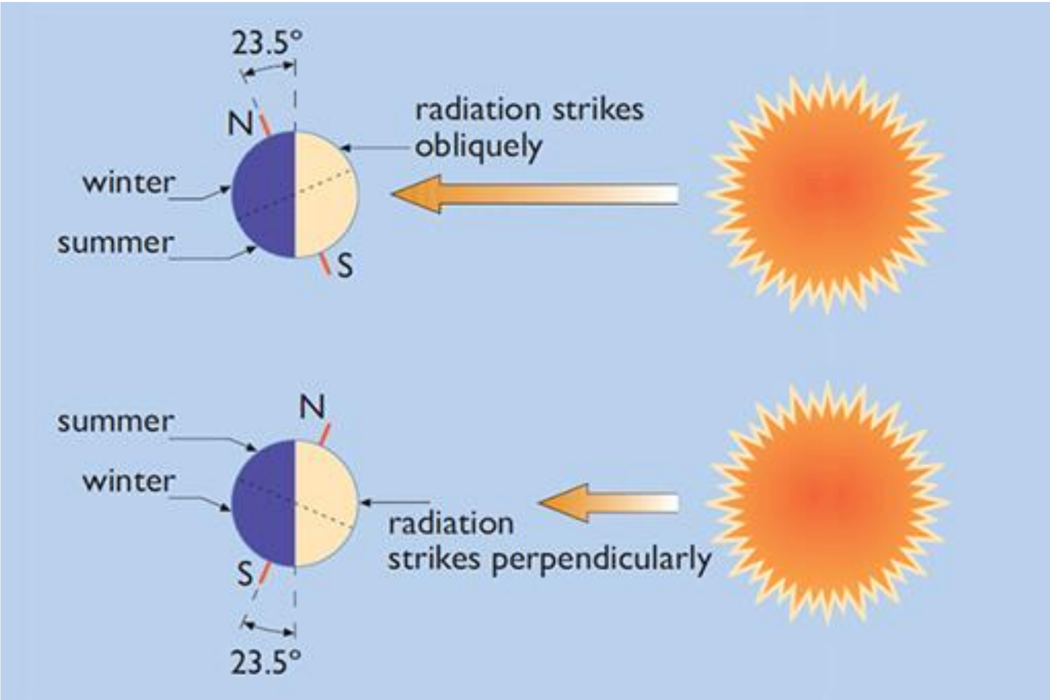

Figure 3 The tilt of the Earth's axis creates summer and winter

Another important factor is that the lower the Sun is in the sky, the further its rays have to pass through the atmosphere, giving them more opportunity to be scattered back into space. When the Sun is at 60° to the vertical its peak energy density will have fallen to one-quarter of that when it is vertically overhead.

Back to Unit 3 Session 3 Activity 1

Activity 3 Passive solar heating

Answer

1. They should be well-insulated to keep down the overall heat losses
2. They should have a responsive, efficient heating system
3. In the northern hemisphere they should face south (anywhere from south-east to south-west is fine), and the glazing should be concentrated on the south side, as should the main living rooms, with little-used rooms, such as bathrooms, on the north.
4. They should be sited to avoid overshading by other buildings in order to benefit from the essential mid-winter Sun.
5. They should be 'thermally massive' to avoid overheating in summer.

Back to Unit 3 Session 4 Activity 1

Activity 4 Lighting in buildings

Answer

Traditional techniques include:

'shallow-plan' design, allowing daylight to penetrate all rooms and corridors light wells in the centre of buildings roof lights

tall windows, which allow light to penetrate deep inside rooms

the use of task lighting directly over workplaces, rather than lighting the whole building interior.

Back to Unit 3 Session 5 Activity 1

Activity 5 Rays of light and reflection

Answer

If the rays enter off-axis, they will not pass through the focal point, so it is essential that the mirror is made to track the Sun.

Back to Unit 3 Session 10 Activity 1

Activity 1

Answer

A typical silicon PV *cell* produces around 0.5 volts. These cells are usually combined into PV *modules* incorporating 60–72 PV cells connected in a series- parallel combination. They are normally around 1.4 to 1.7 m^2 in area (though some are larger), and have a peak power output of some 120–300 watts, depending on the design and technology.

Back to Unit 4 Session 3 Activity 1

Activity 2

Answer

Systems with the highest concentration ratios use sensors, motors, and controls to allow them to track the Sun on **two** axes – azimuth (horizontal orientation) and elevation (vertical tilt) – ensuring that the cells always receive the maximum amount of solar radiation. Systems with lower concentration ratios track the Sun on just **one** axis and can have simpler tracking mechanisms.

Back to Unit 4 Session 3 Activity 2

Activity 3

Answer

Advantages:

Large stand-alone PV plants can:

- Take advantage of economies of scale in purchasing and installing large numbers of PV modules and associated equipment
- Be located on sites that are optimal in terms of solar radiation

Disadvantages:

- The electricity they produce is not used onsite and has to be distributed by the grid, which involves transmission losses, and the price paid for the power by a local electricity utility may only be the ‘wholesale’ price at which it can buy power from other sources.
- Large plants also require substantial areas of land, which has to be purchased or leased, adding to costs – although low-value ‘waste’ land, for example alongside motorways, can be used.

Back to Unit 4 Session 7 Activity 1

Activity 4

Answer

Cons	Pros
initial capital costs of PV systems are currently relatively high	operation and maintenance costs are extremely low in comparison with other energy systems (but PV systems including batteries have additional maintenance requirements)
	no fuel requirements
	no moving parts (except in the case of tracking PV) therefore less maintenance

Back to Unit 4 Session 9 Activity 1

Activity 5

Answer

Studies show that as long as the capacity of variable output power sources such as PV is fairly small in relation to the overall capacity of the grid (around 10–20%) there should not be a major problem in coping with their fluctuating output. The grid is, after all, designed to cope with large fluctuations in *demand*, and similarly fluctuating sources of *supply* like PV can be considered equivalent to ‘negative loads’. Fluctuations would also, of course, be substantially smoothed out if PV power plants were situated in many different locations, subject to widely varying solar radiation and weather patterns.

If PV power stations, and other fluctuating renewable energy sources such as wind power, were in future to contribute a more significant proportion of electricity supplies, then the ‘generating mix’ supplying the grid would have to be changed to include a greater proportion of ‘fast response’ power plant, such as hydro or gas turbines, and increased amounts of short-term storage and/or ‘peaking’ power plant.

Back to Unit 4 Session 10 Activity 1

Activity 1 Variations in yield of crops

Answer

Yields depend on several factors including:

- location
- climate
- weather
- nature of the soil
- supplies of water
- nutrients
- choice of plant.

Back to Unit 5 Session 3 Activity 1

Activity 2 Management system for woody crops

Answer

The most common management system for these types of crop is short rotation forestry (SRF), and a less widespread variant known as short rotation coppicing (SRC). The ‘rotation’ is the periodic cutting of the wood every 8–20 years, with the trees then being re-planted or, for suitable SRC species, left to regrow from the stump after harvesting every 3–5 years.

Back to Unit 5 Session 5 Activity 1

Activity 3 Bioenergy systems

Answer

Some bioenergy systems, such as short rotation forestry or coppice, can increase biodiversity compared to conventional agriculture. Among more experimental technologies, microalgæ don’t take up agricultural land and may be useful in cleaning up both nutrient residues and carbon dioxide, while secondary biofuels, using agricultural residues that would otherwise be burned or ploughed back in, offer another low impact option. More research is needed into these technologies.

Back to Unit 5 Session 8 Activity 1

Activity 4 Needs for energy and needs for food

Answer

Population growth and changing diets look the most likely. It has been suggested that, after allowing for increased food production for a growing world population, as much as 400–700 million additional hectares could be available for energy crops worldwide in the year 2050, without unacceptable loss of biodiversity (UNDP, 2000). Other sources suggest a much lower figure.

Back to Unit 5 Session 11 Activity 1

Activity 1 Plant output size

Answer

With continually rising demand for electricity, and the growth of national transmission networks, capacities of several hundred megawatts have become the norm for modern power stations, and plant outputs below about 10 MW are now referred to as small-scale.

Back to Unit 6 Session 5 Activity 1

Activity 2 Calculating power output

Answer

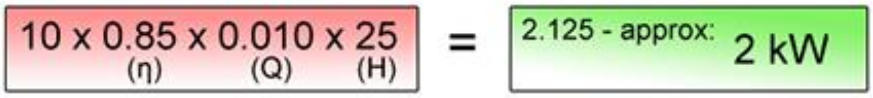

Figure 14 Example calculation of hydro power from given efficiency, flow rate and effective head

Back to Unit 6 Session 6 Activity 1

Activity 1 Factors on total energy generated

Answer

Other additional factors that could affect the total generated energy include:

- transmission losses
- the *availability* of the turbine to generate.

Availability indicates the *reliability* of the turbine installation and is the fraction or percentage of a given period of time for which it is available to generate, when the wind is blowing within the turbine's operating range.

Back to Unit 7 Session 6 Activity 1

Activity 1 Long waves and short waves

Answer

Long waves travel faster than the shorter waves. This is referred to as ‘dispersion’, a unique feature of deep water waves which can lead to dangerous and hard to predict combinations of wave crests.

Back to Unit 8 Session 2 Activity 1

Activity 2 Pros and cons of fixed and shore mounted devices over floating devices

Answer

Table 2 Advantages and disadvantages of fixed and shore mounted devices over floating ones

Advantages	**Disadvantages**
Have a fixed frame of reference	Generally operate in shallow water and hence at lower wave power levels
Are closer to a grid	Geographical location – only a limited number of sites are suitable for deployment
Good access for maintenance purposes	To optimize output, they need to be positioned in an area of small *tidal* range, otherwise their performance may be adversely affected
The seabed attenuates storm waves that could otherwise destroy the device and turbine	

It is also worth noting that mass production techniques are unlikely to be totally applicable to shore-mounted schemes, as site-specific requirements will demand a tailored design for each device, adding to production costs.

Back to Unit 8 Session 4 Activity 1

Activity 1 Variable weather conditions

Answer

The additional electricity connections would allow countries with temporary surpluses of renewable electricity to export these to countries in temporary deficit – and vice versa.

Back to Unit 9 Session 8 Activity 1

Activity 2 Electricity grid enlargement

Answer

They would enable solar-generated electricity from the Sahara to be combined with wind power from the north-west African Atlantic coast, and other renewable electricity sources from central and northern Europe.

Back to Unit 9 Session 8 Activity 2

Activity 5

Discussion

The measures the UK Government has put in place to ensure that these 2020 targets are met include:

1. A Renewables Obligation (RO) – large-scale electricity suppliers must source a significant proportion of their supplies from renewable sources.
2. A ‘Feed-in Tariff’ scheme under which premium prices are paid to small-scale generators of renewable electricity.
3. A Renewable Heat Incentive (RHI) – incentives to encourage the use of heat-producing renewables.
4. A Renewable Transport Fuel Obligation (RTFO) – road fuel suppliers are obliged to blend in a proportion of biofuels.
5. A Green Investment Bank – channelling capital towards renewable energy and energy efficiency projects.

Back to Unit 2 Session 8 Activity 1

Uncaptioned interactive content

Transcript

Welcome to Week 1. In this first week we introduce you to the wide variety of renewable energy sources. But first we begin by looking at the environmental concerns that have given rise to recent interest in renewables. We also introduce you to some basic energy terms and concepts to help you understand the subject.

We begin by looking at the sun, that enormous energy source that powers most of the renewables, either directly in the form of heat, light or electricity or indirectly in the form of bioenergy, hydropower, wind or wave power. We also look at two non-solar renewables, geothermal energy and tidal power.

We then move on to look briefly at energy supply and demand, first on a world scale and then on the much smaller scale of the UK. Then we look at the problem of global climate change largely caused by emissions of planet warming greenhouse gases, mainly carbon dioxide from burning fossil fuels. It's now widely accepted that the world needs to phase out fossil fuels and phase in low and zero carbon energy sources such as renewables.

We follow this with an overview of the main solar and non-solar based renewals. We then look at current European and UK targets for increasing the share of renewables in the energy mix by 2020 to 2030. We discuss the UK government's Electricity Market Reform measures and we look at the UK Climate Change Committee's estimates of the contributions renewables could make to UK energy needs by 2030.

We conclude this week with a case study in the form of three short video segments of Scotland's ambitious aim to produce 100% of its electricity from renewable sources by 2020.

Back to Unit 2 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

Hello. This week we look at the use of the Sun's energy in buildings for space heating, water heating and lighting. Only a small proportion of the Sun's energy is intercepted by the Earth 150 million kilometres away. But it's sufficient to keep the temperature of the planet suitable for life.

We also look at the variations and the amounts of solar energy intercepted in different seasons and regions of the globe. And we look at the design of buildings to make maximum use of solar energy for space heating and lighting passively without the need for special collectors and this building gives a very good example.

We then look at active solar collectors such as the rooftop solar water heaters that are common in many parts of the world. We go on to examine heat pumps which use electricity to raise to a useful temperature the ambience energy that's available from the air, from the ground or from water.

Finally, we look at concentrating solar power systems or CSP for short in which the Sun's rays are concentrated using mirrors or lenses to generate high temperature steam that's used to power electricity generators.

Back to Unit 3 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

Hello again. This week we look at ways of generating electricity from solar radiation directly using solid state electronic devices, photovoltaic or PV panels in arrays like these.

PV panels are made from a specially treated junction between two different types of electronic semiconductor, positive or P-type and negative or N-type. When photons of light fall in this junction they generate an electric current producing useful power.

Most PV panels are made of silicon but other materials can be used. And new materials are being developed that may be cheaper or more efficient or both. PV based panel systems can be used to provide electricity for various purposes such as water pumping where there’s no grid available as in many remote areas.

PV power systems are also increasingly being used in areas connected to the grid. They’re usually mounted on roofs and can supply a significant proportion of the energy demand of houses, offices and non-domestic buildings.

Larger grid connected PV arrays are also being installed on land set aside for the purpose particularly in locations with high direct solar radiation levels such as southern Europe. And as with the concentrating solar power or CSP plants we discussed in Week 2, concentration can be used with PV to reduce the number of panels required to produce a given level of power. And here too, tracking systems are required.

The cost of electricity from PV panels was very high when they were first developed from the US space programme in the 1950's. But costs have dropped dramatically in recent years due to economies and mass production and improvements in efficiency. And although many PV systems currently receive clean energy subsidies, projections show that the power from PV will be competitive with conventional grid power by 2020 without subsidies.

Back to Unit 4 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

This week we look at bioenergy, the most ancient form of renewable energy if we think of the wood fires used by our early ancestors. This form of traditional biofuel is still widely used in many developing countries. But bioenergy is now a much more modern energy source though still derived from the growth of plants.

Plants grow through a process call photosynthesis in which solar energy causes carbon dioxide from the atmosphere to combine with water from the surrounding environment to produce the material of which plants are formed, biomass.

Wood is the most obvious form but bioenergy can take several other forms such as charcoal, biogas, bioethanol and biodiesel.

If properly managed biofuels are carbon neutral because the amount of carbon dioxide that's released when they're burned is the same as the amount absorbed from the atmosphere when the plants are growing.

Sources of biofuel include wood from forests, grassy plants such as miscanthus, starchy or sugary crops such as sugar cane, sugar beet and maize and oil seed crops such as sunflowers, oil seed rape and soya beans.

Bioenergy can also be derived from waste such as straw or rice husks or from urban or industrial wastes. All of which can be burned to release energy.

Animal manure can also be used through a process called anaerobic digestion to produce biogas which can be burned to produce heat or to power engines for electricity generation.

How much energy could biofuels contribute to the world's energy needs in the future? One estimate suggests it could be as much as a fifth of present world energy consumption.

Back to Unit 5 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

This week's renewable energy source is hydropower. Essentially power derived from moving water as in traditional water wheels like this one that have been used for centuries to pump water and grind corn. Modern hydropower plants generate electricity using more sophisticated water turbines that were developed early in the 20th century. The amount of energy that can be derived from water power plants depends essentially on two things, the rate of flow of the water and the head, that's the height through which the water falls.

There are a variety of water turbines designed to suit the characteristics of the low, medium and high head hydro schemes.

Hydroelectric systems now contribute to about 16% of the world's electricity. Many of the hydropower plants are extremely large in scale and can have major effects, negative as well as positive, on the surrounding environment and population.

As well as generating electricity hydropower plants can be used to store electric power by using electricity at times of low demand to pump water up to a high reservoir. When the demand for electricity is increased it can be generated by allowing the stored water to fall down again through turbines powering electric generators.

The UK has two such pump storage schemes at Cruachan in Scotland and Dinorwig in Wales.

Once a modern hydropower plant has been constructed it has extremely low running costs and extremely high capital costs. This makes it desirable to have extremely low interest rates on the invest to capital and a very long payback time.

This means that the future of large hydro schemes are likely to be funded by governments which can satisfy these long term investment criteria.

Back to Unit 6 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

The Earth's winds are caused when different regions of the atmosphere are heated by the Sun to different temperatures causing pressure differences that result in the movement of air. Wind energy has been used for thousands of years, in sailing ships and in windmills for pumping water or grinding corn.

This week we look at modern wind turbines at the atmospheric and aerodynamic processes that power them and at ways of calculating the power and energy they produce. We also look at their environmental impact, the economics and the future prospects of wind technology.

Attempts to generate electricity from wind have been made since the late 19th century but it was only around the 1980's that the technology began to mature.

Between the early 1980's and the late 2000's the costs of wind turbines fell steadily and the power of typical machines increased significantly. Now on reasonably windy and accessible sites wind turbines are one of the most cost effective methods of electricity generation.

Wind turbines are increasingly being deployed offshore where wind speeds are generally higher and planning constraints less demanding. Here the technically accessible wind resources are massively increased. Of course offshore wind involves significant additional technical challenges and the cost of generation is higher.

The reason developments in wind energy technology have made it one of the fastest growing renewable energy sources worldwide, a total of 318 gigawatts of wind power had been installed by the end of 2013. An increase of 10% on the previous year.

We conclude this week with a look at recent developments in wind technology and a discussion of the contribution that wind might make to the needs of the EU and globally by 2050.

Back to Unit 7 Session 1 MediaContent 1

Uncaptioned interactive content

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Back to Unit 8 Session 1 MediaContent 1

Uncaptioned interactive content

Transcript

This final week also includes a series of six short video interviews with key figures in the renewable energy industry who give their expert opinions on how much energy could be supplied by renewables to the UK, other European countries and the world as a whole.

There is little doubt that the technical, social and political challenges involved in phasing out conventional fuels are formidable. But as you will see it’s hard to avoid the conclusion that renewables are likely to play a greatly increased role in world energy supplies. And if the optimists are correct, given sufficient support from governments, industry and the public renewable energy could power the world.

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