THE FUSION CLUSTER

FUSION FOR ALL TEACHERS' PACK

Turning fusion from theory into practice.

FUSION FOR ALL

A pack of resources from The Fusion Cluster

National Curriculum

Links to the KS3 Physics Curriculum:

- Energy
- Energy Changes and Transfers
- Changes in System

Links to the KS4 Physics Curriculum:

- Energy
- Atomic Structure

Links to the KS4 Chemistry Curriculum:

- Atomic Structure and the Periodic Table

(Also touches on other parts of Physics and Chemistry Curricula at KS3 and KS4)

Context

This activity pack will help you learn about:

- Science and technology careers
- Renewable and non-renewable resources
- Transfers between energy stores
- Scientific language and units of energy and power
- Conservation of energy, dissipation, and efficiency
- Atoms, elements, and the periodic table
- The structure of the atom and nuclear reactions

This pack contains:

1. **Fusion for all** (this document) – context, activities, and find out more
2. **Activity Resources: Energy Options** – summaries of the key energy technologies of today
3. **Activity Resources: What does a FUSIONeer do?** – profiles of people working in the fusion sector
4. **Energy in Science and Society** - Extra reading

WHY WOULD WE WANT FUSION FOR ALL?

Context for Teachers & Students

Climate change is melting the world's ice.

Net Zero

The world is getting warmer because of greenhouse gases like carbon dioxide (CO_2) in the atmosphere. Human activity is the overwhelming cause of these emissions.

In 2019 the UK Government set a legally binding target of the year 2050 for the country's greenhouse gas emissions to reach net zero. This means new emissions put into the atmosphere don't exceed the rate they are removed, otherwise known as being "carbon neutral". It makes up a part of the global initiative towards sustainability – three of the United Nation's sustainable development goals are tied to this effort – an emphasis on climate action, developing sustainable cities and communities, and the sourcing of affordable and clean heating and electricity.

To understand how the UK (and the world) intends to meet these targets, we need to look at the way we heat our homes and businesses, the way we transport people and goods, and the way our electricity is produced. Although many countries are getting greener, particularly in generating and using electricity, world's electricity usage is likely to double by 2050.

It's a tricky problem to solve. To understand more, let us look at a key concept – energy.

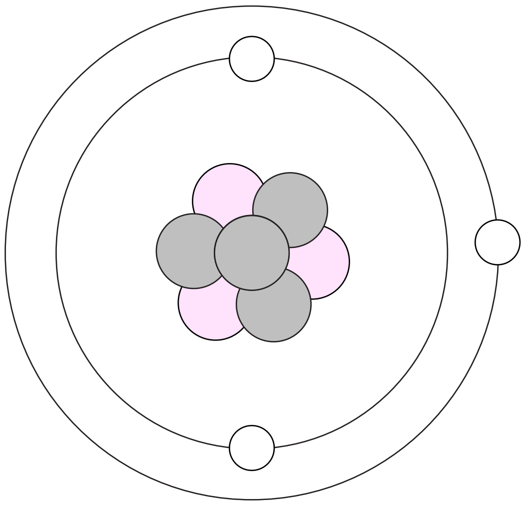
More homes and cars are being powered by electricity.

Energy

Energy is a fundamental idea in science – especially when combined with the law of conservation of energy. To learn more about conservation of energy, and the different ways energy can be stored, take a look at the further reading "Energy in Science and Society". The further reading document also looks at the meaning of energy in the context of our society – meaning the way we heat our homes, fuel our vehicles, and generate electricity. For now, let's just say there are many different technologies available that provide sources of electricity, heating, and mechanical work. In the UK during 2022, burning fossil fuels was the most common way we heated our homes, and was still the most common way of fuelling our cars. It accounted for more electricity generated than by any other method. However, fossil fuels aren't the only option – many homes are turning instead to electric heat pumps to keep warm, battery-powered cars, and the UK's mains electricity is also generated by renewables like wind (which has grown dramatically in recent years), as well as by traditional nuclear power plants. Traditional nuclear power is low-carbon but not strictly speaking renewable. However, there is another technology relying on similar nuclear processes that may become a key component in the world's sustainable future – and that is fusion power.

WHAT IS FUSION?

Fusion is a kind of nuclear reaction. Every atom is made up of a nucleus in the centre, and a number of electrons orbiting the nucleus. Most everyday changes to materials are explained by chemical reactions and by the sharing or transfer of electrons. But in a nuclear reaction, it is the atomic nucleus that is changed, and so in nuclear physics we often ignore the electrons entirely. In most nuclei, protons and neutrons are bound together to make up the nucleus. The number of protons tells you which element you have (hydrogen has one proton, helium has two, and uranium has 92, for example).



An atom of lithium, with its central nucleus and orbiting electrons (white). All lithium atoms have three protons (pink) in the nucleus, but the number of neutrons (grey) can vary.

The simplest nucleus of all is a single proton with no neutrons – this is the most common type of hydrogen nucleus, called hydrogen-1 (sometimes called "protium"). Other forms exist called hydrogen-2 (one proton, one neutron) and hydrogen-3 (one proton, two neutrons) – but they are most commonly called "deuterium" and "tritium". These three different forms are the "isotopes" of hydrogen.

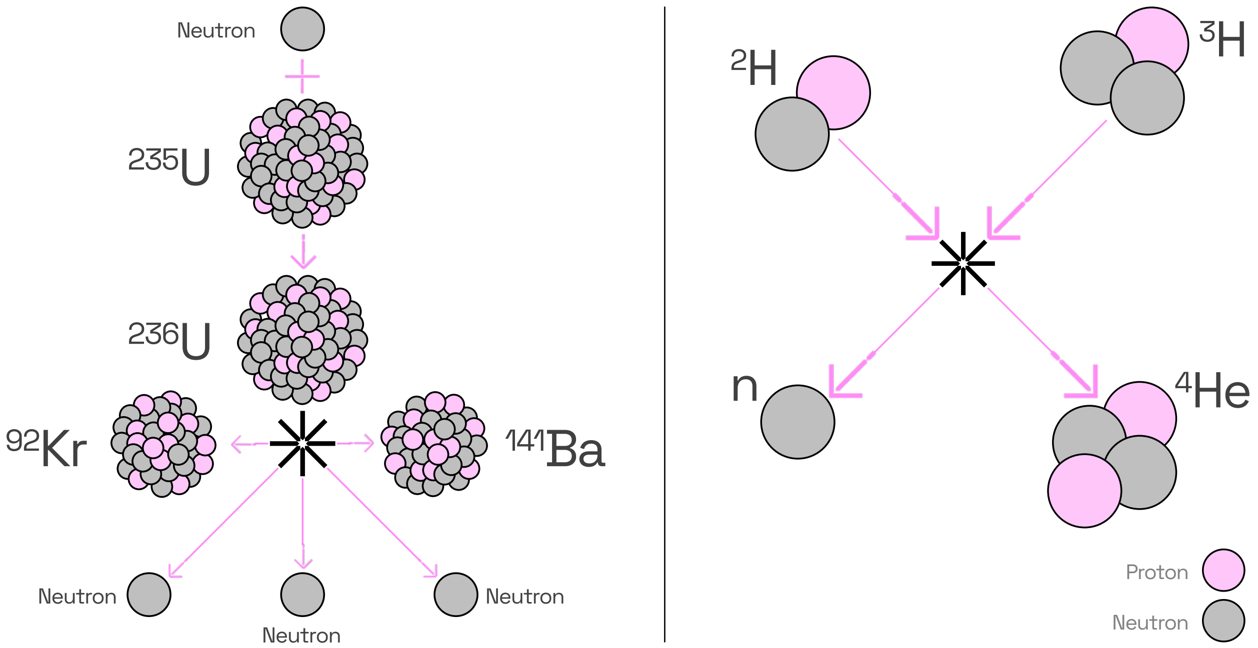
At the other end of the scale, are elements like uranium – all uranium atoms have 92 protons but there are different isotopes: uranium-238 (the most common) contains 146 neutrons, while the next most common isotope, uranium-235, has 143 neutrons.

There are two important types of nuclear reactions that we can use – fission and fusion. Fission is the splitting of a large nucleus into smaller nuclei. For example, firing a neutron at a uranium-235 nucleus causes it to split into two smaller fragments[1], releasing more neutrons and creating a chain reaction. Fusion involves colliding two small nuclei together to create a heavier element – the same process that happens inside the sun. The easiest fusion reaction for us to use is to collide one deuterium and one tritium to give one neutron and one helium-4 nucleus (also known as an alpha particle: it contains two protons, two neutrons).

Every atomic nucleus larger than hydrogen-1 is a store of nuclear energy. We can use these reactions as a useful source of energy if the nuclear energy stored at the start is greater than the nuclear energy stored at the end. Ultimately energy is transferred out of the fusion materials by heating other components of the equipment used to drive the reactions. As in other kinds of power plants, fusion machines will heat up water to make steam that drives a turbine, in order to make electricity.

[1] One neutron will split uranium-235 into a krypton-92 nucleus and barium-141 nucleus, releasing three more neutrons. You can look up the number of protons and neutrons in each nucleus to check this balances out.

HOW DOES A FUSION MACHINE WORK?



Two common nuclear reactions useful in generating electricity. **Left** - the fission of uranium-235 after collision with a neutron. The reaction produces krypton and barium nuclei as well as three more neutrons. **Right** - a fusion reaction between deuterium and tritium (isotopes of hydrogen) producing helium-4 and a neutron.

Fusion machines are still experimental – they don't yet supply electricity to the grid. However, the experimental machines around the world, including those in the UK have solved many of the problems preventing us from reaching that point.

In fusion machines, it's the reaction shown above that's most useful – where isotopes of hydrogen are turned into helium. Deuterium naturally makes up around 0.02 % of the hydrogen atoms found on Earth, but this is enough to allow deuterium to be produced by processing water (H_2O). Tritium however is many billions of times rarer still, and must be produced artificially in a process known as "tritium breeding"[2].

For fusion to happen, the nuclei need to collide – and fast! Both nuclei have a positive charge, and since like charges repel, the speed of the two nuclei must be fast enough to overcome this. That means the fuel must be heated to over 100 million degrees Celsius. At room temperature, hydrogen is a gas, comprising molecules of H_2 – two hydrogen atoms sharing electrons, with the molecule being neutral. As for helium – under normal conditions helium is a gas of individual neutral atoms (simply written He).

At fusion temperatures, the materials involved aren't even gases – they have turned into a plasma – where the electrons have separated from the nuclei, meaning the individual particles are charged. The material is so hot that no container could hold it, and so alternative approaches need to be taken.

[2] Tritium "breeding" is done by firing neutrons at certain lithium compounds (the isotope lithium-6 makes up around 5% of all Earth's lithium atoms and the reaction produces tritium and helium-4).

Most fusion machines use strong magnetic fields to contain the plasma – the charged particles are steered by the field to keep the plasma in a doughnut-shaped region that doesn't actually touch the walls of the machine. This method is called "magnetic confinement", and involves a special ring-shaped confinement chamber known as a "tokamak".

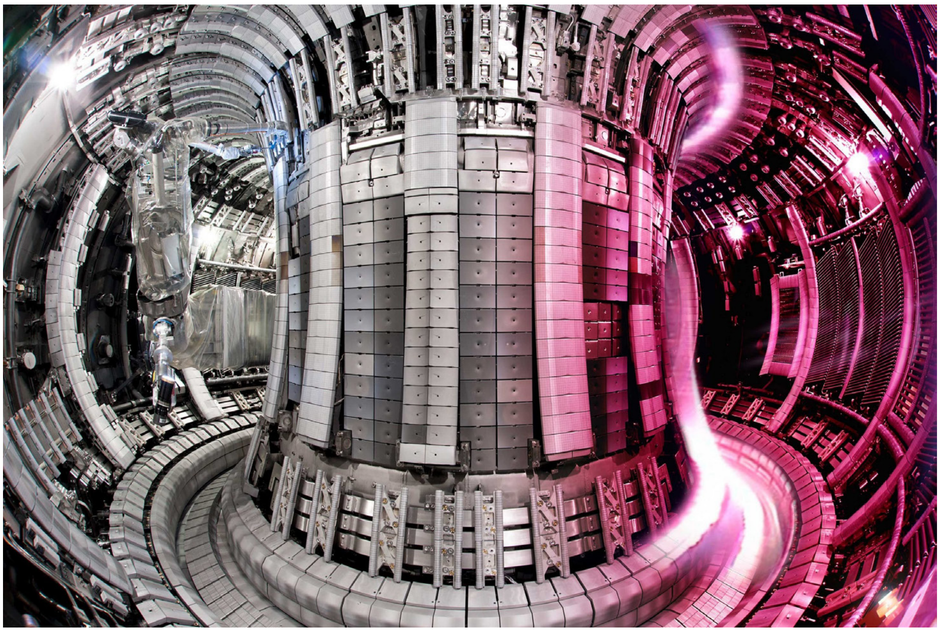
This prevents huge challenges in terms of engineering and choosing materials. Working with fusion machines requires a whole variety of different people with different skills, knowledge and backgrounds to work together.

Another approach is "inertial confinement" involving a small pellet containing the hydrogen isotopes. A shock wave is sent through the hydrogen, compressing and heating it. This creates the conditions needed for fusion. The shock wave can be produced by firing a projectile at the pellet or by using many laser beams. This achieves the conditions needed for fusion.

With either method, the reaction needs to be used to transfer energy in a useful way ("power extraction"). Effective power extraction remains a challenge in both magnetic and inertial confinement.

For magnetic confinement it works as follows. When fusion has been achieved, the reaction produces high speed neutrons. The charged nuclei and electrons are retained in the so-called magnetic confinement field, but the neutral neutrons escape the field and collide with the walls of the chamber. This heats up the chamber walls, which are cooled with a fluid of some sort. In future fusion plants, this process can be used to turn water into steam, driving a turbine. This is the same end process as with other kinds of power plant. Whether it's burning coal or using nuclear fission, most other power stations simply heat up water to make steam, making the turbine spin, producing electricity for the nationwide electricity network (often called "the grid")[3].

Companies and laboratories all over the world are actively working on fusion power. They are aiming to have a working fusion power plant that supplies the grid around 2040 and maybe even sooner!



Photograph of the JET tokamak. This image is taken from inside the ring-shaped chamber for confining the fusion plasma.

[3] For a demonstration of this: https://www.youtube.com/watch?v=MGj_aJz7cTs&ab_channel=BBCStudios

HOW CLOSE ARE WE TO "FUSION FOR ALL"?

Fusion won't be immediate. There are still challenges to overcome. For the first time practical fusion is within our reach because of the lessons we are learning from each generation of fusion machines. One of the key measures of success for a machine is the number of megawatts of power (million joules of energy per second) that its fusion reaction produces, compared to the number of megawatts of heating power needed to reach plasma temperatures.

The six challenges of fusion

1 PLASMA SCIENCE
Confining fusion in a plasma at temperatures ten times hotter than the sun's core.

2 PLASMA EXHAUST
Designing an exhaust system to deal with the intense heat from the plasma.

3 MATERIALS SCIENCE
Developing materials that can withstand the demanding conditions inside a fusion machine.

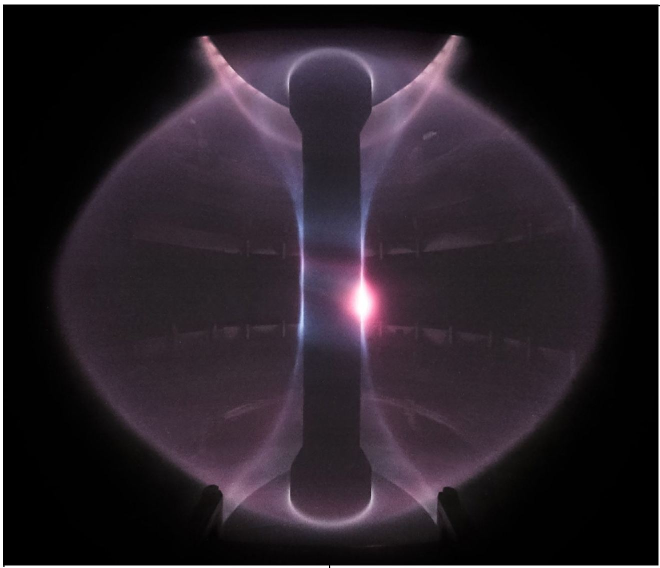
4 FUEL HANDLING
Breeding and handling tritium fuel to power commercial fusion power plants.

5 ROBOTIC MAINTENANCE
Maintaining the power plant entirely with robotics and remote maintenance thechniques.

6 INNOVATIVE ENGINEERING
Taking advantage of new engineering and manufacturing techniques to advance fusion development

The major challenges to overcome in the journey towards a fusion power station. To learn more, follow https://ccfe.ukaea.uk/research/research-challenges/

JET (Joint European Torus) is a fusion experiment in the UK that holds the record for fusion power produced by the magnetic confinement method. It was set up as a collaboration of European countries and is located in Oxfordshire at the Culham Centre for Fusion Energy. In 1997, JET produced 16 MW of power from the fusion reaction, but this was made possible by supplying some 24 MW of power to heat the plasma (it needed more power to be put in than was generated).



An image of the plasma inside the Mega Ampere Spherical Tokamak (MAST). The plasma glows blue in this image, showing the more compact shape of the chamber.

Experiments that followed include **MAST** – the Mega Ampere Spherical Tokamak, which ran on the same site at Culham from 1999 to 2013. The "spherical" nature of the tokamak refers to the compact shape of the containment field – more like a cored apple than JET's doughnut shape. The compact shape is designed to allow greater efficiency. A new project called **MAST Upgrade** began operating in 2020. It is based on the original MAST and is testing new features and better technologies.

ITER – ITER[4] is an international collaboration. The main collaborators are China, the European Union, India, Japan, Korea, Russia and the United States. The machine in the south of France is nearing completion and aims to make its first plasma in 2035. ITER will hold ten times the volume of plasma of any project so far. The project aims to provide a ten-fold return on power (500 MW of fusion power from only 50 MW of heating). No electricity will be produced, but ITER should pave the way for machines that can. The design for the first prototype fusion power stations, which will follow ITER and aim to supply the European electricity grids, goes by the name **DEMO**.

The UK's latest project is a prototype fusion power plant that goes by the name **STEP** – Spherical Tokamak for Energy Production. With a site chosen in Nottinghamshire, STEP should complete the design stages in 2024. The plasma chamber is a more compact shape than other projects, making it more efficient. STEP aims to produce 100 MW of electricity for the grid by 2040. A UK fusion company called **Tokamak Energy** is successfully running a spherical tokamak near Oxford. It has plans to build commercial power plants too.

Research into **inertial fusion** also continues at pace. In the USA, the National Ignition Facility is successfully achieving net energy output. A UK company called **First Light Fusion**[5] in Oxford made inertial fusion happen in 2022. It is planning a bigger machine and a power plant.

How close we are to "Fusion for All" depends on the success of these experiments and prototype power plants. However, the target for fusion remains on roughly the same timescale as the UK Government's net zero target of mid-way through this century. Fusion will work with renewables to provide the energy the world needs.

The journey to net zero, no matter the technology used to get there, will need people from all sorts of backgrounds and all sorts of skillsets from across the world. By 2050, cutting edge energy technology will be in the hands of people who are currently still in school or perhaps not even born yet!

So what will it take for you to be part of that journey?

Have a go at the activities in the rest of this pack to find out!

[4] Originally ITER was an acronym for "International Thermonuclear Experimental Reactor" playing on the latin word "iter" meaning "the way" or "the path". Today, the long form has been dropped and the project is just called ITER.

[5] https://firstlightfusion.com/technology/our-approach

WARM-UP ACTIVITIES

Instructions for Teachers

YOU WILL NEED:

- These activity instructions printed out or displayed on screen (to the whole class)
- The **ENERGY OPTIONS** information printed out or displayed on screen (to the whole class)

You will find the on-screen versions included elsewhere in this pack.

Question 1 - What would you do with an unlimited energy source?

Use the on-screen slide version if you wish. Ask the students to discuss the answer to the following question:

> ***Just imagine... Your energy bills cost you and your family no money at all, no matter what you do, you're not using up any of Earth's limited resources, and there's no pollution either! ...what are your wildest dreams?***

Have them discuss either in pairs or tables and then share their ideas with the whole class. The sillier and **more weird and wonderful** the better! They don't have to be realistic, it's just to get the ball rolling.

Question 2 – Let's get real.

Either give out printed copies of the ENERGY OPTIONS cards (pages 1 and 2 of the energy options document) or show the energy options slides on screen.

Ask your students to discuss in pairs which sources of energy (e.g. wind or nuclear) might be a good option to power their dreams. They may have to make some compromises depending on how weird and wonderful their ideas were to begin with!

Have them write down a couple of sentences about which source they picked and why

(e.g. "I picked solar power because it's renewable").

ACTIVITY SHEET 1

Question 1 What would you do with an unlimited energy source?

Just imagine... Your energy bills cost you and your family no money at all, no matter what you do, you're not using up any of Earth's limited resources, and there's no pollution either...**what are your wildest dreams?**

Discuss as a class, or in groups, and write and answer below.

Question 2 Let's get real.

Do you think there's a realistic way to power your dreams? Take a look at the energy technologies on the **ENERGY OPTIONS** card. If you made small changes to your wildest dreams, you might be able to power them using the technologies shown.

Which technology would you pick? What are the advantages? What are the disadvantages?

Discuss in groups, and write and answer below

Now go to the main activity on sheet 2

MAIN ACTIVITY

Instructions for Teachers

YOU WILL NEED:

- These activity instructions printed out or displayed on screen (to the whole class)
- The "What does a FUSIONeer do?" printed out or shown on laptop/tablet screens for each pair or group of students

You will find the on-screen versions included elsewhere in this pack.

Main Activity

Show students the wordcloud that says "Are you...?" (found on activity sheet 2 and in the on-screen activity document). Ask them to think about what skills and qualities they have, especially ones that might be useful in the world of work. Ask them to write down a few skills/qualities/personal attributes.

Give out printed copies of the "**What does a FUSIONeer do?**" cards, or make sure students can see a version on a laptop/tablet. These are profiles of people working in the fusion sector. Ask them to scan through and pick a profile of someone who sounds a little bit like them. Students should then write down what they have in common with the person they picked.

If any students don't feel they have anything in common with the people in the profiles, ask them instead to write down what sort of job they think their skills would make them good at.

Go round the students and discuss their answers with them. Introspection is hard - so help tease out an answer. However, no-one should feel bad if they don't see themselves as similar to the people in the profiles – everyone has different skills to offer the world.

Extension Activity

You can have the students discuss in groups what you think the future of the UK's energy sector might look like. Which energy sources do you think will become more useful, and which will be scaled back? How will this affect the way we live our lives?

ACTIVITY SHEET 2

Your part in the energy sector - what skills and qualities do you have?

fearless determined optimistic creative detail-oriented teamplayer observant approachable lateral-thinking supportive adaptable enthusiastic practical dedicated initiative finding friendly cooperative problem-solving inventive collaborative communicative curious people-focused specialist improving resilient

Have a think about yourself and what are you're good at. What skills and personal qualities do you have that would be useful for a job in the future?

Circle words on the wordcloud above, or write your answer below:

Read through the career profiles on the cards titled **"What does a FUSIONeer do?".** These people all have jobs linked to fusion – a promising energy source for the future. Choose one profile in particular – try and find someone whose skills and personal qualities sound a bit like you. What skills do you have in common with the profile you picked?

Write your answer here:

One day could you be working in the fusion sector, or the wider energy sector?

FIND OUT MORE

This activity pack is brought to you by The Fusion Cluster – a group of organisations working on fusion across the UK, led by the UK Atomic Energy Authority. Here are lots more ways to learn about fusion as an energy resource and how it fits into the picture of the world's future energy needs.

MORE ABOUT FUSION...

Culham Centre for Fusion Energy

For a series of short videos (between 1 and 4 min) about CCFE, go to the link below and start with "Introduction to Culham Centre for Fusion Energy" for an overview of the centre and an introduction to the key experiments JET and MAST Upgrade:
https://ccfe.ukaea.uk/resources/#publications
For information about arranging an in-person visit or virtual tour for you or your class go to:
https://ccfe.ukaea.uk/about-ccfe/visit-ccfe/

UKAEA

For lots of explainer videos about fusion visit the UK Atomic Energy Authority's youtube channel and look for the Fusion Tutorials:
https://www.youtube.com/@UKAEAofficial

The Fusion Cluster

To find out about the many different industry partners in the UK's fusion sector, visit The Fusion Cluster website, which includes a timeline of the history of fusion research:
https://thefusioncluster.com/what-is-fusion/

ITER

The international Fusion Education Initiative called "Infused" has produced educational materials around fusion, including games, blog posts, slideshows and videos:
https://www.iter.org/education/infused
There are even instructions on 3D-printing your own model of a fusion machine:
https://www.iter.org/newsline/-/3477

MORE ABOUT PHYSICS...

STFC

For teaching resources related to physics and the scientific research done in the UK, try these resources from the Science and Technology Facilities Council (STFC), including a poster called "Inside the Atom" about nuclear physics research:
https://www.ukri.org/what-we-do/teaching-resources/physics-teaching-resources/

MORE ABOUT STEM CAREERS...

Careers

There are lots of resources out there for careers advice. The STEM Learning Centre have put together lots of useful resources for students and teachers, from online careers fairs to arranging mentoring and placements. There's even a sector on "green careers" for those who want a job preserving or restoring our natural environment:
https://www.stem.org.uk/post-16/careers
You can also watch excellent videos, featuring technicians talking about their work in different areas of science and industry, from Gatsby Technicians:
https://vimeo.com/technicians
https://www.technicians.org.uk/

MORE ABOUT SUSTAINABLE ENERGY AND NET ZERO...

UN Sustainability Goals

The 17 Sustainable Development Goals set by the United Nations cover everything from tackling poverty and hunger to upholding human rights and gender equality. The three goals most relevant this pack are: number 7 - Affordable and clean energy, number 11 – Sustainable Cities and Communities, and number 13 – Climate Action. You can find out more about the rest of them at:
https://www.un.org/sustainabledevelopment/

Energy Dashboard

Live and historic data of the UK's energy source mix, including graphs and maps, going back to start of 2009. The interactive graphs show the seasonal generation of solar, wind, hydro, coal, and the change over time in the renewables, particularly wind.
https://www.energydashboard.co.uk/live

2022 summary of Britain's Sources of Electricity

Where does our electricity come from? Over the last ten years or so, we have largely stopped burning coal to make electricity, and instead we've seen a huge rise in wind power. 2022 saw records broken in wind power generation and low carbon electricity – to find out what that really means, read this summary from the company that operates our electricity network:
https://www.nationalgrideso.com/news/britains-electricity-explained-2022-review

Lifetime Emissions

Although technologies like wind, solar, and hydro power produce no CO_2 as part of normal operation, there are emissions associated with building the machinery, transport, and decommissioning. Altogether, the total emissions are called "lifetime emissions". This means most green energy sources are "low-carbon" rather than "zero-carbon", but they are still much less polluting than fossil fuels. Some good summaries are written here:
https://impactful.ninja/the-carbon-footprint-of-renewable-energy/
https://www.rocketsolar.com/learn/energy-efficiency/how-lifetime-emissions-different-energy-sources-stack
Although biomass is renewable (in the sense that plants can be regrown, for example), the lifetime emissions can vary a lot. In some cases, the transport of biomass over long distances (from the growing site to the power station) can ruin the savings in greenhouse emissions compared to burning fossil fuels:
https://www.theecoexperts.co.uk/blog/biomass-power-plant

Hydroelectric Power Worldwide

Britain uses very little hydroelectricity but worldwide, it is the largest renewable. The International Energy Agency's report summary here explains things:
https://www.iea.org/reports/hydropower-special-market-report/executive-summary

Traditional Nuclear Power Stations

Try this video from the BBC's youtube channel, including a demonstration of a steam turbine and a look inside a nuclear reactor core!
https://www.youtube.com/watch?v=MGj_aJz7cTs&ab_channel=BBCStudios
For a quick video with a diagram of how fission-powered nuclear plants work try this from the Nuclear Energy Institute in the US:
https://www.nei.org/fundamentals/how-a-nuclear-reactor-works

Car fuel types on UK roads

In early 2023 around 16% of new cars sold were fully electric:
https://shorturl.at/hCDN7
But with so many second-hand cars on the road, the majority of cars are still fuelled by petrol or diesel:
https://shorturl.at/sCEHJ