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2011 Technology Map
of the European Strategic Energy Technology Plan (SET-Plan)

Technology Descriptions

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Institute for Energy and Transport

SETIS PROVIDING INFORMATION FOR DECISION-MAKING

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SET-Plan Information System (SETIS)

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Preamble

The swift deployment on a large scale of technologies with a low-carbon footprint in the European energy system is a prerequisite for the transition to a low-carbon society - a key strategic objective of the European Union. A necessary condition for the timely market roll-out of these low-carbon energy technologies is an acceleration of their development and demonstration. This is catalysed by the European Strategic Energy Technology Plan (SET-Plan) through the streamlining and amplifying of the European human and financial resources dedicated to energy technology innovation. SETIS, the SET-Plan information system, has been supporting SET-Plan from its onset, providing referenced, timely and unbiased information and analyses on the technological and market status and the potential impact of deployment of low-carbon energy technologies, thereby assisting decision makers in identifying future R&D and demonstration priorities which could become focal areas for the SET-Plan.

The Technology Map is one of the principal regular deliverables of SETIS. It is prepared by JRC scientists in collaboration with colleagues from other services of the European Commission and with experts from industry, national authorities and academia, to provide:

- a concise and authoritative assessment of the state of the art of a wide portfolio of low-carbon energy technologies;
- their current and estimated future market penetration and the barriers to their large-scale deployment;
- the ongoing and planned R&D and demonstration efforts to overcome technological barriers; and,
- reference values for their operational and economic performance, which can be used for the modelling and analytical work performed in support of implementation of the SET-Plan.

This third edition of the Technology Map, i.e. the 2011 update, addresses 20 different technologies, covering the whole spectrum of the energy system, including both supply and demand technologies. The transport sector has however not been addressed, as this has been the focus of the European Strategic Transport Plan, which, at the time of writing, is under development.

Feedback from the previous editions has shown that the Technology Map has been used by national authorities for setting their own R&D and demonstration priorities; and by the research community as a source of authoritative information on energy technologies. We hope that this edition will continue to serve this purpose, whilst at the same time, serving as an invaluable tool for the ongoing implementation of the SET-Plan.

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11. Nuclear Fusion Power Generation

11.1. Introduction

Although nuclear fusion is unlikely to be ready for commercial power generation in the coming decades, it remains nevertheless an attractive energy solution and arguably, the only truly sustainable option for large-scale baseload supply in the long-term. If the research and development in fusion energy deliver the advances predicted, then it will continue on a steady course to achieve this aim in the second half of this century.

Fusion energy's many benefits include an essentially unlimited supply of cheap fuel, passive intrinsic safety and no production of CO_2 or atmospheric pollutants. Compared to nuclear fission, it produces relatively short-lived radioactive products, with the half-lives of most radioisotopes contained in the waste being less than ten years, which means that within 100 years, the radioactivity of the materials will have diminished to insignificant levels.

Fusion energy production has already been demonstrated by the European flagship experiment, the Joint European Torus (JET).[22] The next step on the path to fusion energy is the international project International Thermonuclear Experimental Reactor (ITER),[23] which is under construction at Cadarache (France), see Figure 11.1. It aims to carry out its first experiments before the end of the decade and in the following years it should demonstrate the scientific and technical feasibility of fusion energy. Europe is financing about 45 % of the total construction cost, with one-fifth of this from France as the host state and four-fifths from the EU. The remainder is split between the other six participants (China, India, Japan, South Korea, Russia and USA). The EU Council has capped the EU contribution to ITER construction at EUR 6.6 billion[24] for the period 2007-2020, including about EUR 600 million for associated costs. Most of the hardware is being supplied as in-kind contributions from the seven ITER Parties. Cash contributions from the Parties cover the ITER Organisation's running costs and some centralised hardware procurements. The successful operation of ITER is expected to lead to the go-ahead for the following step, a Demonstration Power Plant (DEMO), which would aim to demonstrate the commercial viability of fusion by delivering fusion power to the grid by 2050.

Figure 11.1: The ITER site in Cadarache (September 2011, preparatory work is well underway) [Source: ITER/Altivue]

11.2. Technological state of the art and anticipated developments

Nuclear fusion occurs when the nuclei of atoms collide with one another and bind together. This releases large amounts of energy, which can be converted to heat and used to generate electricity as with other thermal power plants. The most efficient fusion reaction to use on earth is that between the hydrogen isotopes, deuterium (D) and tritium (T), which produces the highest energy at the 'lowest' (although still extremely high) temperature of the reacting fuels.

For the fusion reaction to occur, the nuclei need to be brought very close together. If the atoms of a gas are heated, the motion of the electrons and the

[22] http://www.jet.efda.org
[23] http://www.iter.org
[24] The modalities for the provision of this funding during the next Multi-Annual Financial Framework are still being developed. In the shorter term, the mechanisms by which an additional EUR 1.3 billion can be provided in 2012 and 2013 (above the originally planned amount for this period, but within the EUR 6.6 billion cap) is being discussed by the EU Council and Parliament.

nuclei will increase until the (negatively charged) electrons have separated from the (positively charged) nuclei. This state, where nuclei and electrons are no longer bound together, is called plasma. Heating the plasma further to temperatures in the range of 100-200 million °C, results in collisions between the nuclei being sufficiently energetic to overcome the repulsive force between them and to fuse. Experiments such as JET and ITER use the favoured "magnetic confinement" approach to fusion, in which strong magnetic fields confine the plasma - no solid material is able to confine a plasma at such high temperatures. The aim is that the plasma should maintain its high temperature over long periods from the heat generated by the fusion reactions. Producing and maintaining a plasma with the necessary high temperature and sufficiently high density, is a challenging problem, requiring for example "additional heating" systems which can inject very high power into the plasma. Results from existing experiments give confidence that this can be done successfully in ITER.

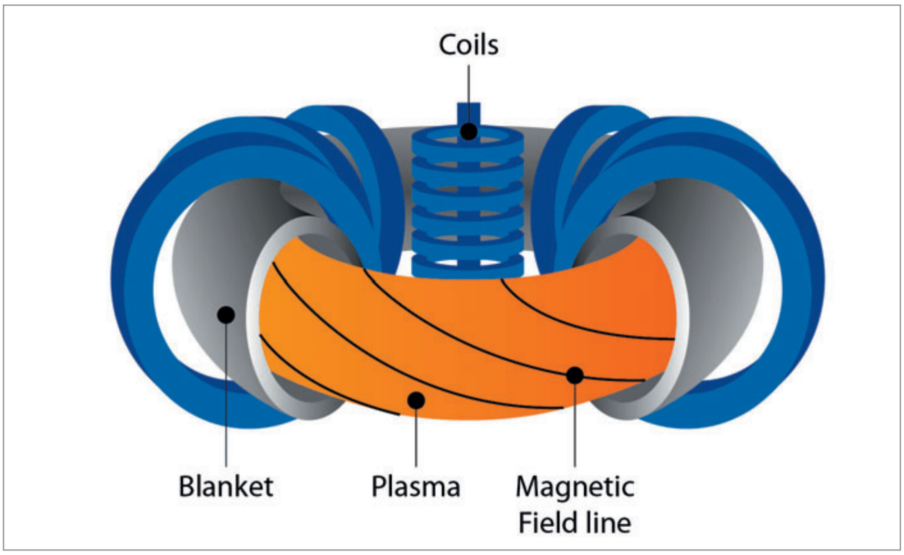

Figure 11.2: Principle of a tokamak [Source: EFDA]

The best developed magnetic confinement device is the tokamak, where a magnetic field is used to confine a plasma in the shape of a torus (doughnut), see Figure 11.2.

The Joint European Torus (JET) located in Culham in the UK, was the first tokamak in the world to be operated with the deuterium and tritium fuels. However, even the most successful experiments in JET still need more input energy than is produced by the fusion reactions. The main purpose of JET is to open the way to future nuclear fusion experimental reactors such as ITER, which will enable scientists to study plasmas under conditions similar to those expected in a future power plant. ITER will be the first fusion experiment to produce power gain, aiming for ten times more fusion power than input power into the plasma. Although the fusion power in ITER should reach some 500 MW for hundreds of seconds at a time, the investment required to produce very limited amounts of electricity is not worthwhile. Rather, the scientific and technical knowledge gained in ITER will provide the basis on which the following step, the Demonstration Power Plant (DEMO) will be built. DEMO should operate at high fusion power for long periods, so that the demonstration of reliable electricity generation will be possible.

While ITER is being constructed and DEMO is in its conceptual phase, a number of fusion installations, with different characteristics and objectives, will continue to operate around the world to conduct complementary research and development in support of ITER. Fusion research in Europe has evolved through a number of generations of devices. Several of these, although smaller than JET and not able to operate with the real fusion fuels, deuterium and tritium, continue to make important contributions.

Outside Europe, a number of countries are pursuing the tokamak approach. Both the USA and Russia have been major players in fusion research since the early days - the tokamak concept was first developed in the Soviet Union at the end of the 1960s. Japan also has a substantial fusion R&D programme. More recently, China has shown an impressive ability to develop its fusion research capacity and has constructed a tokamak using superconducting coils to generate the magnetic fields. It started its experimental programme in September 2006. A South Korean tokamak is intended to study aspects of magnetic confinement fusion, as part of that country's contribution to the ITER effort. India is a relative newcomer to this field, but like the others, has joined ITER since it will provide the best way to move the research forward quickly with shared costs and risks.

The research into fusion devices other than the tokamak is centred mainly on stellarators, which is considerably more complex to design and build, but which may have significant operational advantages. A large, advanced stellarator is currently under construction in Germany, and it is anticipated that its results will be used to optimise the DEMO design.

An alternative to magnetic confinement is the so-called "inertial confinement" approach to fusion in which extremely high power, short pulse lasers are used to compress a small pellet of fuel to reach fusion conditions of density and temperature. Major facilities have been constructed in France and the USA, but primarily for military purposes since the micro-explosions of inertial fusion model the processes in nuclear weapons. The lasers used in these experiments fall far short of the necessary efficiency and repetition rate which would be needed for a fusion power plant. This issue, nevertheless, will be a primary focus of an experiment being proposed in the UK, called HiPER.

In addition to the plasma devices, fusion research employs a number of facilities to study the technologies needed for fusion. The most challenging area of fusion technology is to develop materials suitable for the lining of the reactor, so-called "plasma facing" materials, which must maintain structural integrity under strong thermal and nuclear loads. In Japan, the engineering design phase of the International Fusion Materials Irradiation Facility (IFMIF) has begun. This installation, part of the "Broader Approach" Agreement between Europe and Japan, will test and qualify the advanced materials needed for DEMO and future fusion plants.

Costs

Many studies have been carried out to estimate the cost of fusion generated electricity. When trying to predict costs of power plants decades in advance, huge uncertainties are to be expected and consequently the cost range fluctuates drastically. A study by the Socio-Economic Research on Fusion (SERF) estimated a projected cost-of-electricity (COE) of €0.165/kWh [Borrelli et al., 2001], where COE is the sum of the capital costs for the fusion core (39 %) and the rest of the plant (23 %), the costs for the replacement of diverter and blanket during operation (30 %), fuel, operation, maintenance and decommissioning (8 %), assuming an annual load factor of 75 %, an operating lifetime of 30 years and a real interest rate (corrected for inflation) of 5 %, and based on expected investment costs for DEMO of roughly €10 000/kW (1995). A paper from 2002 [Cook et al, 2002] shows how the internal COE from a fusion power station depends on the extent to which the plasma physics and materials technology of fusion are optimised as a result of further R&D. The paper shows that the projected internal cost of fusion electricity is in the range $0.07-0.13/kW (in 1996 dollars). It is concluded broadly that the expected internal costs of fusion electricity are competitive with typical renewables (without storage costs) and about 50 % greater than coal (without emission abatement costs) or fission.

A study by Maissonnier [2007] using a mathematical model with the latest data on costs and varying the free parameters of the design so as to minimise the cost of electricity, concluded that the costs to supply electricity from fusion varies between €0.03-0.09/kWh. This would make fusion power competitive with other sources of energy. An earlier paper by Ward [Ward et al., 2005], stated that a mature fusion technology could supply electricity in the range €0.03-0.07/kWh.

11.3. Market and industry status and potential

Fusion energy differs from all other low-carbon energy technologies, in that it will not make any viable and commercial contribution into the electricity grid until after 2050. Nevertheless, with the continued progress in ITER and the increased in-kind contributions from the partner countries, this suggests an industrial involvement would be expected, especially regarding DEMO, where it is essential that industry contributes strongly to the DEMO design team from an early stage, in addition to industry's key role in ITER construction and operation. A timeline overview of fusion technology is shown in Figure 11.3.

Installed capacity

It is premature to speculate about the situation in 2050, but the current planning foresees fusion starting to be rolled out on a large-scale around the middle of the century. There do not appear to be any resource issues that would prevent fusion being deployed at least as rapidly as fission was deployed after the mid-20th century, given the will and the funding to do so.

Cooperation

To combat the challenges of fusion energy, the European Fusion Development Agreement (EFDA) was created in 1999 to provide a framework between European fusion research institutions and the European Commission in order to strengthen their coordination and collaboration and to participate in collective activities [Fusion news, 2009]. EFDA

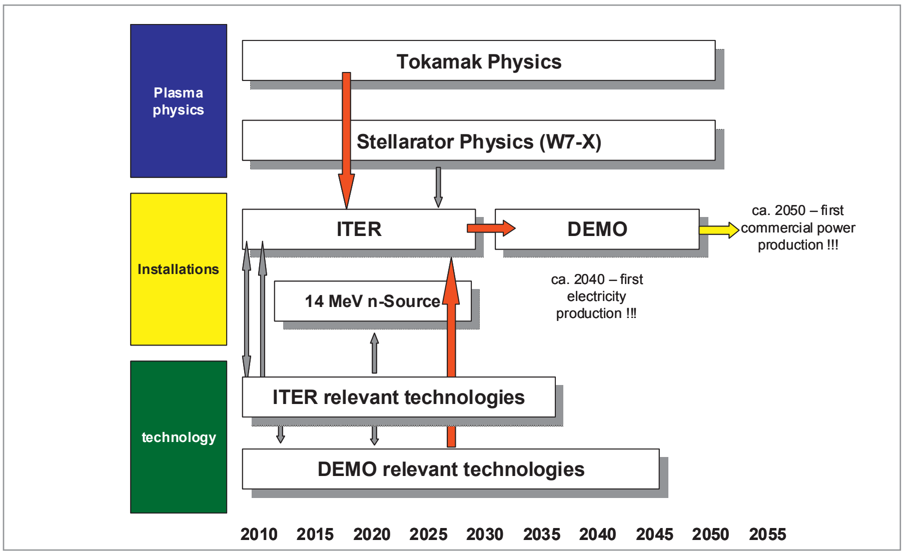

Figure 11.3: Fusion energy research and development timeline [Source: Stand der Fusionstechnik, Prof. Dr. Günther Hasinger, Max-Planck Institute for plasma physics, Garching Germany.]

is responsible for the exploitation of JET, the coordination and support of fusion-related R&D activities carried out by the Associations and European Industry, and the coordination of the European contribution to large-scale international collaborations, such as ITER. In 2006, a significant change to the structure of the European Fusion Programme was introduced. The ITER parties agreed to provide contributions to ITER through legal entities referred to as "Domestic Agencies". Europe fulfilled its obligation by launching the European Domestic Agency called "Fusion for Energy" (F4E), in 2007 [F4E, 2007]. In 2008, the IAEA and ITER signed a Fusion Cooperation Agreement to cooperate on training, publications, organisation of scientific conferences, plasma physics and modelling and fusion safety and security [IAEA-ITER, 2008]. Recently, in April 2011, the Domestic Agency of China signed the 54th and 55th Procurement Agreements.

Another important step was the "Broader Approach" agreement in 2009 between the EU and Japan [EU, 2007], which includes final design work and prototyping for the International Fusion Materials Irradiation Facility (IFMIF) [Ehrlich and Möslang, 1998], which will subject small samples of materials to the neutron fluxes and fluences that will be experienced in fusion power plants. The goal beyond ITER and IFMIF is to demonstrate the production of electricity in a demonstrator fusion power plant (DEMO), with its first demonstration of electricity production in about 30 years hence, after which it is hoped that fusion will be available for deployment on a large scale [Maisonnier et al., 2006].

11.4. Barriers to large-scale deployment

Fusion power is still at the research phase. Even under an optimistic scenario fusion research will need another 30-35 years or even longer until all technological and physical problems are solved. The first commercial fusion power plant is not expected to enter the energy mix before 2050.

There are currently no political barriers to nuclear fusion development. Public perception, in particular concerning safety and waste, will be important once a commercial plant is planned for construction. The potential for difficulties will very much depend on the reputation of conventional nuclear (fission) energy production.

Financial barriers will remain, since funding is derived from national and international sources with limited industrial contributions. As for many first-of-a-kind plants, the costs are very high, with some hundreds of millions of euro required to accelerate the research and complete the DEMO design. The Component Test Facility is estimated as a few billion euro and the cost of the planned DEMO of at least EUR 10 billion.

Scientific and technical barriers include plasma physics and materials engineering, which already figure in the Fusion Technology Roadmap. The lack of appropriate harmonised European Codes and Standards may also delay the necessary developments.

From a report by Ecorys [Rademaekers, 2010], the following question was posed "What would be the consequences if the EU withdrew from fusion research and ITER in particular?" A number of relevant points were raised:

- On the political level: the EU would lose considerable credibility at the international level by withdrawing from the ITER project. If the EU withdrew from a project which it has strongly supported in the past, the international partner countries may lose faith in the EU as a reliable partner for international cooperation;

- On the economic level: The EU would miss out on "making the last step" towards the commercialisation of nuclear fusion energy and risk wasting the investments already made;

- On the technological level: The EU would face the risk of a knowledge drain. Some of the partner countries would certainly continue to pursue commercial electricity from fusion energy and would be likely to seek to take the knowledge, including the expert scientists, away from Europe.

Lastly, as fusion is now moving from R to the R&D phase under a multi-national, multi-institutional approach, Intellectual Property Rights (IPR) is also an issue that will need addressing properly.

11.5. RD&D priorities and current initiatives

Ongoing research

Although the concept of fusion has been demonstrated there are still a number of fundamental issues relating to the physics where understanding needs to be improved [Andreani, 2000], including: plasma containment and operating modes; magneto-hydrodynamics and plasma stability; particle and power exhaust; and alpha particle physics.

One of the most important technology areas is the development of materials that can operate for long periods and extended lifetimes in the extreme conditions of thermal load and neutron irradiation in close proximity to plasma. A number of materials have been identified as candidates for future fusion power plants, but detailed experimental data is limited since there is presently no neutron source comparable to a fusion power plant. The availability of suitable materials will be an important factor determining the cost of electricity from a future fusion power station.

Another area where technology development is required concerns the part of the reactor known as the blanket. The blanket surrounds the vacuum chamber which contains the plasma and plays a vital role in fuel cycle required for a reactor to maintain continuous fusion and production of power. The neutrons produced in the fusion reaction are absorbed in the blanket and react with lithium contained within it to produce tritium which re-enters the plasma and sustains the fusion reaction. A working fluid is circulated around the blanket. This working fluid transfers the heat energy produced to the electricity generating equipment (known as the balance of plant). Identifying and refining the steels required to produce a blanket with reasonably long life is a key challenge. The blanket will eventually degrade and need replacement due to the high neutron load and extreme temperatures it faces. Blanket longevity and ease of replacement is key to the availability, and hence cost of electricity produced, of a fusion reactor.

Another technology area that is key to minimising the down time of a fusion reactor is remote handling. This describes the machinery that is required to access those parts of a fusion reactor where it would be impossible for humans to enter due to the heat, radiation and need for cleanliness. Such entry is periodically required to replace and service components.

Beyond ITER

ITER is the bridge towards a plant that will demonstrate the large-scale production of electrical power and tritium fuel self-sufficiency. The next step after ITER is DEMO. This first demonstration of electricity production is expected in the next 30 years, with fusion then becoming available for deployment on a large scale. Nevertheless, there are still many issues and challenges to be resolved, such as those around reliability.

It is also under serious consideration that electricity production could be demonstrated sooner, within the next 25 years, by a relatively modest 'Early DEMO' or 'EDEMO' plant. It would not be required to produce electricity at a stipulated cost and would use known materials that are expected to survive under fusion power plant conditions. This approach may gain the interest of industry earlier by demonstrating fusion feasibility.

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