**Fusion energy**

**Introduction to fusion**


Nuclear fusion is one of the most promising options for generating large amounts of carbon-free energy in the future.

Fusion is the process that heats the Sun and all other stars, where atomic nuclei collide together and release energy (in the form of neutrons, see diagram on the right). Fusion scientists and engineers are developing the technology to use this process in tomorrow's power stations.

To get energy from fusion, gas from a combination of types of hydrogen – deuterium and tritium – is heated to very high temperatures (100 million degrees Celsius). One way to achieve these conditions is a method called ‘magnetic confinement' – controlling the hot gas (known as a plasma) with strong magnets. The most promising device for this is the ‘tokamak', a Russian word for a ring-shaped magnetic chamber.

*See also:* [***How fusion works***](http://www.fusion.org.uk/How_fusion_works.aspx)

**Advantages of fusion power**

The world needs new, cleaner ways to supply our increasing energy demand, as concerns grow over climate change and declining supplies of fossil fuels. Power stations using fusion would have a number of advantages:

* *No carbon emissions.* The only by-products of fusion reactions are small amounts of helium, which is an inert gas that will not add to atmospheric pollution.
* *Abundant fuels.* Deuterium can be extracted from water and tritium is produced from lithium, which is found in the earth's crust. Fuel supplies will therefore last for millions of years.
* *Energy efficiency.* One kilogram of fusion fuel can provide the same amount of energy as 10 million kilograms of fossil fuel.
* *No long-lived radioactive waste.* Only plant components become radioactive and these will be safe to recycle or dispose of conventionally within 100 years.
* *Safety.* The small amounts of fuel used in fusion devices (about the weight of a postage stamp at any one time) means that a large-scale nuclear accident is not possible.
* *Reliable power.* Fusion power plants should provide a baseload supply of large amounts of electricity, at costs that are estimated to be broadly similar to other energy sources.

*See also:* [***Why fusion is needed***](http://www.fusion.org.uk/Why_fusion.aspx)

**Progress in fusion research**

Many of the scientific hurdles in fusion have now been overcome by researchers. The world's largest tokamak, [**JET (Joint European Torus)**](http://www.jet.efda.org), has produced 16 megawatts of fusion power and proved the technical feasibility of fusion using deuterium and tritium, currently considered the most efficient fuels. The challenge now is to prove fusion can work on a power plant scale.

**The next steps**

International fusion research is following a roadmap to achieve power generation within 30 years. It focuses on three main projects:

* [**ITER**](http://www.iter.org) – a multinational project that is being built in the south of France. ITER will be a 500 megawatt tokamak (equivalent to a small power plant) and aims to confirm that fusion power will be possible on a commercial scale;
* IFMIF (International Fusion Materials Irradiation Facility) – a device that will test the materials needed in a fusion power station, planned to operate in parallel with ITER;
* DEMO – a demonstration power plant supplying fusion electricity to the grid. This is being designed now and would be constructed during ITER and IFMIF operation. If successful, it will be followed by the first generation of commercial fusion power stations.

*See also:* [***Achieving fusion power***](http://www.fusion.org.uk/Fusion_power.aspx)

**Fusion in the UK**

*The United Kingdom's fusion research programme is based at Culham Centre for Fusion Energy (CCFE) in Oxfordshire. The work is funded by the* [***Engineering and Physical Sciences Research Council***](http://www.epsrc.ac.uk/) *and by the European Union under the Euratom treaty.*

*The UK contributes to fusion research in two main ways:*

* *Its own fusion programme, centred on the* [***MAST (Mega Amp Spherical Tokamak)***](http://www.fusion.org.uk/MAST.aspx) *device. The UK programme also makes important contributions to ITER preparations and to theory, materials and technology research;*
* *Operating JET, Europe's flagship experiment. JET is situated at CCFE next to the UK's fusion laboratory. CCFE operates the JET facility on behalf of all the partners in the* [***European Fusion Development Agreement***](http://www.efda.org/)*.*

 *See also:* [***Research at CCFE***](http://www.fusion.org.uk/Research.aspx)

## Why fusion is needed

New, environmentally sustainable forms of electricity will be required to meet the aspirations of a growing world population.

By 2050, an expected rise in global population from six billion to nine billion and better living standards could lead to a two to threefold increase in energy consumption.

No single technology will fulfil this demand. Each has strengths and weaknesses, and a mix of power sources will be needed to meet the challenges of energy security, sustainable development and environmental protection. Future energy supply options may comprise fossil fuels, nuclear fission, fusion, and renewables.

At present, 80% of the developed world's energy comes from fossil fuels. Environmental problems – the greenhouse effect and the effects of acidic pollution – and diminishing fuel supplies mean that reliance on coal, gas and oil will have to be severely constrained.

Nuclear fission will continue to make a major contribution to electricity generation but its growth could be curtailed by issues of public and political acceptability. Supplies from renewable sources are reliant on environmental conditions, and are therefore not guaranteed to be constant. They are also subject to technology challenges of energy storage. To provide constant baseload electricity, predictable, non-varying sources of energy are needed. This means a short-term reliance on fossil fuels and fission and then the addition of fusion power as soon as it becomes available.

Fusion offers a secure, long-term source of supply, with important advantages. These include: no production of greenhouse gases from the fusion process; no long-lived radioactive waste (all waste will be recyclable within 100 years); inherent safety features; and almost unlimited fuel supplies. On current estimates, the cost of fusion-generated electricity is predicted to be broadly comparable to that obtained from fission, renewables and fossil fuels.

Fusion, therefore, could have a key role to play in the energy market of the future, with the potential to produce at least 20% of the world's electricity by 2100.

## How fusion works

In a fusion reaction, energy is released when two light atomic nuclei are fused together to form one heavier atom. This is the process that provides the energy powering the Sun and other stars, where hydrogen nuclei are combined to form helium.

To achieve high enough fusion reaction rates to make fusion useful as an energy source, the fuel (two types of hydrogen – deuterium and tritium) must be heated to temperatures over 100 million degrees Celsius. At these temperatures the fuel becomes a plasma.

This incredibly hot plasma is also extremely thin and fragile, a million times less dense than air. To keep the plasma from being contaminated and cooled by contact with material surfaces it is contained in a magnetic confinement system.

Magnetic confinement is the approach that Culham and many other laboratories are researching to provide energy from fusion. A plasma of light atomic nuclei is heated and confined in a circular bottle known as a tokamak, where it is controlled with strong magnetic fields.

In a magnetic fusion device, the maximum fusion power is achieved using deuterium and tritium. These fuse to produce helium and high-speed neutrons, releasing 17.6MeV (megaelectron volts) of energy per reaction. This is approximately 10,000,000 times more energy than is released in a typical chemical reaction. A commercial fusion power station will use the energy carried by the neutrons to generate electricity. The neutrons will be slowed down by a blanket of denser material surrounding the machine, and the heat this provides will be converted into steam to drive turbines and put power on to the grid.

###### Animation of the fusion reaction



(Courtesy of [**www.efda.org**](http://www.efda.org))

**The tokamak**

The tokamak is the most developed magnetic confinement system and is the basis for the design of future fusion reactors using this method. It was invented in the Soviet Union during the 1960s and soon adopted by researchers around the world. The Joint European Torus (JET – pictured), located at Culham Centre for Fusion Energy, is the largest and most powerful tokamak currently operating.

The main tokamak components and functions are as follows:

* The plasma is contained in a *vacuum vessel*. The vacuum is maintained by external pumps. The plasma is created by letting in a small puff of gas, which is then heated by driving a current through it.
* The hot plasma is contained by a *magnetic field* which keeps it away from the machine walls. The combination of two sets of magnetic coils – known as toroidal and poloidal field coils – creates a field in both vertical and horizontal directions, acting as a magnetic ‘cage' to hold and shape the plasma.
* Large *power supplies* are used to generate the magnetic fields and plasma currents.
* *Plasma current* is induced by a transformer, with the central magnetic coil acting as the primary winding and the plasma as the secondary winding. The heating provided by the plasma current (known as Ohmic heating) supplies up to a third of the 100 million degrees Celsius temperature required to make fusion occur.
* Additional plasma heating is provided by *neutral beam injection*. In this process, neutral hydrogen atoms are injected at high speed into the plasma, ionized and trapped by the magnetic field. As they are slowed down, they transfer their energy to the plasma and heat it.
* *Radiofrequency heating* is also used to heat the plasma. High-frequency oscillating currents are induced in the plasma by external coils or waveguides. The frequencies are chosen to match regions where the energy absorption is very high (resonances). In this way, large amounts of power may be transferred to the plasma.

Take a closer look at the technology of tokamaks with our [**interactive model of the MAST device**](http://www.fusion.org.uk/MAST_diagram.aspx).

**Diagram of magnetic confinement in a tokamak**



# Fusion energy

## Achieving fusion power

Fusion is expected to become a major part of the energy mix during the second half of this century. With adequate funding, the first fusion power plants should be operating by 2040. To achieve this, a series of development steps need to be taken.



### ITER

ITER is the next major international fusion experiment and a crucial step towards commercial fusion energy. It is expected to prove the feasibility of electricity generation from fusion by releasing some 500 megawatts of fusion power (from a 50 megawatt input) for up to 500 seconds. It will be the first fusion experiment to produce net power – ten times more than the amount required to heat the plasma.

A truly global undertaking, the participants in ITER represent more than half the world's population: China, the European Union, India, Japan, South Korea, Russia, and the United States of America. It is the world's largest international co-operative scientific research and development project.

The ITER site is next to an existing energy research site at Cadarache in southern France. An international team is now constructing the machine, with the first plasma expected in 2019. This will be followed by a 20-year period of operation that will test essential physics and technologies for the fusion power plants of the future.

More information on the UK's contributions to ITER preparations is in the [**Research**](http://www.fusion.org.uk/ITER.aspx) section.

Full details on the project are at the [**ITER website**](http://www.iter.org).

### IFMIF

Selecting the right materials for commercial fusion plants will be crucial. The metals used in tokamaks will need to withstand the extreme conditions produced by high-energy fusion neutrons.

In parallel with ITER, IFMIF (the International Fusion Materials Irradiation Facility) will be constructed to test materials for future fusion power plants against neutron damage and irradiation. IFMIF is a particle accelerator that will produce high-energy neutrons and fire them at samples of materials identified as suitable for the walls of commercial tokamaks. Completion of IFMIF's design is now being taken forward as a joint European/Japanese project and a site for the facility is being identified, with operations planned to start in 2017.

### DEMO

Once the scientific and engineering systems have been tested on ITER and IFMIF, the next stage will be to build a demonstration fusion power plant integrating the results. Designs are already advanced for this prototype machine, known as ‘DEMO'.

DEMO will produce two gigawatts of electrical power to the grid, a similar output to a standard electrical power plant, and could be online in the 2030s. If successful, it will lead to the first generation of commercial fusion power stations.

###### Components of a fusion power plant


(Courtesy of [**www.efda.org**](http://www.efda.org))

* [Introduction to fusion](http://www.fusion.org.uk/introduction.aspx)
* [Why fusion is needed](http://www.fusion.org.uk/Why_fusion.aspx)
* [How fusion works](http://www.fusion.org.uk/How_fusion_works.aspx)
* [The tokamak](http://www.fusion.org.uk/Tokamak.aspx)
* [**Achieving fusion power**](http://www.fusion.org.uk/Fusion_power.aspx)
* [Frequently Asked Questions](http://www.fusion.org.uk/FAQ.aspx)
* [Support fusion research](http://www.fusion.org.uk/Support_fusion.aspx)

**Fast track to fusion**

[A report on how commercial fusion power can be achieved. It contains the findings of a panel of experts chaired by former UK Government Chief Scientist Sir David King (PDF file)](http://www.fusion.org.uk/assets/Documents/fasttrack.pdf)

**Fusion power plant video**

[A fly-through animation based on designs from recent European fusion power plant studies.](http://www.ccfe.ac.uk/videos.aspx?currVideo=17&currCateg=0)

## Frequently Asked Questions

Below are questions that we are often asked about fusion power, mainly by sixth-form students, and our answers. If you have a question to ask, please use [**this form**](http://www.fusion.org.uk/contact_us.aspx#Contact_online) and we will reply as soon as possible.

* [**How is the plasma contained?**](http://www.fusion.org.uk/FAQ.aspx#Contained)
* [**How are the very high temperatures achieved?**](http://www.fusion.org.uk/FAQ.aspx#Temperatures)
* [**Why are toroidal devices used?**](http://www.fusion.org.uk/FAQ.aspx#Toroidal)
* [**How do charged particles escape from the magnetic field?**](http://www.fusion.org.uk/FAQ.aspx#Escape)
* [**What are the dominant costs foreseen in a fusion power plant?**](http://www.fusion.org.uk/FAQ.aspx#Costs)
* [**Are the fuel costs significant?**](http://www.fusion.org.uk/FAQ.aspx#Fuel)
* [**How is deuterium obtained from water?**](http://www.fusion.org.uk/FAQ.aspx#Deuterium)
* [**Where is lithium found?**](http://www.fusion.org.uk/FAQ.aspx#Lithium)
* [**Is any use made of advances in superconductors?**](http://www.fusion.org.uk/FAQ.aspx#Superconductors)
* [**Is the depletion of water significant?**](http://www.fusion.org.uk/FAQ.aspx#Depletion)
* [**Is the atmospheric pollution due to helium significant?**](http://www.fusion.org.uk/FAQ.aspx#Helium )
* [**What is the power input to the fusion reactor used for?**](http://www.fusion.org.uk/FAQ.aspx#Input)
* [**How is electrical energy created from the reactors (heat)?**](http://www.fusion.org.uk/FAQ.aspx#Electrical)
* [**Are there any negative safety or environmental implications of a fusion reactor?**](http://www.fusion.org.uk/FAQ.aspx#Safety)
* [**Do you think that fusion is a viable energy resource for the 21st century?**](http://www.fusion.org.uk/FAQ.aspx#Viable)
* [**How much energy could you get from a litre of water compared with a litre of petrol?**](http://www.fusion.org.uk/FAQ.aspx#Litre)
* [**Could fusion be powered by other hydrogen isotopes or other light elements?**](http://www.fusion.org.uk/FAQ.aspx#Hydrogen)
* [**How much fuel would a fusion power plant consume in a day?**](http://www.fusion.org.uk/FAQ.aspx#Day)
* [**Can the economic cost of fusion's environmental impact be estimated, including the costs of constructing and dismantling the power plant?**](http://www.fusion.org.uk/FAQ.aspx#Economic)
* [**When can we expect electricity generated from fusion to be available?**](http://www.fusion.org.uk/FAQ.aspx#Electricity)

###### How is the plasma contained?

A helical magnetic field of typically a few Tesla at the centre is sufficient to provide good insulation from the material surfaces and to balance the plasma pressure. This allows the low density of the plasma to be heated to the very high temperatures required for fusion. The combination of very high temperature and low density leads to a plasma pressure comparable to atmospheric pressure.
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###### How are the very high temperatures achieved?

The magnetic field provides insulation some 40 times better than loft insulation and is up to ten times thicker. With such good insulation, the application of high power (in the megawatt range) leads to very high temperatures, above 100 million degrees Celsius.
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###### Why are toroidal devices used?

The effect of the magnetic field is to confine the charged plasma particles by applying a force that opposes the motion across the field. There is no such force in the direction parallel to the magnetic field so, if the magnetic field lines were to connect the ends of a linear device, for instance, particles would be able to escape rapidly to the ends. In a toroidal device, the particles primarily spiral along the field lines, travelling around the machine typically a million times before escaping.
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###### How do charged particles escape from the magnetic field?

Although the forces applied to the charged particles are such as to prevent them moving to the plasma edge, the effect of collisions and turbulence is to lead to a random walk of particles, reaching the plasma edge in around one second.
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###### What are the dominant costs foreseen in a fusion power plant?

As you might expect in a magnetic confinement system, the largest cost item is anticipated to be the superconducting magnets. The next largest cost is anticipated to be the buildings needed to house the plant. These two items together are estimated to make up more than half of the cost of a fusion power plant. There is the expectation that the cost of superconducting magnets will reduce with time.
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###### Are the fuel costs significant?

The fusion energy obtained from each kg of fuel is very high (ten million times higher than from fossil fuels) so the fuel costs are a very small part of the expected costs. Using present costs, the fuel would contribute much less than 1% to the cost of electricity.
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###### How is deuterium obtained from water?

The conventional method of concentrating deuterium in water uses isotopic exchange in hydrogen sulphide gas, although more advanced techniques are being developed. Separation of different isotopes of hydrogen can also be done using gas chromatography and cryogenic distillation, which use the differences in physical properties to separate the isotopes.
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###### Where is lithium found?

Lithium is a light alkali metal found in several different minerals, such as spodumene. It can also be extracted from brines and clays, Natural deposits are particularly found in South America. It is presently widely used in batteries.
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###### Is any use made of advances in superconductors?

Most experimental devices do not use superconducting magnets since the required experimental plasmas, lasting less than one minute, can be achieved without the additional complexity. Those experiments that do use superconducting magnets have so far relied on conventional technology.
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###### Is the depletion of water significant?

Deuterium represents approximately 0.015% of hydrogen in water. Even so, there is enough deuterium to generate present levels of energy consumption for billions of years. Depletion of water is not an issue.
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###### Is the atmospheric pollution due to helium significant?

Because of the large amount of energy produced per unit mass of fuel, the production of helium is rather low, ten million times less than the CO2 production of an equivalent fossil fuel power plant. If the whole world's energy requirements were met by fusion, the helium production would still be small compared to the present helium production of around 25,000 tonnes per year.
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###### What is the power input to the fusion reactor used for?

The best existing experiments need as much power to heat the plasma as they produce in fusion power. In a power plant, which would be larger, the fusion power would be around 20 to 30 times higher than the heating power.
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###### How is electrical energy created from the reactors (heat)?

In a future power plant, it is envisaged that the heat from a fusion power plant would generate electricity in just the same way as existing power plants, in which the heat is used to raise steam, driving turbines. The possibility of using the plasma energy more directly has been considered but does not seem practical.
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###### Are there any negative safety or environmental implications of a fusion reactor?

It is an intrinsic property of fusion that enables power plants to be designed that are inherently safe with low environmental impact. Extensive studies over the last decade have shown that no internally-generated accident could result in the need to evacuate public from outside the site, and that the waste products from fusion power will not be a burden for future generations.
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###### Do you think that fusion is a viable energy resource for the 21st century?

Fusion provides one of the few options for future baseload electricity generation and it is essential that we develop it, along with other sources, particularly renewables. We cannot reliably predict the future, but the trends towards less polluting energy sources are clear and we must do our best to establish ways of electricity production that are consistent with those trends.
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###### How much energy could you get from a litre of water compared with a litre of petrol?

One litre of ordinary water contains enough deuterium to provide the energy content (when fused with tritium) of more than 500 litres of petrol.

What is the calculation that shows, in terms of binding energies, that 17.6 MeV of energy is released per colliding D-T pair, and why is it split 14.1/3.5 between the neutron and the alpha particle?

The masses of the particles concerned, in terms of the proton mass are:

|  |  |
| --- | --- |
| D | 1.99900 |
| T | 2.99371 |
| alpha | 3.97260 |
| neutron | 1.00138 |

The gain is that the alpha is more tightly bound. The net energy gain is mc2, where the mass difference is 0.01873 proton masses. This gives 17.6 MeV (or 2.8x10-12 J) per reaction. In order to conserve momentum, the heavier alpha particle must take a smaller part of the energy (smaller by the ratio of alpha to neutron mass, that is 1:4 ).
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###### Could fusion be powered by other hydrogen isotopes or other light elements?

Yes. We concentrate on fusion of deuterons and tritons for energy production as it is the easiest way we know of getting a net energy gain. We have also investigated D-D and D-3He. Other reactions are demonstrated in the sun, for instance p-p, D-p, 3He-3He. There are a large number of possible fusion reactions, other than D-T, that produce energy. However, their usefulness in a terrestrial power source remains to be demonstrated.
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###### How much fuel would a fusion power plant consume in a day?

A large power station generating 1,500 megawatts of electricity would consume approximately 600 grammes of tritium and 400 grammes of deuterium each day.
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###### Can the economic cost of fusion's environmental impact be estimated, including the costs of constructing and dismantling the power plant?

Yes, estimates are made using the method developed by the EU's ExternE project. This considers the total environmental impact of power production, from the original extraction of materials, through to the operation and subsequent recycling/dismantling of the facility. This is done by associating a cost to everything from CO2 emissions to accidents at work. The conclusions in published work have been very favourable, with fusion estimated to be considerably less harmful than conventional oil, coal, and gas.
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###### When can we expect electricity generated from fusion to be available?

Experimental fusion machines have now produced fusion powers of more than ten megawatts. A new machine under construction, called ITER, will be capable of producing 500 megawatts of fusion power. ITER is expected to start operating in 2019. Although it will be on the scale needed for a power station, there will still be technological issues to address to produce steady, reliable electricity, so it is anticipated that a prototype power station will be needed after ITER. Electricity generation is expected in 30 to 40 years, depending on funding and technical progress.
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* [Support fusion research](http://www.fusion.org.uk/Support_fusion.aspx)

## Support fusion research

If you would like to support fusion research, here are some ways you can help:

### Join our Fusion Fanclub

[**Click here**](http://www.fusion.org.uk/registration.aspx) to sign up for Culham Centre for Fusion Energy's quarterly email newsletter with updates on events, campaigns and news on fusion research progress.

### Fusion on Facebook and Twitter

Joining [**Culham Centre for Fusion Energy's Facebook group**](http://www.facebook.com/home.php#/pages/Culham-Centre-for-Fusion-Energy/163104564319) and [**Twitter feed**](http://twitter.com/fusionenergy) is a good way to show support for fusion, receive news and debate energy issues. Please spread the word and encourage others to sign up too.

### Give a talk on fusion

If you would like to give a talk on fusion to a group or organisation, here is a presentation with useful facts and figures, in Powerpoint and Adobe PDF format.

[**Fusion presentation – Powerpoint file (3435kbs)**](http://www.fusion.org.uk/assets/Documents/Fusion%20presentation.ppt)
[**Background information on fusion – PDF file (57kbs)**](http://www.fusion.org.uk/assets/Documents/fusion_energy.pdf)

### Letters, online debates and blogs

Writing letters to the press and adding comments on energy-related news stories on the web or in discussion forums are also ways to tell people about fusion's potential. And if you have a blog, why not inform your readers about fusion?