Nuclear power - harnessing the energy of the atom
Investigating the use of nuclear power now and in the future

Even the mention of 'nuclear power' causes concern for many people. They remember the Chernobyl disaster in Ukraine in 1986 and the Fukushima Daiichi disaster in Japan in 2011. They also worry about the disposal of the radioactive waste; *(this has been discussed in the Earthlearningidea 'Nuclear waste disposal')*. Nuclear power, however, is a secure and reliable source of carbon-free electricity.

What is nuclear power?

- Nuclear reactions release large amounts of heat which is used to drive turbines to generate electricity. Electricity from nuclear power is produced predominantly today by nuclear fission (breaking apart) of atoms of uranium-235 and plutonium-238 in nuclear power plants.
- Nuclear power can be obtained from nuclear decay and is sometimes used to power space probes.
- Theoretically, nuclear power can also be obtained from nuclear fusion reactions (joining atoms together). Generating electricity from nuclear fusion remains the focus of international research, as it is difficult to achieve the conditions of temperature and pressure required for fusion.

How does nuclear fission work?

Some elements of high atomic mass are radioactive; their atomic nuclei emit neutrons and ionising radiation which can damage living organisms, so people handling nuclear material need special protection. If a neutron hits another atomic nucleus, that nucleus may break into (usually) two parts which are the atomic nuclei of other, lighter, elements, or form isotopes of the same element with the same number of protons but differing numbers of neutrons. Further neutrons are released together with a large amount of heat energy. If enough (the critical mass) of radioactive material is present, neutrons continue to split further atoms in a chain reaction. The reaction can be controlled or moderated by slowing down neutrons in carbon rods or in water.

Pressurised water reactor (PWR)

Originally designed as a small installation for nuclear submarines, the PWR uses water both to moderate and to cool the reactor. The water is highly pressurised to prevent it from boiling. Extremely hot water passes through a heat exchanger to a steam generator. Superheated steam drives turbine-alternator sets and passes to a closed-circuit condenser. This type of reactor is used in many countries, shown in the table below. In 2021 there were 302 PWR power plants in operation or operable. Sizewell B in the UK is of this type. The fuel used is enriched uranium.

Boiling Water Reactor (BWR)

This basic design has a core cooled and moderated by pumped water. Boiling water and steam passes in a closed loop through the core to steam turbine-generator sets and returns through a condenser. This type was used at Fukushima. It has major disadvantages in that the turbines are within the radioactive zone, moderation depends on external pumps (a safety hazard) and, because the difference between the input and outlet temperatures of the turbines is low, system efficiency is poor, around 25%.

Pressurised heavy water reactor (PHWR)

This is similar to the usual (light water) PWR but the use of heavy water D_2O allows it to use neutrons more efficiently, so allowing the use of less-enriched or unenriched uranium fuel.

Advanced Gas-cooled Reactor (AGR)

Currently, the UK has a number of nuclear power stations in use. Other than Sizewell B, mentioned below, all are of the AGR type. The AGR reactor uses enhanced uranium-235 with graphite moderating rods. It is cooled by pressurised carbon dioxide gas in a closed chamber. The gas, at about 650°C, passes

Nuclear power plants in operation or operable 2021:
https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	302	287.0	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	63	64.1	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	24.5	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	14	7.7	natural U (metal enriched) UO_2	CO_2	graphite
Light water graphite reactor (LWGR)	Russia	12	8.4	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	2		PuO_2 and UO_2	liquid sodium	none

through a heat exchanger to generate superheated steam which operates steam turbines (similar to coal-fired installations), which in turn drive 50Hz alternators. Exhaust steam passes through a condenser in a closed circuit. This design, used only in the UK, dates from the 1960s, when it was developed from the earlier Magnox reactors. It is a much less compact installation than the PWR. Though installations of this type continue reliably to provide a substantial part of UK base-load electricity, unfortunately this design has proved to be expensive both to build and to maintain. The overall thermal efficiency is typically 30%. The last station of this type, Torness, is due to close in 2030.

Hinkley Point C UK
This power station is now under construction for estimated completion in 2025 at a cost of some £20 billion. It has taken several years of prevarication, enquiries and court hearings to reach this point and the costs are still severely criticised. The pre-agreed or 'strike' price for electricity produced may be double the going rate.
Hinkley Point C is the first new nuclear power station built in the UK in 30 years. It is an EPR, (originally European) Pressurised Reactor, a development of the PWR, and thought to be significantly safer than preceding types. The site occupies some 230 acres. There will be two reactors, each producing 1600MW of electricity. Base structures for the two reactors will be 3m thick and will consume some 20,000 cubic metres of concrete. However, George Monbiot, the writer on sustainability and a supporter of nuclear energy, says the reactor design is already outdated. An identical new power station is proposed at Sizewell C.

Hinkley Point C, 2019
Press release www.edfenergy.com

Light water graphite reactor (LWGR)
Russia has several of these boiling water reactors of unusual design dating from the 1960s. There are serious design shortcomings. This was the type of reactor involved in the Chernobyl disaster.

Fast Neutron Reactor (Fast Breeder Reactor) (FBR)
This reactor takes highly enriched uranium-238 and produces plutonium-239 which can be used in conventional reactors, together with enough enriched uranium to maintain itself. In theory, it extracts more energy from the fuel than other types. This principle appeared attractive in the 1970s, but proved ruinously expensive and has been generally abandoned. Two remain in Russia used for electricity generation.

The future?
(1) Liquid fluoride thorium reactor (LFTR)
These reactors are in advanced investigation in several countries. They differ from classic fission reactors in almost every aspect. They are 'breeder' reactors which make their own fuel. Thorium-232, as mined, is 'fertile', i.e. it can absorb a neutron, and after a few days, changes to uranium-233 which is fissile. Fission produces enough neutrons to generate electricity and to make more uranium fuel from thorium indefinitely. There is very little radioactive waste.

A typical LFTR has two closed loops of liquid (molten) fluoride salt. The first loop contains the uranium-233 fuel distributed within it, so there is no separate fuelling process. This loop is contained within a blanket of thorium which is gradually changed to uranium-233 fuel. Heat is taken from the relatively small reactor core and passed through an external heat exchanger to the second, non-radioactive, loop and on to a steam generation plant and turbine alternator sets. In an alternative design, thorium-232 is also contained in the first loop, avoiding the need for a separate thorium blanket.

(2) Small Modular Reactors (SMR)
These will be scaled-down versions of several types of existing reactors, made to standard plans in a factory and assembled on site. They offer a number of advantages:
- they are fully self-contained and very secure;
- they are widely distributed and interconnected, so a failure or external attack on one cannot cause a power outage, neither is there need for backup diesel generators;
- because of standardised component construction, both design and construction costs are much reduced;
- because land and site costs are minimised, electricity produced may be cheaper than other sources;
- unlike some renewable energy sources, they have a consistent output;
- the output can be moderated within a wider range than in older designs;
- the up-to-date design means that there is minimal radioactive waste;

- they will have a long operating life with long refuelling intervals, if needed at all.

A possible problem with SMRs is that regulatory legislation is a long way behind the technological advances.

In the UK, the Rolls-Royce company is heading a consortium of UK companies to promote these new nuclear power installations. They are typically of 220 to 440 MW capacity and each will require a site of only around 4 acres (1·6 ha). Plans are advanced for 16 units around the UK, potentially replacing a power station of the size and cost of Hinkley Point C (above).

Further information is available at the following sites:-
https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/nuclear/smr-brochure-july-2017.pdf
https://world-nuclear-news.org/Articles/Rolls-Royce-on-track-for-2030-delivery-of-UK-SMR

Artist's impression of a seashore SMR
(Rolls-Royce publicity brochure)

Your local area
Go with your group to a local area where you have a good view of the surrounding region or just look out of the window, or study a view on a screen to discuss the points below. Remember that thermal power stations, whatever fuel they use, require large quantities of cold water for their condensers, so are often located near the sea.

Discuss the following:
Could an SMR (Small Modular Reactor) be built here, in this area?
List the advantages
Possible answers are given in the information about SMRs
List the disadvantages
Possible answers:
- *they use nuclear fuel which many people are against;*
- *regulatory legislation is a long way behind the technological advances.*

What impact might it have on the local community?
Possible answers:
- *create jobs*
- *improve infrastructure*
- *cause distress to some of the people living nearby even though the risks are much lower than with older designs as they require infrequent access for maintenance.*

If it could happen here, should it happen here?

Back up
Title: Nuclear power - harnessing the energy of the atom

Subtitle: Investigating the use of nuclear power now and in the future

Topic: The various types of nuclear power stations are discussed and the future of nuclear power is considered. This is followed by a discussion about siting SMRs (Small Modular Reactors) in the local area.

Age range of pupils: 16 years upwards

Time needed to complete activity: from 30 minutes plus depending on the potential of the local area and the levels of discussion.

Pupil learning outcomes: Pupils can:
- explain what is meant by nuclear power;
- describe how nuclear fission works;
- describe various types of nuclear power stations;
- consider the future of nuclear power with LFTRs and SMRs;
- describe the advantages and disadvantages of siting an SMR in the local area;
- consider the impacts of an SMR on the local area.

Context:
Government 'net-zero' targets will affect many areas across the world. This Earthlearningidea explores what contribution nuclear power might make to the energy mix of countries. It reviews what nuclear power is, various types of nuclear power stations, both past and future, and what the impacts of building SMRs might be in your local area.

Following up the activity:
Evaluate the possibilities for energy sources alternative to fossil fuels using the Earthlearningidea, 'What is/are the least bad option(s) for plugging the future global energy gap?' at
https://www.earthlearningidea.com/PDF/343_Plugging_energy_gap.pdf
for other ideas of what could be developed in your area.

Underlying principles:
- Nuclear reactions release large amounts of heat which is used to generate electricity.
- Electricity from nuclear power is produced in most cases by nuclear fission of uranium-235 and plutonium-238.
- Nuclear power can be obtained from nuclear decay and is sometimes used to power space probes.
- Theoretically, nuclear power can also be obtained from nuclear fusion reactions.
- Some elements of high atomic mass are radioactive; their atomic nuclei release neutrons and ionising radiation (alpha, beta and gamma photons).
- If a neutron hits another atomic nucleus, that nucleus may break into (usually) two parts which are the atomic nuclei of other, lighter, elements or may form isotopes of the same element.
- If enough (the critical mass) of radioactive material is present, neutrons continue to split further atoms in a chain reaction.
- The chain reaction can be controlled or moderated by slowing down neutrons in carbon rods or in water.
- The AGR reactor uses enhanced uranium-235 with graphite moderating rods. It is cooled by pressurised carbon dioxide gas in a closed chamber.
- The BWR and PWR use water both to moderate and to cool the reactor. In the PWR the water is highly pressurised to prevent it from boiling.
- Hinkley Point C in the UK is a development of the PWR and thought to be significantly safer than preceding types.
- In the future liquid fluoride thorium reactors (LFTR) may be developed. These are 'breeder' reactors which make their own fuel. Thorium-232 accepts a neutron, becoming thorium 233 which by two stages of beta-decay becomes firstly protactinium-233 and then uranium-233.
- Small Modular Reactors (SMR) are being developed. These are scaled-down versions of several types of existing reactors using standardised parts and have a number of advantages.
- All thermal power stations, including nuclear, generate electricity with steam turbines, and have an upper efficiency limit in the order of 50-55%. Turbine output is maximised with a high temperature and pressure at the steam input and, at the steam outlet, a low temperature and low pressure achieved through condensing the steam by external cooling to produce a partial vacuum. The energy lost to external cooling has to be replaced in the next heating cycle. Thus there is a limit to the overall system efficiency.
- Although nuclear power generation is carbon neutral, the carbon footprint during the building phase of a large nuclear power station is huge.

Thinking skill development:
A pattern develops as the various types of past and future nuclear power reactors are considered. As discussion (metacognition) takes place, cognitive conflict occurs when it is realised that nuclear power could solve the future energy crisis and, once the plants are constructed, cut down on greenhouse gas emissions. Imagining SMRs in the local environment involves bridging skills.

Resource list:
- a view, either from a hill, a window or on a screen

Useful links:
What are the safest and cleanest sources of energy?
https://ourworldindata.org/safest-sources-of-energy
Search 'net-zero' on the Earthlearningidea website to find other Earthlearningideas relating to climate change mitigation or adaptation. The full list is on the next page.
Use a search engine like Google to explore the internet for more information about likely global impacts of 'net-zero'. You can access a tool to help visualise how climate change might affect your local area in the UK at:
https://www.bbc.co.uk/news/resources/idt-d6338d9f-8789-4bc2-b6d7-3691c0e7d138

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The ‘How will the ‘net-zero’ target affect your local area?’ series of Earthlearningideas

Topic			**Earthlearningidea title**
Introduction			How will the ‘net-zero’ target affect your local area?
Possible mitigation measures	Use alternative energy sources	Solar	Harnessing the power of the Sun
		Wave	Harnessing the power of waves
		Wind	Farming the wind: through onshore and offshore windfarms
		Tidal	Tidal energy
		Nuclear	Nuclear power - harnessing the energy of the atom
		Nuclear waste	Nuclear waste disposal
		Biofuel	Liquid biofuels: keeping our wheels turning into the future
		‘Blue’ hydrogen	Blue hydrogen: the fuel of the future?
		Geothermal – hot rocks	Deep geothermal power from ‘hot dry rocks’: an option in your area?
		Geothermal – flooded mines	A new use for old coal mines
		Hydro – small scale	Small-scale hydroelectric power schemes
		Heat pumps	Heat from the Earth
		Waste – incineration	Energy from burning waste
		Waste – methane	Energy from buried waste
	Stop fuels releasing greenhouse gases	Carbon capture	Capturing carbon?
	Store energy from sources that give irregular energy supplies	Batteries	Nuclear batteries: the future?
		‘Green’ hydrogen	Green hydrogen used to even out renewable energy supplies?
		Hydro – storage	Matching supply and demand using stored water
		Compressed gas	Storing gas underground: What can we store? How can we do it? How will it help?
	Provide raw materials for new technologies	Electric vehicles	Electric vehicles: the way to go?
		Insulation	How do I choose the best insulation?
	Remove carbon form the atmosphere	Enhanced weathering	Speeding up nature to trap carbon dioxide
		Tree planting	Let’s plant some trees
Possible adaptation measures		Coastal flooding	How will rising sea level affect our coastlines?
		Inland flooding	Inland flooding: a Sheffield case study
		Landslides	Landslide danger
		Agriculture	The future for global agriculture