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"ROADMAP LONG VERSION"
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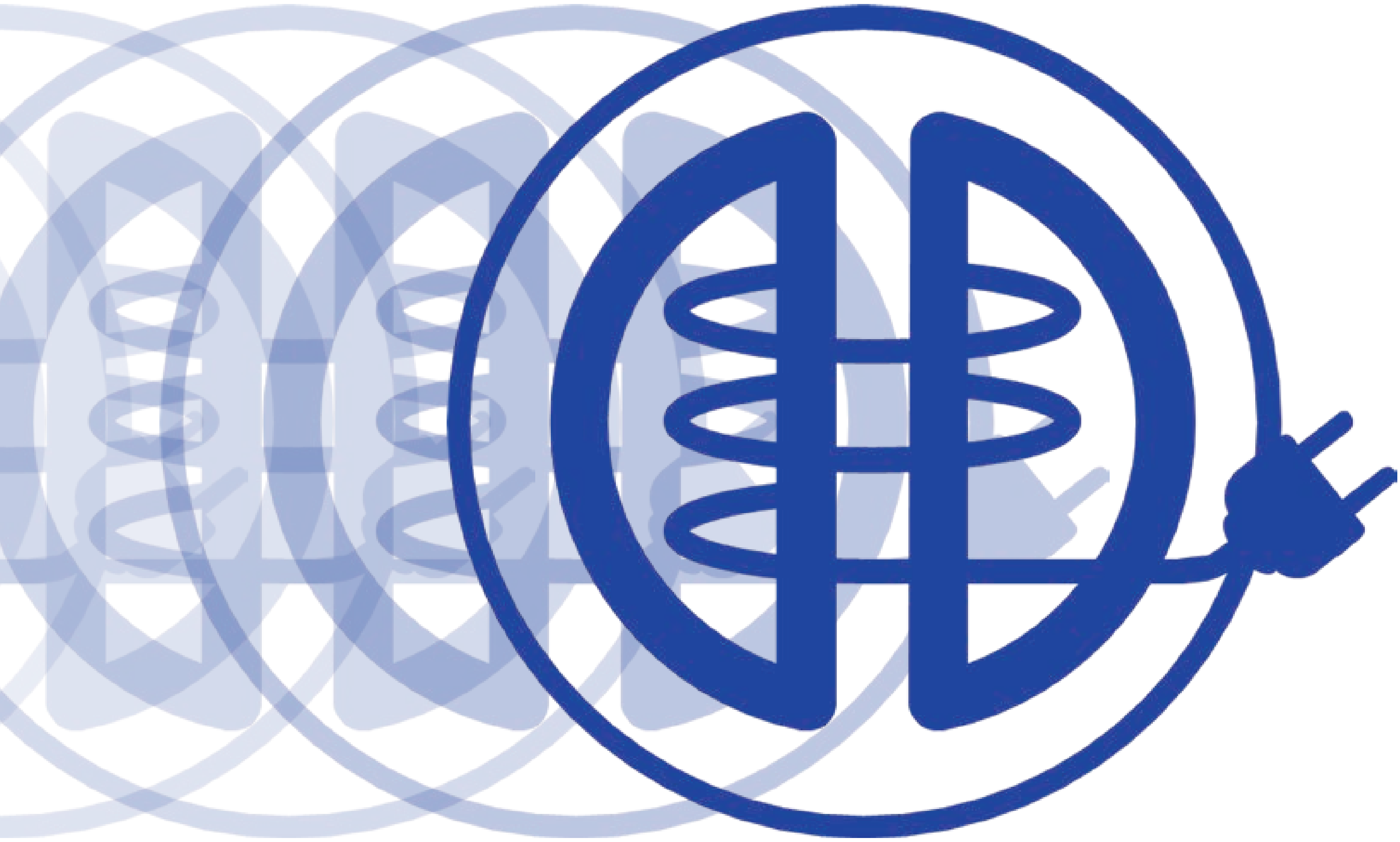
European Research Roadmap to the Realisation of Fusion Energy

LONG VERSION



EUROfusion

Preface

There is a well-established global need for sustainable low-carbon sources of electricity, especially for reliable and predictable baseload power generation. Fusion is one of the few technologies with the potential to meet this need. The science and technology challenges for fusion are great and interwoven. This drove the European fusion community to create a coherent, and ambitious but pragmatic plan providing fusion electricity to the grid by the middle of the 21st century via a comprehensive integrated science, technology and engineering programme.

In 2012, EUROfusion's predecessor, the European Fusion Development Agreement (EFDA) published the first Fusion Roadmap: Fusion Electricity – A roadmap to the realisation of fusion energy. Since its conception, the Fusion Roadmap has been a fundamental document to align the priorities in fusion research and development towards the ultimate goal of achieving electricity from fusion energy. The general approach is retained in this update.

The strategy of the fusion roadmap is built on three main pillars: the international ITER tokamak that will demonstrate the scientific and technological feasibility of fusion as an energy source, a fusion neutron source facility for materials development and qualification, and a demonstration power plant DEMO, which will deliver hundreds of megawatts of electricity to the grid and operate with a closed fuel-cycle. In addition a strong research and innovation programme is needed supporting these and looking towards commercial fusion power plants. The programme to implement this strategy involves designing DEMO while ITER is in its construction and early operation phase, before it has reached its ultimate performance goals. However, DEMO takes advantage of the science, technology and engineering advances and knowledge already being developed for ITER. Naturally, its final design can be adapted following ITER results.

The ultimate goal is commercial electricity, and so it is critical that DEMO is on this path, even though an early DEMO (a nuclear facility) cannot be based on too large extrapolations from ITER in science and technology. This is achieved in several ways: keeping several options for DEMO open for as long as possible; designing DEMO to be able to test and develop technologies during its operation; engaging industry as a stakeholder as well as a supplier; and using new in-silico design techniques to reduce prototypes. Finally, parallel research and innovation programmes will look directly into affordable commercial power plant designs and include alternative approaches, notably the stellarator. In pursuing this goal, Europe should seek all the opportunities for international collaborations for mutual benefit from the intellectual diversity of the whole fusion community and from the sharing of resources and facilities.

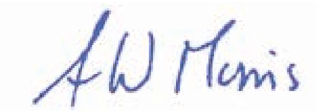
This large and diverse science, technology and engineering programme will naturally lead to many synergetic benefits in other fields, both in technical areas and in the realisation of major integrated projects, and both in the research community and in industry. Conversely, fusion will benefit from advances in other research fields and industries. The European programme is designed to nurture both paths.

The success of the fusion endeavour in Europe will depend on two further elements: (1) funding from the European Union and from participating countries, and (2) attracting and developing outstanding and innovative scientists and engineers for the community and industry.

This research roadmap describes the steps to realise the ambitious goal of developing future fusion power plants for wide deployment.

September 2018

Tony Donné
[EUROfusion Programme Manager]



William Morris
[Chair of the EUROfusion Science and Technology Advisory Committee]

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Executive Summary

The quest for fusion power is driven by the need for large-scale sustainable and predictable low-carbon electricity generation, in a likely future environment where the global electricity demand has greatly increased. This demand is expected to perhaps reach 10 TW in the second part of this century, by which time the vast majority of energy sources needs to be low-carbon. To make a relevant contribution worldwide, it is estimated that fusion must generate on average 1 TW of electricity in the long-term, i.e., at least several hundred fusion plants in the course of the 22nd century. Today, Europe is a leader in fusion research and development, and can aim to be a key player in the fusion market. Meeting this long-term need in time requires a strong programme in parallel with the construction and exploitation of ITER. This second edition of the roadmap accommodates the schedule of the ITER International Organization announced in 2016. There are several steps to achieve this goal, which for magnetic confinement fusion may be summarised as follows:

1. Technical demonstration of large scale fusion power – this is the first goal of ITER (500 MW for 400 seconds);

2. Electricity delivered to the grid via a DEMOnstration fusion power plant (DEMO) which would do the following (1) generate, early in the second part of this century, hundreds of MW of electricity for at least several hours at a time, (2) operate with a closed fuel cycle and (3) have other features that could be extrapolated to early commercial fusion power plants;

3. In parallel, a science, technology, innovation and industry basis to allow the transition from the demonstration fusion plant to affordable devices suitable for large scale commercial deployment (stellarators[1] might prove particularly attractive);

4. Large scale industrial production of fusion plants.

The European fusion roadmap addresses the first three of these goals, all in the context of the final goal. This plan leads to early conceptual design(s) of a European DEMO by around 2027. The plan will shape an Engineering Design Activity aiming at a decision to construct DEMO a few years after high performance deuterium-tritium (DT) operation of ITER is achieved and the first results from the ITER Test Blanket Modules (TBMs) are available to confirm the design decisions. DEMO will be operational around 20 years after high power burning plasmas are demonstrated in ITER. The second step will assume a certain performance from ITER's DT phase, ITER's TBMs and the materials programme (including IFMIF-DONES/A-FNS[2]). Hence, the DEMO design and the supporting plasma science need to accommodate a range of outcomes from ITER, to allow a prompt construction decision. This is one of many places where theory-based modelling and large-scale computation will be key.

There are several elements in this strategy, all of which need to be closely integrated, and are outlined below. A pictorial overview is given in Figure 1.

[1] The stellarator and many other terms are explained in the glossary

[2] There are two lighter variants of the International Fusion Materials Irradiation Facility (IFMIF): IFMIF-DONES in Europe and A-FNS in Japan. The decision on which of the two devices is to be built remains open. When IFMIF-DONES is mentioned, in this document, either IFMIF-DONES or A-FNS is implied.

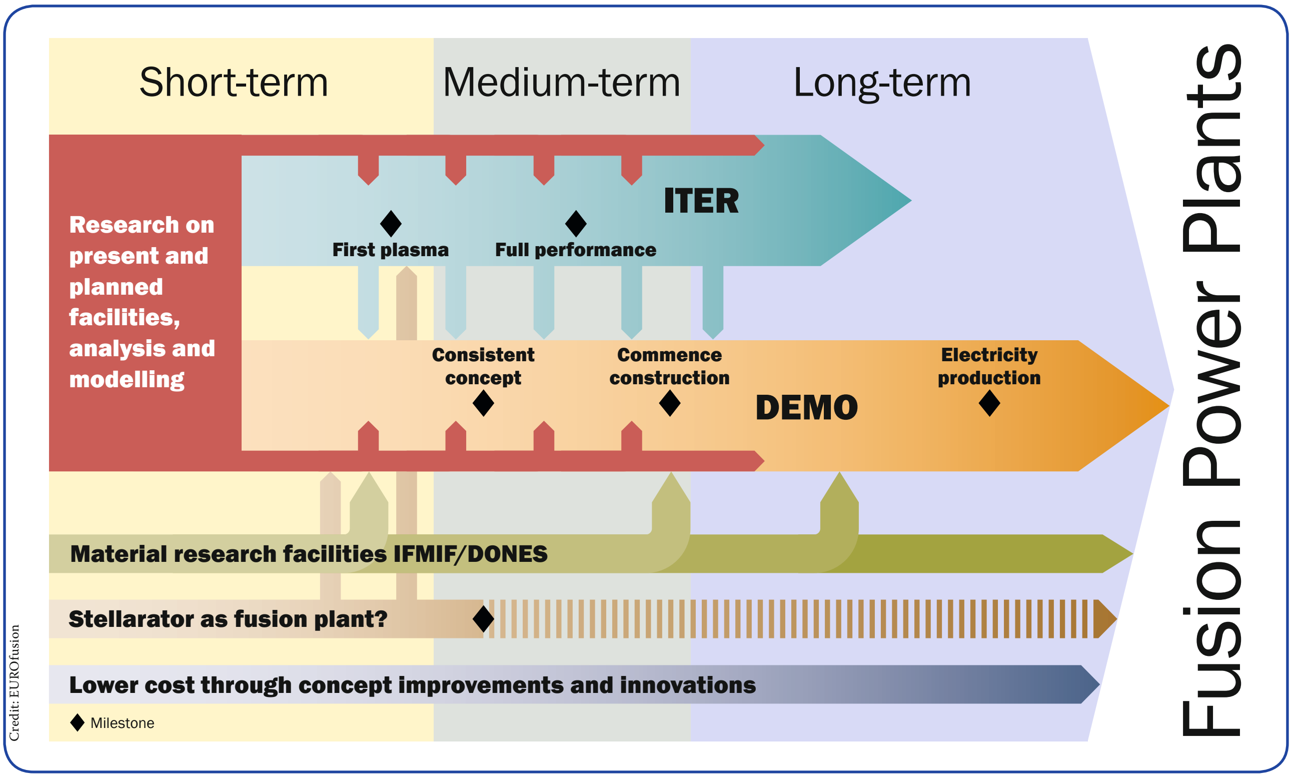

Figure 1: The European Roadmap in a nutshell: The specific challenges will be introduced in Section 3 and then further described in Section 4. Research on present-day devices, as well as theory and modelling, give input to ITER and (possibly via ITER) to DEMO. For clarity not all interrelations are included.

A high performance plasma is at the heart – ITER

ITER will break new ground in fusion science and the European laboratories will focus their effort on its exploitation. To ensure its success, a team is needed with deep understanding of the critical plasma issues and equipped with comprehensive validated modelling tools to design and optimise the plasma and its control. In other words: there needs to be a focus on making ITER a success. The principal facilities for preparation are JET (in Europe) and JT-60SA (in Japan). Small- and medium-sized tokamaks with proper capabilities, both in Europe and beyond, will play a role addressing specific topics. The Wendelstein 7-X stellarator will also contribute to the physics and technology of ITER. No major facility gaps exist in the foreseen world programme to develop plasma operation scenarios for ITER and, with ITER and JT-60SA, DEMO. JET will provide the key experimental data to prepare for ITER operation and the early plans for high performance DT operation, and exploitation of JET and its data will focus on optimising the ITER research plan. JT-60SA will provide major additional input after JET,[3] and will bring new information and developments in many areas. JT-60SA will be a major centre for DEMO plasma scenario design and a range of enhancements are planned, including a metal wall, to maximise relevant input. High fidelity theory-based plasma models for the integrated scenarios including plasma exhaust are needed in support of the experiments to bridge the gaps between present facilities and ITER and then DEMO.

A solution for the heat exhaust in the fusion power plant is needed

A reliable solution to the problem of heat exhaust and helium removal is one of the main challenges in realising magnetic confinement fusion. It is conceivable that the baseline strategy, with a conventional divertor as pursued in ITER, cannot be extrapolated to DEMO and commercial fusion power plants. Hence, in parallel to the programme in support of the baseline strategy, an aggressive programme on alternative solutions for the heat exhaust is necessary. This will focus on improved plasma facing materials and components, and on new divertor configurations. Several concepts will be tested at a proof-of-principle level in upgrades of existing devices, and their technical feasibility for application in a fusion power plant are being assessed. Since the extrapolation from the present devices (largely the medium-sized tokamaks) to DEMO based on modelling alone, is considered too large, involvement in a dedicated tokamak exhaust facility[4] might be necessary, based on a coherent and comprehensive strategy for reference and alternative exhaust approaches.

[3] The end date of JET operation was under discussion at time of writing. There are strong arguments to keep JET in operation as close to the first plasmas on ITER as possible.

[4] Italy is presently planning to build a new tokamak focused on plasma exhaust (I-DTT). EUROfusion will decide on the nature of its involvement in the facility, after results from the proof-of-principle experiments on present devices are made available and after the construction of I-DTT will be close to completion. The Czech tokamak COMPASS-Upgrade is another new device that will come available to the fusion researchers, and that needs to be considered for the European fusion programme.

Robust materials are essential, needing a dedicated neutron source for validation and development

The mechanical and thermal properties of materials can change substantially under neutron irradiation. Therefore, to design the highly irradiated components of DEMO and commercial power plants suitable design codes and structural criteria standards are needed using new data interpreted with advanced theory-based models. Irradiation studies up to at least 50 dpa[5] (displacements per atom) with a fusion neutron spectrum are needed for the reference structural materials (such as EUROFER[6]) to determine and optimise the lifetime of components for DEMO and to design lasting and high-performing components for commercial fusion power plants. While a full performance International Fusion Materials Irradiation Facility (IFMIF) would provide the ideal fusion neutron source, the schedule for fusion deployment requires the acceleration of material testing. An earlier DEMO Oriented Neutron Source (IFMIF-DONES, Europe) or the Advanced Fusion Neutron Source (A-FNS, Japan) must be constructed soon enough to provide a source with a fusion-relevant neutron spectrum to the community for materials testing.

In parallel, a comprehensive programme using materials test reactors (MTRs) is needed as the main source to establish data bases of neutron irradiated materials as in any case much of the structure of DEMO and commercial fusion power plants only sees lower neutron energies similar to a fission spectrum. This will be the basis for the engineering design of the rear part of internal components and will also allow design of front parts able to survive the first phase of operation of DEMO. It remains to be seen whether the reference materials for structural, plasma-facing and high-heat flux zones of the breeding blanket and divertor areas will meet all the specifications for DEMO and fusion power plants. Therefore, a combination of alternative or advanced materials and improved designs is needed (to sidestep some materials limitations for economically viable power plants). These new materials would have specific features like enhanced operating temperature windows; their development programme will exploit synergy with other advanced materials programmes outside fusion (such as GenIV fission power plants), in particular in R&D[7] and modelling. An industrial supply chain for large quantities of the materials will need to be established.

Tritium self-sufficiency is a key requirement for DEMO and commercial power plants

DEMO and commercial fusion power plants must be self-sufficient in tritium, have a controlled inventory, and also breed enough surplus tritium to allow successor power plants to start up. Breeding occurs in a blanket surrounding most of the plasma, and the blanket is also the primary heat source in the power to electricity conversion cycle. Adequate breeding needs to be factored into the design of the power plant and this has many ramifications: (1) in the optimisation of

[5] Damage is indicated by dpa – displacements per atom.

[6] EUROFER(97) is an RAFM (Reduced Activation Ferritic Martensitic) steel developed over several decades.

[7] R&D stands for Research and Development

the blanket design for breeding and extraction of tritium and its other functions and (2) in the layout of the device to maximise the area available for breeding. In addition, some of the technical features of the blanket, especially the coolant, pervasively affect the overall efficiency and the design layout of the plant, and bear a strong impact on design integration, maintenance and safety because of the interfaces with all key systems. Finally, the blanket has to handle much of the exhaust heat from the plasma without excessive attenuation or loss of neutrons before they reach the breeding material, and it also has to shield the vacuum vessel from neutrons. A suitably co-ordinated test blanket programme on ITER will be indispensable, and Europe will need to explore a sufficient range of blanket options for DEMO and commercial power plants to ensure a solution that meets the tritium-breeding, materials and thermal efficiency requirements.

DEMO needs a fully integrated design approach including safety

The studies since 2012 have confirmed the critical importance of considering the many interdependencies between systems in DEMO or a commercial fusion power plant, including the plasma operation scenario and the electricity generation, in a rigorous and organised way. The DEMO plant must be designed with a fully integrated systems engineering approach in order to steer it towards a global optimum. There will be a number of uncertainties for some time (including the nature of the information from ITER exploitation), but it is necessary to focus on a representative design point (with variations at system/component level) in order to uncover the key design integration issues, and steer the R&D. Alternative DEMO plant architectures must also be investigated in parallel to ensure that opportunities are not missed. Addressing issues in detailed design point studies builds the capabilities and knowledge base that can be applied to the alternate DEMO designs and to commercial power plants. In support of this, near-term modest targeted efforts and investments need to be made in system development (magnets; blankets; divertors; balance of plant; tritium, fuelling, and vacuum; heating and current drive; diagnostics and control; containment structures; and remote maintenance). The plasma design will be conducted in close cooperation with the teams working towards and on ITER. Safety will be an all-encompassing element as will environmental aspects such as waste minimisation and recycling strategies. Finally, it will be important from an early stage to develop cost minimisation and manufacturing strategies. Substantial investments for the construction of medium to large-scale mock-ups and prototypes are expected during the Engineering Design Activity.

Industry must be involved early in the DEMO definition and design

The evolution of the programme requires that industry progressively shifts its role from being a provider of high-tech components to being the driver of fusion development. Industry must be able to take on the main responsibility for commercial fusion power plants after successful DEMO operation. For this reason, DEMO cannot be defined and designed by research laboratories alone, but requires deep involvement of industry in all technological and systems aspects of the design. Increased involvement of industry is especially required in the design and monitoring process from the early stage to ensure that early attention is given to industrial feasibility, manufacturability, costs, nuclear safety and licensing aspects. This is an evolution of the role of industry compared to that in ITER, and an early launch of the DEMO engineering design after the completion of ITER construction and beginning of operation would facilitate maintaining industrial competences and engagement. Industry involvement needs a policy to maintain industrial competence in fusion technology. It is also expected that industry will play a key role in developing effective, low cost and innovative manufacturing techniques, some of which may have applications outside fusion.

The European stellarator programme will exploit Wendelstein 7-X and move towards a power plant concept

The stellarator is a possible long-term alternative to a tokamak fusion power plant and is an integral part of the strategy to provide a sound basis for future fusion deployment. In addition, it provides support to the ITER physics programme. In the short-term, the main priority is the scientific exploitation of Wendelstein 7-X under steady-state conditions. While Wendelstein 7-X (a Helias) will allow the assessment of the predicted improved properties of optimised stellarators, a next step Helias burning plasma and technology experimental device may be required to address the specific issues of a burning stellarator plasma as well as the power plant aspects (blankets, remote maintenance, etc.). The exact goal of such a device can be decided only after a proper assessment of the Wendelstein 7-X results and probably a first look at the nature of a stellarator power plant; however, preparatory pre-concept design studies can be performed sooner, using the evolving experience from ITER and the tokamak DEMO work. The ambitious programmatic strategy to high-performance, steady-state operation will include a critical assessment of optimised stellarators as an alternative fusion power plant concept.

Theory and modelling in plasma and material physics is crucial

Fusion research has to make substantial steps between each generation of facilities. Time, resources and cost can be much reduced by making use of theory-based modelling to extrapolate from the available experimental data. This can allow effective prediction of plasma, materials and component performance, and also their optimisation. For the plasma, models should cover the core and exhaust plasma together, including their control schemes, and consider the plasma-materials interactions. Computer modelling of materials needs to play an increasing role in the development of fusion materials and to guide and interpret fission irradiations and their application to the fusion environment. Furthermore, it needs to interpret fusion-spectrum neutron irradiations at low doses and hence to help guide and shape the mission of the IFMIF-DONES and the IFMIF programmes. Modelling can also be used to support the materials design codes and standards needed for DEMO and commercial fusion power plant engineering design. Advances in computer science and technology and in big data are expected to transform the modelling capabilities in the future, e.g., to multiscale modelling of the whole plasma or complete components.

Innovation and improvement are essential ingredients

While the European programme focuses on a pragmatic approach to ITER and DEMO, building on science and technology where the confidence is greatest, it is important for many reasons that there should be continuous emphasis on improving the performance of the plasma, components and systems. This will increase the attractiveness of fusion as a power source, by increasing the plant efficiency and availability, reducing the cost, and possibly the size, and also making the plants as easy as possible to operate.

Europe seeks all opportunities for strong mutually beneficial international collaborations

ITER will bring together expertise from all around the world and will provide a prime path for information sharing. There are however other avenues to be pursued; furthermore, Europe's comprehensive integrated design of DEMO, so far unmatched by other ITER parties, can provide a useful focus. Currently, China has a very aggressive programme in fusion and clearly there can be mutual benefit from European participation in the design, construction and operation of their facilities. The Broader Approach with Japan has led, in particular, to the joint construction of the large JT-60SA tokamak and development of the technologies for IFMIF-like neutron sources. It thus provides a good example of an effective collaboration that can bring many further benefits through the phases of the roadmap. Europe continues to actively collaborate with facilities of many international partners, which include amongst others, tokamaks such as DIII-D and NSTX-U (United States), EAST, HL-2A and HL-2M (China), KSTAR (South Korea), SST-1 (India), JT-60SA (European Union and Japan), stellarators such as LHD (Japan) and other testing devices like PISCES-B and the Magnetohydrodynamic PbLi Experiment (MAPLE) in the United States. There has been a long history of collaboration on materials irradiations with Russia and the US. In addition to joint experimental work there are widespread collaborations on theory and modelling of plasma and materials.

Fusion benefits from and contributes to other European R&D activities

In recent years there have been enhanced interactions with other communities and projects, with strong mutual benefit, and this will continue to be expanded. For example fusion R&D is being applied in the European Spallation Source, and there is strong synergy with large scale computer science and big data activities. A powerful fusion neutron source such as IFMIF-DONES can be used by other communities to complement other neutron sources, without disrupting its main purpose, as shown by recent studies in both Japan and Europe, and the unprecedented ion accelerator at its heart shares expertise and innovation with the accelerator community. Materials science programmes interact extensively especially on steels, where there is also a strong fusion-fission synergy, especially with GenIV. There are growing and fertile two-way links in the field of remote handling and robotics. Within the framework of EIROforum[8] there are continuous exchanges of know-how and best practices in the field of instrumentation, big data, management of large research facilities, etc.

Industry involved in delivering instruments or components to big science projects, is often forced to innovate to cope with the requirements of state-of-the-art research equipment. This push for innovation in industry has the beneficial effect that the involved companies attain a better competitive position and therefore see an increase of their turn-over in related markets. Fusion technology leads to spin-offs. The superconducting cables used in Magnetic Resonant Imaging equipment is a spin-off from fusion, the same is true for the cockpit of the A380 which is made by explosive forming of large structures, where fusion has taken an existing process and significantly extended its applicability. EUROfusion has gathered many of these fusion spin-offs in a brochure.[9]

Management structure of European fusion research

There are two major organisations responsible for the European fusion programme: Fusion for Energy (F4E) which is responsible for the European contribution to ITER construction and other major projects, and EUROfusion which is responsible for the accompanying R&D programme.

Shortly after publication of the first version of the Fusion Roadmap in 2012, a start was made with the reorganisation of the European Fusion Research programme. The many bilateral agreements between Euratom and the various member countries were terminated at the end of 2013, and the EUROfusion consortium, comprising 29 Research Institutes in 27 countries was officially established in the course of 2014.[10]

Before 2014, Euratom funded all magnetic confinement fusion research in its member states for 20% up to a ceiling (which varied from country to country). Additionally, the European Fusion Development Agreement (EFDA) had a limited budget to fund research along certain priority areas. From 2014 onwards, under EUROfusion, funding has been strictly aligned with the priorities of the Fusion Roadmap, with co-funding by the national programmes. This implies that continued long-term matching by national funding represents an essential element.

Fusion for Energy (F4E) is the European Union's Joint Undertaking for ITER and the Development of Fusion Energy. F4E is responsible for providing Europe's contribution to ITER, the world's largest scientific partnership that aims to demonstrate fusion as a viable and sustainable source of energy. It also supports fusion research and development initiatives through the Broader Approach Agreement, signed with Japan. Ultimately, F4E will contribute towards the construc-

8 EIROforum is the European consortium of eight of the largest European research facilities (CERN, EMBL, ESA, ESO, ESRF, EUROfusion, ILL and XFEL).

9 https://www.euro-fusion.org/spin-offs/

10 In 2017 Ukraine has joined EUROfusion as the 30th member.

tion of the demonstration fusion power plant, DEMO; in the meantime this topic has been outsourced to EUROfusion.

In very coarse terms, it could be stated that F4E is largely focused on building and manufacturing large scale fusion projects (ITER, JT-60SA, IFMIF, etc.) involving many industrial procurements, while EUROfusion is focused on fusion R&D at the national research institutes and universities.

Research advances since the introduction of the roadmap in 2012

EUROfusion has seized the unique opportunity to develop an integrated scientific programme including experiments and modelling on devices with different sizes, i.e., on medium-size tokamaks and on JET to provide a step-ladder approach for extrapolations to JT-60SA, ITER and DEMO. Strong synergy in the programme of the various European devices has been central and has focused on optimising ITER's performance from day one of its exploitation.

The main development in ***plasma scenarios*** has been the move to tokamak operation with metallic walls like ITER and DEMO (previously carbon was the normal plasma-facing material which proved unsuitable for ITER and DEMO). This has led, as hoped, to strongly reduced tritium retention and much lower levels of dust production. The introduction of metallic walls initially had an adverse effect on the plasma performance for standard plasma scenarios but this has already been largely recovered by various remedies and modified scenarios developed to assist rapid progress when ITER starts to operate.

In the challenging area of ***plasma exhaust***, there has been good progress in understanding the likely exhaust loads in ITER and DEMO. As a response, a comprehensive high-level strategy has been developed and a range of facility enhancements funded in support. Furthermore, in 2018, the Italian government has decided to proceed with the funding for the construction a new divertor test tokamak (referred to as I-DTT) focused on exhaust issues. The Czech government has funded COMPASS-Upgrade, a high-field tokamak that will also contribute to the research topics under mission 2.

In the field of ***materials***, beside numerous scientific advances, a preliminary engineering design of IFMIF-DONES has been completed, and with F4E, a potential European site has been identified.

Fundamental to the European ***DEMO design*** development strategy has been the establishment of a baseline architecture that integrates all the major DEMO sub-systems into a coherent plant concept. This provides a framework to find holistic designs that are consistent with the DEMO stakeholder requirements and thus reveal the extent to which current plasma, materials, component and systems performance are adequate. The implementation of a philosophy of integrated design and a 'systems orientated' approach represents a significant advance over anything achieved previously. It has brought much greater clarity to a number of critical design issues, and the overall integration challenge. This includes: (i) identification of critical interface issues, project risks and innovation opportunities; (ii) establishment of an 'integration culture'; (iii) system optimisation studies.

A major highlight has been the completion of the superconducting Wendelstein 7-X ***stellarator***. Its commissioning and first operation exceeded expectations, demonstrating a strong base for future scientific exploitation and development of the stellarator.

1. Introduction – Make fusion a credible option

The quest for fusion power is driven by the need for large-scale sustainable and predictable low-carbon electricity generation, in a likely future environment where the global electricity demand has greatly increased (see Figure 2) by 2050. The demand is expected to increase substantially more in the second part of this century, to perhaps 10 TW, by which time the vast majority of energy sources needs to be low-carbon (see Figure 3). A predictable baseload electricity supply is needed to handle short-term and seasonal variations in the renewable sources such as wind and solar[11,12,13] A recent study "Buffering volatility: a study on the limits of Germany's energy revolution" has come to the conclusion that wind and solar could have a share in the combined German, Swiss, Austrian, Danish and Norwegian electricity market of only up to 50%[14]. Other sources of electricity are required to be able to fully replace fossil fuels as the baseload supply. To make a relevant contribution worldwide, fusion should aim to generate, on average, 1 TW of electricity in the long-term, i.e., at least several hundred fusion plants, in the course of the 22nd century. Today, Europe is a leader in fusion research and development and can aim to be a key player in the fusion market. This long-term need remains despite delays in ITER, so this second edition of the roadmap includes strategies to recover lost time relative to the eventual goal. There are several steps to achieve the goal, which for magnetic confinement fusion may be summarised as follows:

1. Technical demonstration of large scale fusion power – this is the first goal of ITER (500 MW for 400 seconds);

2. Electricity delivered to the grid via a DEMOnstration Fusion Power Plant (DEMO) which would generate, early in the second part of this century, hundreds of MW of electricity for several hours and operate with a closed fuel cycle and include other features that could be extrapolated to early commercial fusion power plants;

3. In parallel, a science, technology, innovation and industry basis to allow the transition from the demonstration fusion plant to affordable devices suitable for large-scale commercial deployment (stellarators might prove particularly attractive);

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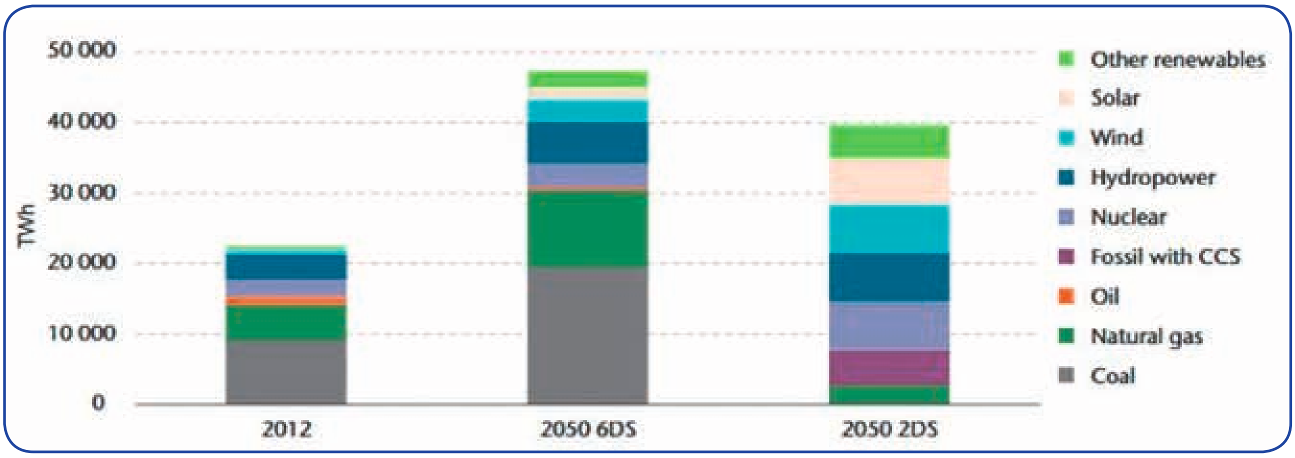

Figure 2: Projected electricity production and contributions by different existing technologies in 2050 according to two scenarios (6°C and 2°C increase in the global temperature), showing the large growth in low-carbon generation needed especially in 2DS. (source: International Energy Agency[15]

[11] D.J.C. MacKay, Sustainable Energy – Without the Hot Air (2009) UIT Press, ISBN-13: 978-0954452933.

[12] F. Wagner, Electricity by intermittent sources: An analysis based on the German situation 2012, Eur. Phys. J. Plus 129 (2014) 20.

[13] K. Muraoka et al., Short- and long-range energy strategies for Japan and the world after the Fukushima nuclear accident, J. Instrum. 11 (2016) C01082.

[14] H.-W. Sinn, Buffering volatility: a study on the limits of Germany's energy revolution, National Bureau of Economic Research Working Paper Series, www.nber.org/papers/w22467 (2017). European Economic Review, 99, 130 (2017).

[15] Technology Roadmap – Nuclear Energy, 2015 Edition, International Energy Agency, France, and IEA "Energy Technology Perspectives 2015, fig 1.9).

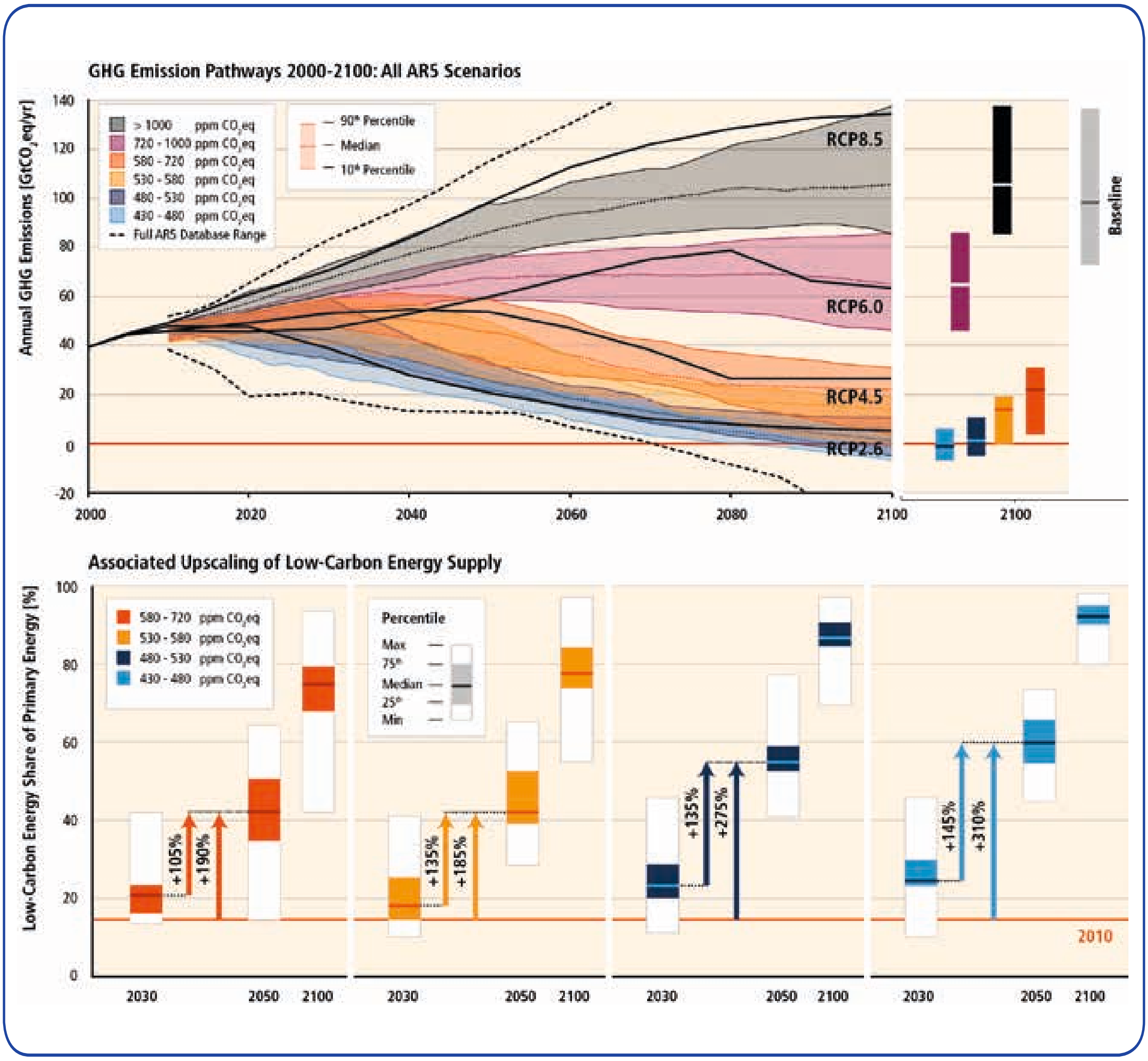

Figure 3: (Top) Pathways of global greenhouse gas (GHG) emissions in baseline and mitigation scenarios for different long-term concentration levels and (bottom) associated upscaling requirements of low-carbon energy (% of primary energy) for 2030, 2050 and 2100 compare to 2010 levels for different mitigation scenarios. (Source Intergovernmental Panel on Climate Change[16]).

There are several elements in this strategy, all of which need to be closely integrated, and are outlined below. A pictorial overview is given in Figure 1. A roadmap generated now cannot address the complex commercial/industrial interplay of the transition to large-scale fusion deployment, so it focuses on providing the prototype (DEMO) and accompanying science, technology and industry base to prepare for the subsequent steps.

[16]IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; Figure SPM 4, page 11.

Fusion: a virtually unlimited energy source

Fusion of light nuclei is the energy source that powers the sun. A fusion power plant utilises the fusion reaction between tritium and deuterium. The process yields a helium nucleus and a neutron, whose energy is harvested for electricity production. Deuterium is widely available, but tritium exists only in tiny quantities. The fusion power plant has to produce it via a reaction between the neutron and lithium. Lithium, again, is abundant in the Earth's crust and in sea water. The global deuterium and lithium resources can satisfy the world's energy demand for millions of years.

Background

The Fast Track approach to fusion energy[17] in 2001, described three main elements:

- The ITER project as the first essential step towards energy production;
- The International Fusion Materials Irradiation Facility (IFMIF) or an equivalent, for material qualification under intense neutron irradiation, in parallel with ITER;
- A single step (DEMO) between ITER and the first commercial fusion power plant designed "as a credible prototype for a power-producing fusion reactor, although in itself not fully technically or economically optimised"

Magnetic confinement of hot fusion plasmas

Atomic nuclei are positively charged and repel each other. They only fuse if they collide fast enough to overcome the repelling force. As particle speed corresponds to temperature, the fusion fuels have to be heated to about 200 million °C, 20 times hotter than the core of the sun. At these temperatures, atoms separate into nuclei and electrons, forming a gas of charged particles called plasma. The hot fusion plasma must not touch the confining wall, and it is therefore confined by means of magnetic fields. The technology of confining hot plasmas in a doughnut shaped chamber is routine in fusion experiments worldwide.

[17] D. King et al., Conclusions of the Fusion Fast Track expert meeting, 27 November 2001.

The major aspects of the programme have been the subject of several external reviews in the period 2007-2017:

- The SET plan;[18,19]
- The Facility Review in 2008;[20,21]
- The Working Group on JET and Accompanying Programme;[22]
- The Analysis of the Strategic Orientations of the Fusion Programme;[23,24]
- The DEMO Working Group[;25]
- The Material Assessment Group, established by the former CCE-Fu;[26]
- The Ad-Hoc Group on Options towards IFMIF;[27]
- The Plasma Exhaust Assessment Panel Report;[28]
- The Review on the ITER TBM/DEMO BB Programmes.[29]

[18] COM (2007) 723 "Towards a European Strategic Technology Plan".

[19] This document, the European Research Roadmap towards Fusion Energy, guides and prioritises the European fusion research and technology in the coming decades, a limited number of references of important underlying reports that are only available inside the European fusion community are included.

[20] "The European Fusion Research Programme. Input to the Facility Review Panel prepared by the EFDA Leader, the EFDA Associates and F4E" 2008.

[21] R. Cashmore, J.M. Delbecq, V. Elsendorn, T. Hartkopf, E. Iarocci, K. Itoh, J. Li, R. Parker, V. P. Smirnov, H. Bruhns "R&D Needs and Required Facilities for the Development of Fusion as an Energy Source" (2008) Report of the Facilities Review Panel.

[22] Y. Capouet, S. Cowley, G. Hasinger, K. Hesch, G. Marbach, J. Pamela, A. Pizzuto, F. Romanelli, J. Sanchez, M. Q. Tran, R. Weynants, S. Zoletnik "Report of the CCE-FU on JET and the accompanying programme" CCE-FU 50/2.

[23] C. Cesarsky, Ph. Garderet, J. Sanchez, M. Q. Tran, C. Varandas, B. Vierkorn-Rudolph, S. Paidassi "Strategic orientation of the Fusion Programme - Report of a group of experts assisting the European Commission to elaborate a roadmap for the fusion programme in Horizon 2020 – the Framework Programme for Research and Innovation" CCE-FU 53/3c.

[24] A. Wagner, H. Chang, J.M. Delbecq, M. T. Dominguez, L. Maiani, W. Dominik, R. Orbach, J. Wood "Strategic orientation of the EU Fusion Programme (with emphasis on Horizon 2020) - Report by an Independent Expert Group Review Panel of the European Commission" Ref Ares (2011) 1114818.

[25] P. Batistoni, S. Clement Lorenzo, K. Kurzydlowski, D. Maisonnier, G. Marbach, M. Noe, J. Pamela, D. Stork, J. Sanchez, M.Q. Tran, H. Zohm, "Report of the AHG on DEMO activities" CCE-FU 49/6.7.

[26] D. Stork et al 2012 "Assessment of the EU R&D Programme on DEMO Structural and High-Heat Flux Materials Final Report of the EFDA Materials Assessment Group (December 2012)" Ref: EFDA_D_2MJ5EU.

[27] "Accelerator - driven Neutron Sources for materials irradiation, Report from the TAP Ad Hoc Group on Options towards IFMIF (Dec. 2014)", chaired by R. Aymar.

[28] M.R. de Baar et al., "Plasma Exhaust Assessment Panel Report, (October 2016)", chaired by R.J. Hawryluk.

[29] M. Gasparotto et al., TBM/DEMO BB Programs Review, Final report September 2017.

The European Commission has updated its Strategic Energy Technology plan[30] again recognising the potential of fusion as an energy source towards the end of this century, and it stresses the importance of ITER.

The present document outlines an integrated programme for electricity production from fusion in the second half this century. Specifically, the roadmap has been constructed in such a way that the primary critical path is ITER. It focuses on solutions that minimise the construction of large and complex test facilities, relying as far as possible on existing facilities, on access to the facilities of the international collaborators and on a comprehensive theory and modelling activity to use the experimental data to address remaining gaps.

The roadmap addresses three separate periods with distinct main objectives.

First period: start ITER operation[31] with other parties and complete DEMO conceptual design(s) (<2030):

1. Construct and commission ITER with industry;
2. Secure the success of future ITER operation via preparation and early experiments; specifically this should include DT operation of JET;
3. Prepare the ITER generation of scientists, engineers and operators;
4. Finalise the design and construct a fusion spectrum neutron source (IFMIF-DONES); initial operation;
5. Lay the foundation of a DEMO fusion power plant (DEMO Conceptual Design Activity);
6. Explore the stellarator as an alternate approach to power plants;
7. Promote innovation and European industry competitiveness in fusion technology and beyond.

Second period: burning plasma on ITER and DEMO engineering design (2030-2040):

1. Exploit ITER with hydrogen, helium and deuterium to prepare for high performance DT operation; R&D in support of ITER to ensure it is a success;
2. Optimise ITER performance with operation in DT plasmas at Q=10;
3. Acquire other information from ITER operation to support DEMO design;
4. Exploitation of the IFMIF-DONES fusion materials testing facility and collect critical data for DEMO;
5. Carry out the detailed engineering design of DEMO, with industry, and prepare for construction;
6. Targeted development of long lead-time, power plant relevant materials and technologies;
7. Depending on progress in Wendelstein 7-X and any decision taken regarding a next-step device, develop a pre-conceptual design for a stellarator power plant;
8. Promote innovation and European industry competitiveness;
9. Establish industrial involvement in DEMO, building on the ITER experience;
10. Prepare the DEMO generation of scientists, technologists and engineers, and include industry.

Third period: plasma and technology optimisation on ITER and construction of DEMO (>2040):

1. Use ITER to prepare for DEMO and commercial fusion power plant plasmas (including steady state and technology testing);
2. Exploitation of the DONES fusion materials testing facility and its upgrade to IFMIF – to develop and qualify materials for long life in DEMO and commercial power plants;
3. Finalise the design and then construct DEMO;
4. Demonstration of electricity generation at the beginning of the second half of this century;
5. Qualification of power-plant relevant technologies and materials for the commercial phase;
6. Take the next step along the stellarator path, such as a facility combining a burning plasma and key technology, depending on the progress and prospects;
7. Cooperate with industry for the later deployment of fusion, via either tokamak or stellarator power plants.

General objectives for the first period are described in this document, while a more global evaluation is given for the second period and the third one is only outlined.

[30] C(2105) 6317 “Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation”, and http://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan.

[31] ITER activities mentioned in this document are performed in collaboration with the other ITER Parties.

2. ITER and DEMO – Key facilities on the roadmap

ITER and then DEMO-class devices are the critical stages to test the relevance of fusion power on a commercial scale. ITER will demonstrate that a burning plasma can be created and sustained, the most important single step for fusion, generating hundreds of megawatts of fusion power and developing the scientific know-how for the plasma and some of the technology. A European DEMO will take fusion to the next level – a fully-integrated science and technology demonstration of fusion.

ITER is the key facility for the first stages of the roadmap. ITER is expected to achieve robust burning plasma regimes and to test the conventional physics solutions for power exhaust. ITER's success remains the most important overarching objective of the programme. In the present roadmap, the vast majority of European resources for the first period are devoted to ensure that ITER is constructed, its operation is properly prepared and that a new generation of scientists and engineers is trained for its operation and exploitation.

ITER construction has already triggered major advances in enabling technologies for the main components and the auxiliary systems. The ITER licensing process has confirmed the intrinsic safety features of fusion and incorporated them in the design.

ITER will continue to play a key role over the subsequent two periods of this roadmap. The ITER exploitation up to its maximum performance (demonstration of a fusion gain Q=10) will require focused effort by scientists and engineers during the period up to the early 2040s. In the period beyond, ITER will complete its objectives by qualifying advanced regimes of operations and targeted technology developments such as extended tests of breeding blanket modules (the first tests should be done earlier), plasma heating systems and measurement and control techniques. In order to continue to make research and development at the cutting edge, ITER, like any other major facility, will require upgrades. Furthermore, given ITER's critical task of supporting the various designs of DEMO-class devices that will emerge around the world, its role is likely to evolve, e.g., in the plasma scenarios needed for these DEMO-class devices.[32]

Since ITER is expected to achieve the main plasma milestones on the path to the fusion power plant, the plasma preparation and the strategy proposed in this roadmap has been, to a large extent, built on that proposed by the ITER Organization (IO) to prepare ITER operation. Most of the EUROfusion plasma programme will therefore simultaneously prepare ITER for success and provide the critical basis for the decision on the European demonstration fusion power plant (DEMO).

ITER

ITER, the world's largest and most advanced fusion experiment, will be the first magnetic confinement device to produce a net surplus of fusion energy. It is designed to generate 500 MW fusion power which is equivalent to the thermal output of a medium size power plant. For a planned injected power of 50 MW, this corresponds to a fusion gain Q=10 in the plasma. ITER will also demonstrate some key technologies for a DEMO fusion power plant. ITER is not intended to generate any electricity to the grid from fusion.

The realisation of fusion energy depends completely on ITER's success. Therefore, the vast majority of EU fusion resources over the next decade are dedicated to the construction of ITER and the preparation of its exploitation. ITER is being built in southern France in the framework of a collaboration between China, Europe, India, Japan, Korea, Russia and the USA.

In the European strategy, DEMO is the only large tokamak between ITER and a commercial fusion power plant. Its general **goals** are to achieve:[33,34]

1. Predictable power output of 300 - 500 MW of electricity to the grid;
2. Safety and environmental sustainability;
3. Self-sufficiency in fusion fuel (tritium);
4. Resolution of all physics and engineering issues foreseen in the plant and demonstration of fusion power plant relevant technologies;
5. The basis for an assessment of the feasibility and economic viability of an fusion power plant.

To meet the goal of fusion electricity demonstration early in the second half of the century, i.e., about 20 years after ITER achieves reliable Q=10 performance, construction of a European DEMO has to begin in the early 2040s, to allow the start of operation in the 2050s. As shown in the remainder of this document, meeting such a schedule is possible provided that ITER achieves its goals, a pragmatic approach to DEMO is chosen, including the project organisation, taking advantage of the ITER experience, and finally that there is sufficient funding.

[32] Naturally there are ideas for DEMO class devices around the world, even if at present Europe has the most comprehensive and integrated design activity. All the other ITER parties have a strategy for the next steps.

[33] V. Massaut, W. Muench, M. Sforna, M. T. Dominguez, H. Tuomisto,R. Stieglitz, G. Zollino, D. Perrault, J. Elbez-Uzan, C. Ibbott , "Report of the DEMO Stakeholder Group", 18th March 2015.

[34] P. Batistoni, S. Clement Lorenzo, K. Kurzydlowski, D. Maisonnier, G. Marbach, M. Noe, J. Pamela, D. Stork, J. Sanchez, M.Q. Tran, H.Zohm "Report of the AHG on DEMO activities" CCE-FU 49/6.7.

DEMO: The step between ITER and a commercial power plant

DEMO will mark the very first step of fusion power into the European energy market by supplying electricity to the grid. DEMO will largely build on the ITER experience. Beyond that:

- DEMO will breed its own tritium, which is part of the fusion fuel;
- DEMO will demonstrate materials suitable for handling the fluence of neutrons produced during the fusion reactions;
- DEMO will demonstrate safety and environmental sustainability, and sufficient technology to allow a first commercial power plant to be constructed.

To achieve fusion electricity early in the second half of the century, a European DEMO construction has to start in the early 2040s, shortly after ITER achieves the milestone of Q_{DT} = 10 operation. DEMO engineering design will become a major activity after 2030.

Innovation combined with pragmatism

DEMO and also the later commercial fusion power plants require a significant amount of innovation in critical areas such as heat exhaust, materials, remote handling and tritium breeding. However, to design DEMO on the basis of the ultimate technical solutions in each area would postpone the realisation of fusion indefinitely. For this reason a pragmatic approach is advocated here. To meet its initial goals, DEMO will use technical solutions and regimes of operation that are sufficiently well established to allow it to meet its initial goals with confidence and as early as possible,[35] as far as possible extrapolated from ITER, and using the materials proven for the expected level of neutron fluence from a first phase of DEMO operation. Some other DEMO architectures will be pursued in parallel to ensure a wide enough design space is explored and that no major opportunities are missed, including different plasma scenarios. This also addresses the challenge of designing DEMO before all the information is available from ITER and materials testing. It is important that industry be involved from the beginning to ensure that early attention is given to industrial feasibility including the supply chain, nuclear safety and licensing aspects, and costs. Figure 4 indicates how information from ITER, during its four-phase assembly and operation phase flows into the DEMO design.

In addition, DEMO must be capable of addressing the fourth step (large scale industrial production of fusion plants) through the test of advanced components and technical solutions that will be developed in parallel for application in a fully-fledged fusion power plant, such as improved blanket concepts. Therefore, DEMO should be designed to have adequate flexibility for such tests (a Component Test Facility role). Some other technologies desirable for advanced fusion power plants, but not mature enough to be incorporated in DEMO, will be pursued in parallel.

Innovations in fusion are required to arrive at economically attractive fusion power plants. They need to be pursued both by industry and by research laboratories, and it is by facing the challenge of constructing large projects like ITER and DEMO that their realism can be tested and their benefits can be fully exploited. For this reason, a close interaction between industry and research institutes is envisaged. Innovation here refers to:

- Innovation in industry, through the development of enabling technologies and the selection of effective and low-cost technical solutions for DEMO. This requires an early involvement of industry as a full partner in a number of key areas: power plant architecture and engineering on innovative approaches to buildings and layout; manufacturers for the major components, and for low-cost manufacture of large numbers of specialist components (such as plasma facing units) and the development of advanced materials that are also suitable for large scale production;
- Innovation in research laboratories, through the investigation of advanced or new concepts in the most critical areas and pursuing basic research to seed further innovation.

As in all large science projects, success relies on the balance between pragmatism and innovation.

[35] The exact choice of the DEMO regime of operation will depend on the ITER results. Regimes based on advanced physics often require advanced technologies as well. For example, the heat-exhaust may be more complex for advanced regimes, and more auxiliary power may be needed for plasma control requiring higher thermodynamic efficiency cycles.

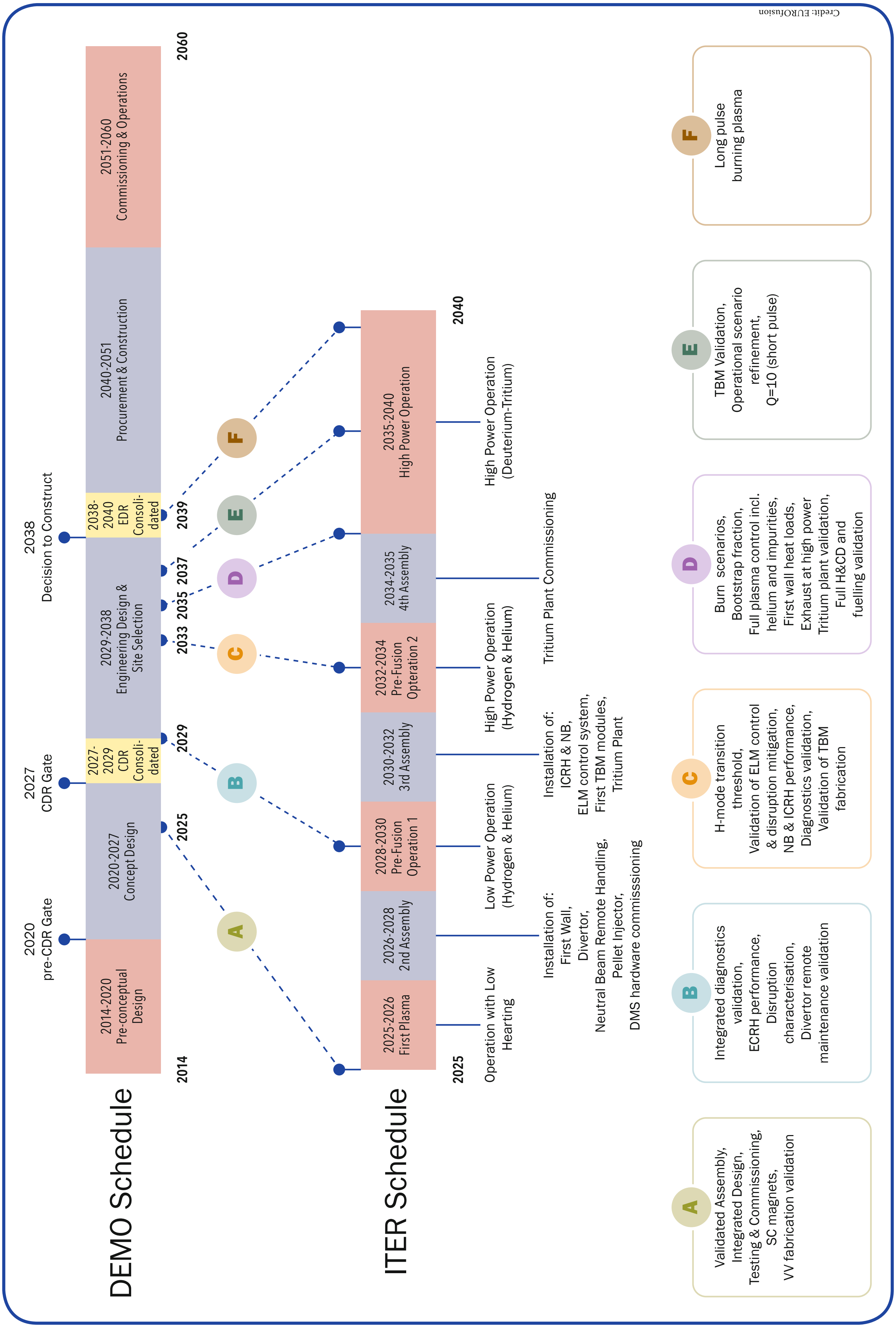

Figure 4: Diagram depicting how information from ITER, during its four-phase assembly/operation phase, flows into the DEMO Conceptual and Engineering Design Activities. CDR=Concept Design Review. The dates are indicative.

3. The fusion challenges

The realisation of fusion energy has to face a number of challenges:

1 Plasmas must be confined at temperatures 20 times higher than the temperature of the core of the sun. This requires the minimisation of energy losses due to turbulence and the control of plasma instabilities, and magnetic confinement configurations have been chosen accordingly. **Plasma regimes of operation** will be developed and qualified for use on ITER, combining experiments and theory-based models. DEMO and commercial power plants are likely to need advances above the minimum needed to meet the first ITER objectives. These advances then need to be fully integrated with the engineering design.

2 **Heat exhaust:** The power necessary to maintain plasmas at high temperatures has to be exhausted. This is done via the main chamber wall and a region called the divertor. The heat flux can be extremely high. Plasma facing materials and exhaust systems, which should be adequate for ITER, have already been developed, but their operation needs to be developed and qualified. The development of an adequate solution for the much larger heat exhaust of DEMO is still an experimental and theoretical challenge and calls for advanced plasma facing components and strategies to spread the power over as large an area as possible using radiative processes in the main and divertor plasmas, integrated with the main plasma and the rest of the DEMO design.

3 **Neutron tolerant materials** that can withstand the flux of neutrons up to 14MeV and maintain adequate structural and other physical properties for long periods over a sufficiently wide window of operation are not a significant issue for ITER but need to be developed for DEMO and commercial fusion power plants. This is the way to ensure efficient electricity production and adequate plant availability. The goal of the experimental and theoretical research is to produce suitable structural and high-heat flux materials that also exhibit reduced activation so as to avoid permanent waste repositories and allow recycling.

4 **Tritium self-sufficiency** is mandatory for DEMO and future commercial fusion power plants. Tritium self-sufficiency requires efficient breeding and extraction systems to minimise the tritium inventory. The choices of the materials and the coolant of the breeding blanket will have to be made consistently with the choice of the components for the transformation of the high-grade heat into electricity (in the so-called Balance of Plant). A successful Test Blanket Module (TBM) programme on ITER will be an important validation stage of the DEMO designs, and needs to be supported by substantial additional R&D to address performance uncertainties and feasibility issues.

5 Fusion has **intrinsic safety** features; their implementation in a coherent architecture is a key goal for any DEMO design to ensure the inherent passive resistance to any incidents and to avoid the need of evacuation in the worst incident case. The main development steps are methods for reducing the presence of tritium in the components extracted for disposal and the identification of appropriate disposal and recycling routes.

6 Combining all the fusion technologies, materials and the plasma into an **integrated DEMO design** will benefit largely from the experience that is being gained with ITER construction. Compared with ITER, DEMO will add a self-sufficient tritium producing blanket, more efficient technical solutions for remote maintenance as well as highly reliable components. Ensuring an adequate level of reliability and availability is one of the primary goals critical to the overall cost and attractiveness. In addition, DEMO will have a complete Balance of Plant including the heat transfer and associated electrical generation systems.

7 Fusion power plants must have attractive cost to play a significant role in the future energy supply. Although this is not a primary goal for DEMO, the perspective of **economical electricity production** from fusion has to be set as a target, e.g., minimising the DEMO capital and operational costs as a first step. Building on the experience of ITER, design solutions that demonstrate a reliable plant with a high availability are pursued. These aim at a credible basis for commercial energy production and transfer to industry. Socioeconomic research activities on fusion energy in the context of global energy needs and costs will help in maintaining a long-term perspective and in optimising the strategies for deployment of fusion.

8. In addition, a specific mission has been defined to **bring the stellarator line to maturity** as a possible long-term alternative to tokamaks. Stellarators have intrinsic advantages relative to the tokamaks as they do not need a plasma current and are therefore inherently steady-state capable and free from some classes of instability. However, their physics basis is presently not mature enough to achieve the goal of electricity from fusion early in the second half of the century. In the meantime, they provide useful scientific and specific technology information for the tokamak.

For all these technical challenges, candidate solutions have been developed individually and the goal of the programme is to demonstrate that they also work at the power plant scale and can be integrated into a consistent plant design. Based on these eight challenges, eight different missions have been defined to guide the long-term programme:

M1. Plasma regimes of operation:

Demonstrate plasma scenarios (based on the tokamak configuration) that increase the success margin of ITER and satisfy the requirements of DEMO.

M2. Heat-exhaust systems:

Demonstrate an integrated approach that can handle the large power leaving ITER and DEMO plasmas.

M3. Neutron tolerant materials:

Develop materials that withstand the large 14MeV neutron flux for long periods while retaining adequate physical properties.

M4. Tritium self-sufficiency:

Find an effective technological solution for the breeding blanket which also drives the generators.

M5. Implementation of the intrinsic safety features of fusion:

Ensure safety is integral to the design of DEMO using the experience gained with ITER.

M6. Integrated DEMO design and system development:

Bring together the plasma and all the systems coherently, resolving issues by targeted R&D activities

M7. Competitive cost of electricity:

Ensure the economic potential of fusion by minimising the DEMO capital and lifetime costs and developing long-term technologies to further reduce power plant costs.

M8. Stellarator:

Bring the stellarator line to maturity to determine the feasibility of a stellarator power plant.

For all the missions, a **theory and modelling** effort tightly integrated with the experimental programme will be crucial in providing the capability of extrapolating the available results to ITER, DEMO and commercial fusion power plants through carefully validated models and codes. This will also require detailed measurements in relevant experimental conditions. Special provisions will be made for high-performance computing and related supporting activities to promote both basic research and the modelling effort required under the various missions. The rapid development of **computational techniques and technologies** in the wider community is expected to be transformative, in the engineering as well as physics domain, and the fusion programme will be designed to exploit the advances.

4. How to face the challenges – the missions for the realisation of fusion

The eight missions listed in Section 3 all interact, as shown in Figure 1, but for clarity they are discussed separately in this and the following chapters. Section 4 describes the situation for each of the missions, Section 5 deals with how they are addressed, along with the facilities, activities and goals for different time periods.

Mission 1 – Plasma regimes of operation

The plasma is the source of the fusion power so it must be as high performance as possible consistent with being reliable and controllable, and fitting with the overall design. Plasma regimes of operation (based on the tokamak configuration) for power plant application need to achieve, sustain and control stable burning plasmas with high fusion gain by minimizing the energy losses due to small-scale turbulence and by controlling plasma instabilities. Access, sustainment and control of the plasma regimes of operation require the availability of reliable and efficient multi Mega-Watt long duration heating and current drive systems. In addition, in order to comply with acceptable heat loads on the plasma facing components (Mission 2), a large fraction of the total heating power (mostly from alpha particles) must be radiated from the confined plasma to spread the load around the vessel, while minimizing any adverse impact on fusion power production due to cooling the hot centre. Ideally, these regimes would need to be maintained in fully steady-state conditions (see also Mission 8 for the common tokamak/stellarator physics and technology of steady-state operation). However, it may be sufficient to maintain them for a duration of several hours (inductive regimes), which significantly simplifies the plasma and heating requirements, and for today's established plasma scenarios allows higher net electrical power output from a fusion plant. Specific emphasis will be given to plasma control using systems compatible with power plant conditions; the goal is to make the operator's role as simple as possible. Off-normal events such as disruptions[36] and edge-localized modes (ELMs[37]) must be avoided or adequately mitigated.

Mission 1 can be fully accomplished by ITER and the accompanying research programme, together with integration of an exhaust solution and the rest of the DEMO engineering design (Missions 2 and 6; see Figure 5). ITER's inductive regimes of operation will be demonstrated with the achievement of the Q=10 milestone and the demonstration of controlled long-duration / steady state regimes of operation will follow. In this regard, it should be noted that ITER will have to address scenario issues for DEMO that go beyond the achievement of the headline goals of Q=10 (inductive) and steady-state operation. It will be necessary to investigate DEMO specific scenario issues as part of the ITER research programme addressing experiments, theory and predictions with validated theory-based models. DEMO issues to which ITER will make essential contributions include the progress on fast particle physics and theory validation for burning plasma regimes where performance will be dominated by fusion born fast particle dynamics, the development of operation regimes without off-normal transient events (e.g., edge localised modes and disruptions) and the sustainment / real time control over long durations of a burning plasma state using only DEMO relevant actuators and sensors (diagnos-

[36] A disruption is the rapid and usually unexpected termination of the plasma, resulting in large thermal and mechanical loads on the tokamak structure.

[37] ELMs lead to short intense pulses of energy and particles to the plasma-facing components, shortening their life.

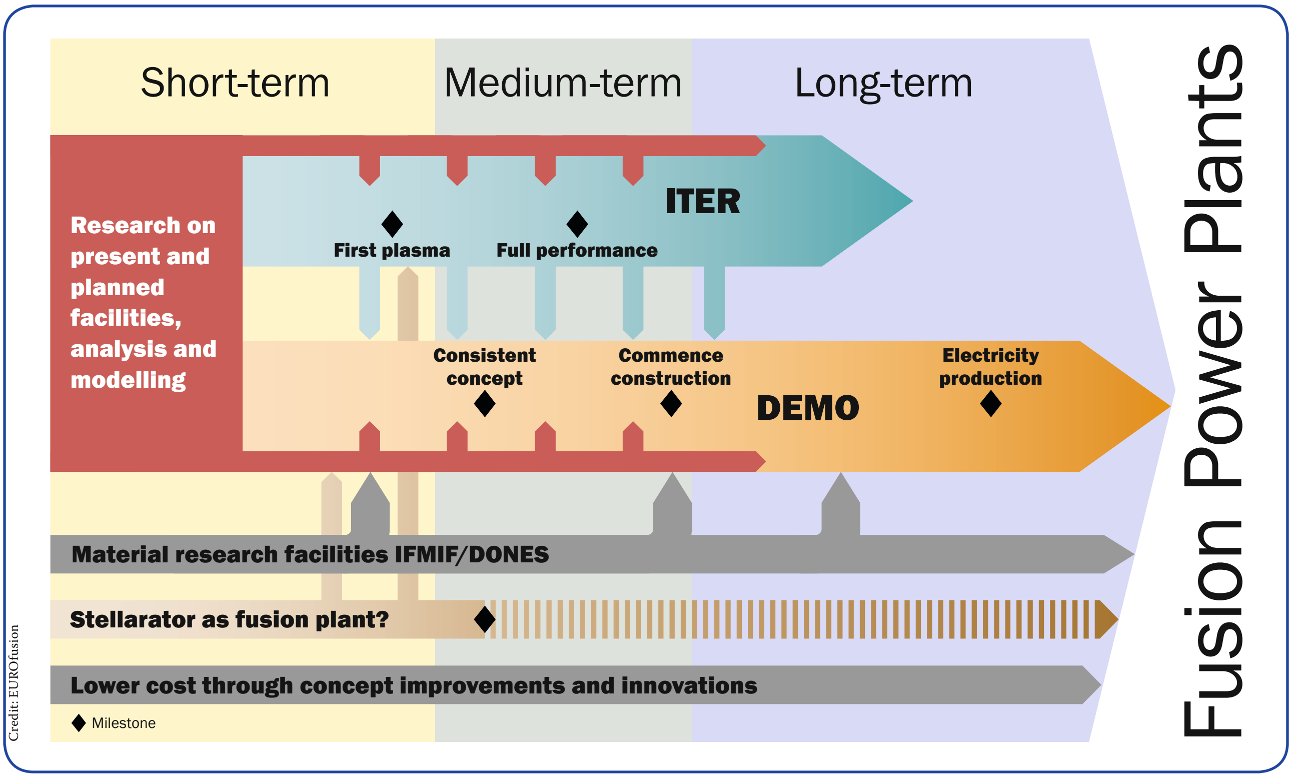

Figure 5: Mission 1 and 2 elements of the roadmap (coloured) involve JET, JT-60SA, the medium-sized tokamak facilities, and the plasma-facing component test facilities (the red arrows at the top). Also ITER will contribute to tackling these two missions and give input to DEMO. The Wendelstein 7-X stellarator (Mission 8) will give valuable input to Missions 1 and 2.

tics). Additionally, ITER can provide important results on the compatibility of a high radiative power fraction, required for power exhaust in DEMO, and high confinement taking advantage of likely future ITER upgrades to reach the maximum possible level of input power. However, achieving full compatibility may require relying on a divertor concept that cannot be tested on ITER, as further detailed under Mission 2. The overall plasma scenario may need to be adjusted to match these alternative exhaust concepts. Important elements of Mission 1 are the preparation of ITER operation on JET (inductive regimes) with similar fuel mix (deuterium and tritium), and, with the same combination of plasma facing materials as ITER, and operation of JT-60SA (steady-state as well as inductive regimes). Small and medium size tokamaks, both in Europe and abroad, with proper capabilities[38], will complement the activity on JET and on JT-60SA for preparing ITER operation and by addressing specific DEMO issues, e.g., alternative modes of operation without off-normal transient events for power plant application, controlled long duration operation at high density with a high level of radiation, and if possible simpler to operate. In addition, the exploitation of dedicated fusion technology facilities such as the Neutral Beam Test Facility will provide improvement in the availability, reliability and efficiency of externally applied heating and current drive sources.

No major gap[39] exists in the foreseen world programme for Mission 1. However, the success of ITER and DEMO will rely on: (i) the strong integration of the experimental progress made in present fusion facilities through theory-based first principle and integrated modelling to identify which innovations will extrapolate to ITER burning plasma state and DEMO, and, (ii) on adequate enhancements of JT-60SA (to be carried out in the period beyond 2025) and ITER (in the period beyond the achievement of Q=10 milestone). These include enhancement of the heating and current drive capabilities of the control system and operation with a full metal wall. The experience with tokamaks to date is that with a suitably careful design their operation and systems can be adapted to discoveries made after their core design is frozen. Therefore, it is reasonable to use this latter period of ITER operation to inform the operational phase (not the core design) of DEMO. This will be reinforced by first principles and integrated computation of non-linear coupled plasma physics/technology phenomena to understand the role of various effects in present operational scenarios and their extrapolation to ITER and, especially, DEMO. It has become clear that a strong theory and modelling programme is essential because empirically-based predictions are uncertain in unexplored environments like ITER and particularly DEMO, and this will be a stronger focus than foreseen earlier. It will make use of advanced computational techniques and high performance computers. Ultimately, the plan is for theory, computation developments and knowledge integration to provide a comprehensive fusion facility simulator (e.g., numerical tokamak) capable of a level of simulation fidelity to predictively reproduce the whole complexity of the fusion facility coupled with all the ancillary sub-systems (e.g., diagnostics, heating and current drive sub-systems, control systems, etc.). This would allow prediction and optimisation of the performance of a full ITER discharge using essentially all the accumulated understanding of tokamaks, and similarly for DEMO to support design and construction decisions.

[38] The relevant capabilities include: ITER-like geometry, metallic plasma facing components, auxiliary systems required for realising ITER scenarios.

[39] Gaps are defined here as part of the programme that cannot be addressed with the existing facilities or those under construction.

Mission 2 – Heat-exhaust systems[40]

Heat-exhaust systems must be capable of withstanding the large heat and particle fluxes of a fusion power plant and at the same time allow as high performance as possible from the core plasma. The **baseline strategy** for the accomplishment of Mission 2 consists of operating with a conventional single-null divertor in a full-metal PFC environment and reducing the heat load on the divertor targets by radiating a sufficient amount of power from the plasma and by producing "detached" divertor conditions. It is assumed that this will require an active control system. This approach is presently pursued using the existing set of facilities to assess the extrapolability of the results to DEMO and a fusion power plant. Finally, ITER will test this approach in support of DEMO operation. Maximising the chances of success of this strategy requires a programme including experiment, theory development, modelling and system design in the areas of divertor/scrape-off layer physics and plasma wall interactions, and in integration with the core plasma scenarios. In particular, the development of a predictive modelling tool for exhaust will require an increased effort in this area in the first period of this fusion research roadmap. Finally, the performance of the plasma facing materials and components in the presence of neutron damage needs to be assessed and optimised in terms of lifetime versus performance and load carrying capability (with Missions 3 and 6).

The integrated plasma exhaust solution includes protection of the first wall. If the radiative and conductive losses from the main plasma are too high or too localised then the first wall armour becomes challenging due to both the heat load and possible impact on the tritium breeding (attenuation and absorption of neutrons). Furthermore, ITER and DEMO will both require dedicated diagnostics to ensure efficient operation of the plasma-facing components (wall protection systems, fuel retention and dust diagnostics, etc.).

Although highly radiative core plasmas with good plasma performance have been obtained in present day devices, it needs to be verified whether high-confinement regimes of operation are compatible with the larger core radiation fraction required in DEMO (see Mission 1). If alternate exhaust strategies were to be only explored in the event of ITER showing that the baseline exhaust strategy cannot be extrapolated to DEMO, the realisation of fusion would be delayed by at least 10 years. Hence, in parallel to the necessary programme to optimise and understand operation with a conventional divertor, an aggressive programme to extend the performance of high heat flux components and to develop **alternative solutions** for the divertor is necessary as

[40] A comprehensive strategy for all exhaust concepts has been developed within EUROfusion: "Strategy for the Plasma Exhaust" (Report of the PEX AHG, 2016) – Phase 2.

a possible back-up solution for DEMO. The leading options have been identified (double-null, snowflake, X- and super-X magnetic configurations as well as the use of liquid metal targets) and are being tested at proof-of-principle level in medium-sized facilities using a number of upgrades agreed in 2017. These concepts (or combinations) will not only need to pass the physics proof-of-principle test but also to show that they work and are controllable at DEMO-parameters. Moreover, their technical feasibility and design integration, remote maintainability in DEMO must be confirmed. It is expected this will be addressed by an iterative optimisation of the plasma design and the overall DEMO system design, to determine the further steps. Just as for the conventional divertor, this requires an integrated programme including experiment, theory development, modelling, technology, engineering and system design. The aim is to arrive at a concept selection in the first half of the 2020s, consistent with the DEMO planning (Mission 6).

The ultimate goal is to bring an alternative exhaust strategy (or a combination of baseline and alternative strategy) to a sufficient level of maturity to allow the DEMO Engineering Design to proceed even if the performance of the baseline divertor is not entirely satisfactory. However, for the alternative approaches the extrapolation from proof-of-principle devices to DEMO based on modelling alone is considered too large. If a promising alternative concept emerges, a divertor optimised for the concept will be implemented in the Italian Divertor Test Tokamak (I-DTT) facility as a joint European collaboration.

Mission 3 – Neutron tolerant materials

Preamble: DEMO and future commercial fusion power plants will need robust materials incorporated into reliable components, able to perform well under the combined neutron, thermal and mechanical loads. The driving forces for material development and complementary engineering include safety, reliability (robustness), thermal efficiency, economy and environmental sustainability. Mandatory functions include tritium production, heat removal capability, neutron and gamma shielding and low after-heat. Safety and environmental aspects also require low T inventory, low activation, and low levels of waste. Economics and low cost require high availability, high performance (extended operating temperature windows), extended lifetime, easy maintenance and replacement, easy industrial manufacturing and low cost decommissioning. The list of requirements and restrictions (in particular activation and waste) significantly narrows down the chemical composition and material classes, and this has led to a reduced, but still extensive portfolio. The Mission 3 elements to the roadmap are depicted in Figure 6.

A specific **fusion challenge:** In addition to the displacement damage (indicated by dpa- displacements per atom) observed with fission neutron spectra, the high energy neutrons in a fusion spectrum produce He and H in components near the plasma with generation rates that can be orders of magnitude higher than that in fission-based Material Test Reactors (MTRs). This can substantially accelerate irradiation embrittlement, depending on temperature and deformation rate, and promote early degradation and failure.

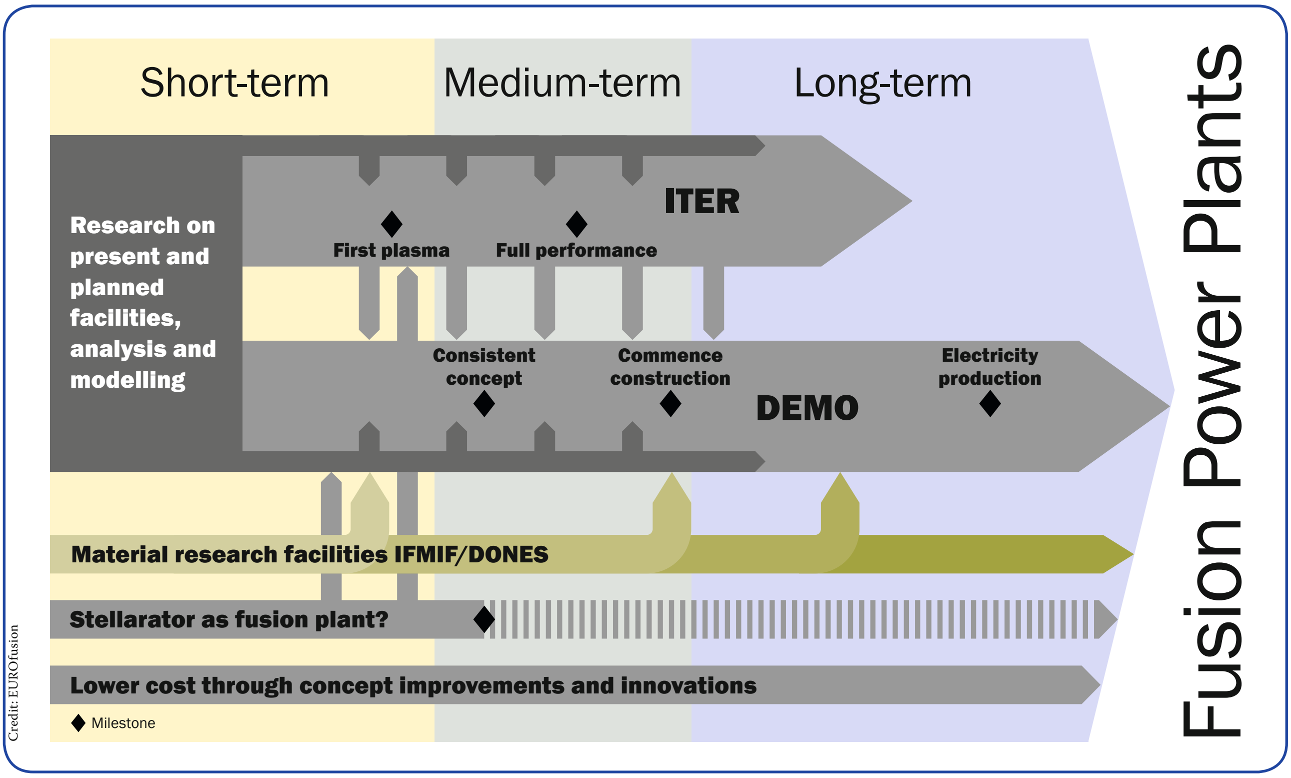

Figure 6: Mission 3 elements of the roadmap (coloured) involve testing on Materials Test Reactors and ultimately validation in the International Fusion Materials Irradiation Facility (IFMIF) or its smaller version IFMIF-DONES (DEMO Oriented Neutron Source).

The **main tasks** for the next decade(s) include: (a) characterize and finally **validate baseline materials**, thereby (b) develop an adequate **engineering materials property handbook and design rules** for DEMO environmental (irradiation) conditions, (c) develop **advanced materials**, and (d) select and optimise **functional materials** for some breeding options and various components and systems.

The **portfolio of baseline structural and high heat flux materials:** The structural and armour **'baseline' materials** for DEMO is built upon (i) EUROFER(97) an RAFM (Reduced Activation Ferritic Martensitic) steel as the structural material for the breeding blanket, (ii) tungsten as the plasma facing component armour material, and (iii) CuCrZr, a copper alloy, as the heat sink material for the divertor coolant interface.

The **strategy for design and licensing of divertor and blanket structures** (Missions 2 and 4) is driven by material issues and constraints in knowledge. As described in Mission 6, it is foreseen that DEMO will utilise a "starter" blanket using EUROFER RAFM steel and conservative design margins with a restricted operation window where He-effects are considered low to moderate, e.g., for RAFM steels below about 20 dpa (20 dpa corresponds to around 2 full power DEMO years, which will be ample to demonstrate effective electricity production). This will use a data base mainly gained from MTRs with moderate extrapolation, augmented by selected data from a dedicated Fusion Materials Neutron Source (FMNS; see below) to validate the design rules for this dpa limit and license for first operation. Depending on extensive further data from an FMNS when helium effects will become more important, the operating limits and lifetime of these first components may be extended. If necessary or desirable, there can be a move on to a second set of blankets with improved structural materials for longer life (e.g., up to about 50 dpa) and improved temperature window (higher thermal efficiency), i.e., advanced materials. In addition to developing the base materials, joining techniques need to be developed and qualified.

The **facilities**: Currently, engineering material data, both properties and rules, are based on fission neutron irradiation campaigns, not fully covering the temperature and other operational conditions, thus implying large uncertainties that are compensated in engineering design by large "safety factors". Improved design criteria are needed for an optimised design and these in turn need additional and more coherent data and knowledge. Achieving all this needs various comprehensive irradiation campaigns in MTRs, complementary ion beam facilities, as well as a range of materials test facilities (including high heat flux and plasmas), all tied together with a **comprehensive multi-scale modelling programme** to combine information and predict in-service performance. The validation and qualification of materials for the first DEMO operation, in particular for licensing and regulatory authorities, give additional requirements, and a powerful **fusion material neutron source (FMNS)** with a fusion-like neutron spectrum is mandatory.

IFMIF, as developed with Japan under the Broader Approach, provides the best fusion-spectrum device towards validation at high neutron doses. To accelerate the schedule, a more modest facility, IFMIF-DONES (in Europe) or A-FNS (in Japan), with an IFMIF-like neutron spectrum, is planned. This facility will have a reduced scope aligned with the need of "early" DEMO operation and yet with the possibility of a staged approach to full IFMIF. Construction of IFMIF-DONES needs to be started as soon as possible.

Advanced/alternate structural and high heat flux materials: It is presently assumed these shall be of the same material class as the portfolio of baseline materials, i.e., RAFM steels, tungsten, and copper alloys or composites of these materials. The present parallel development focuses on 9Cr RAFM steels that are operated (a) at lower temperature for water-cooled applications and (b) at high temperature for other coolants and higher thermal efficiency. Experience from the successful approach to make EUROFER(97) an AFCEN-RCC code qualified material indicates that ~ 10-15 years are needed to produce a fully developed and characterised nuclear-grade material. Similarly, advanced/risk-mitigation materials for high heat flux applications have to be developed, which include fibre-or particle-reinforced materials. Attention must also be given to scalability in manufacturing towards industrialisation.

Functional materials: These are of many types for many purposes and include: breeder materials (e.g., lithium-containing ceramics); tritium barriers, anti-corrosion coatings, insulators, windows, metal mirrors, fibres and sensors for plasma heating, diagnostics and remote maintenance systems. Their functional and mechanical performances have to be considered together along with the specific challenge of joining intrinsically dissimilar materials.

Mission 4 – Tritium self-sufficiency

The feasibility and reliability of the **tritium breeding blanket** is crucial to the operation of DEMO and commercial power plants. For the first blankets on DEMO, the capability to develop reliable solutions that can be delivered in the required time must be secured very early so as to decrease delays on the critical path to demonstration and subsequent deployment of fusion power. The technical characteristics of the breeding blanket to be used (e.g., the type of coolant, the type of breeder, etc.) affect the overall design layout, maintenance and safety of the nuclear plant, and because it interfaces with all key nuclear systems (e.g., plasma, primary heat transfer systems, tritium recovery and purification systems, heat exchangers) as well as energy storage and power conversion systems. Undisputedly, ITER represents a first and unique opportunity to test breeding components in an actual fusion environment. There is a strong Test Blanket Module (TBM) programme for ITER whose R&D will inform the DEMO design decisions and whose results will support DEMO operation and improved blankets as well as the construction decision. This means that the DEMO blanket design programme and the European part of the ITER TBM programme should be aligned, e.g., so that the TBM programme covers a wide enough combination of coolants, breeding materials and technologies to match attractive breeding blanket design options for DEMO. This alignment is described later under Mission 6. It is proposed to test in ITER both high temperature/ high pressure coolants (helium and water) and breeder materials (liquid PbLi and solid ceramic/Be). Blankets for commercial power plants may need to be more advanced than the main blanket selected for DEMO, and so DEMO should be equipped to test improved designs, which could be further developed using for example international collaborations.

Figure 7 shows the contributions of Missions 4, 5 and 6 to the roadmap.

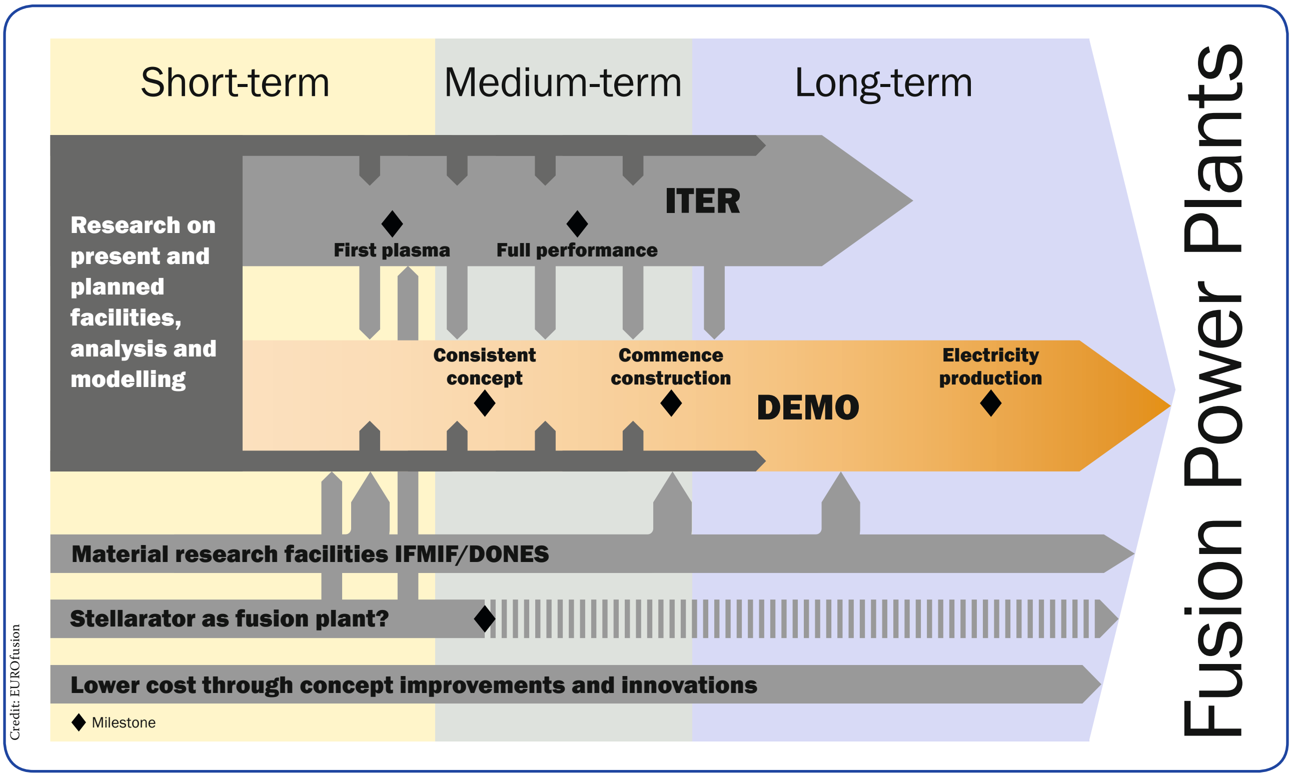

Figure 7: Mission 4, 5 and 6 elements of the roadmap (coloured) involve work on the Tritium Breeding Blankets (Mission 4), Safety (Mission 5) and the Integrated DEMO Design (Mission 6).

Mission 5 – Implementation of the intrinsic safety features of fusion

The experience of the ITER licensing process has provided confirmation of the intrinsic safety of fusion and has pointed out the areas that are expected to impact the licensing of a fusion power plant. In this field, the main ways in which DEMO differs from ITER will be (i) the use of high pressure and high temperature coolants to remove the power from the blanket and to convert this into electricity (using a conventional power conversion system), (ii) much larger tritium throughput and inventories, (iii) higher neutron fluence on the blanket and divertor materials, with the associated challenges related to the management of activated materials. Investments will have to be made in the development of efficient detritiation techniques, effective material **recycling** capability and in the selection of adequate disposal routes. The roadmap foresees a fusion plant free from any materials that could be used for proliferation, and sensitive radioisotopes added should be readily identifiable and hence straightforward to control. However, since neutrons can be used to change one element or isotope to another, safeguards would be applied, at the design level, in manufacture, operation, maintenance and decommissioning. The experience of ITER emphasises that the safety of the device against 'Design Basis Accidents' must be assured by 'passive safety' and 'defence in depth', and puts the emphasis for a toroidal confinement device on the integrity of the vacuum vessel, the existence of expansion volumes, and the limitation of directly mobilisable inventories. The containment systems for DEMO, notably the vacuum vessel, are intended to use well-proven materials (i.e., not new fusion-specific ones) and the device is designed to ensure operation in well-proven engineering regimes, and in particular ensure that the neutron effects are modest and covered by fission experience (i.e., the vessel is well shielded). In this sense, the structural integrity of the internal components will not be the primary licensing issue, provided engineering (e.g., double containment) barriers are designed in. An engineering code must be developed for designing in-vessel components, such that it can be demonstrated to the licensing authority that DEMO meets the regulatory requirements. Although some of the materials to be used will be in an early stage of development, it is expected that it will be already possible to exploit the benefit of reduced activation materials for the first set of DEMO in-vessel components. Specific techniques for recycling will be developed in parallel to the development of low activation materials (Mission 3). The experience from DEMO is expected to translate directly to commercial fusion power plants with few additional issues.

Mission 6 – Integrated DEMO design and system development

Mission 6 is focused on the integrated design of DEMO. Together with accompanying longer term R&D aimed at fusion power plants in other missions, it aims towards the overall roadmap objective of preparing the entry into the commercial phase of fusion. The analysis of DEMO requirements, system modelling, and design integration of the various systems, including the plasma (Missions 1 and 2), that form the overall DEMO plant is key to the success of Mission 6. It will be necessary to assess the influence of key design drivers on the achievement of the overall plant mission requirements. The **experience gained in the ITER construction** will be to a large extent directly used for the integrated DEMO design (see Figure 4).

The DEMO planning takes into account: (i) the revised ITER schedule (later achievement of Q=10), and (ii) a recommendation from the DEMO Stakeholder Group (SHG) to explore a broader concept design space.

The new sequence for the pre-conceptual, conceptual, and engineering design of DEMO consists of three phases, of which the first two are expected to be completed by 2030 (see Figure 8).

- **Pre-conceptual design:** Multiple plant design concepts will be assessed in parallel, and compared against a reference concept (referred to as the "baseline"). Emphasis should be on engineering and operational challenges, safety, power conversion aspects, and reliability of the power plant. A concept primarily comprises the major parameters (size, aspect ratio, field, current), plasma configuration (especially the exhaust), whether pulsed[41] or steady state (or both), the coolant and balance of plant, and the remote maintenance approach (e.g., vertical access). Sub-variants can include different breeder materials, different heating and current drive combinations, modest changes in plasma scenario, different plasma facing components etc. The completed engineered configuration of the whole plant is referred to as the architecture. This phase culminates in the down-selection to one or more concepts with the highest likelihood of success (the baseline(s)), and potentially one alternative design for back-up and/or exploitation of potential opportunities (using promising technologies that are still being developed).

- **Conceptual design (Conceptual Design Review and Engineering Design Activity) preparation:** The selected concepts are taken in the conceptual design phase

[41] It appears that cyclic operation of tokamaks rather than steady state can be more energetically attractive since the power to sustain the plasma in steady state is presently an inefficient use of the electrical output. Energy storage can be used to maintain continuous electrical output and reduce thermal cycling if required. There are several aspects to consider and this area is under continual review.

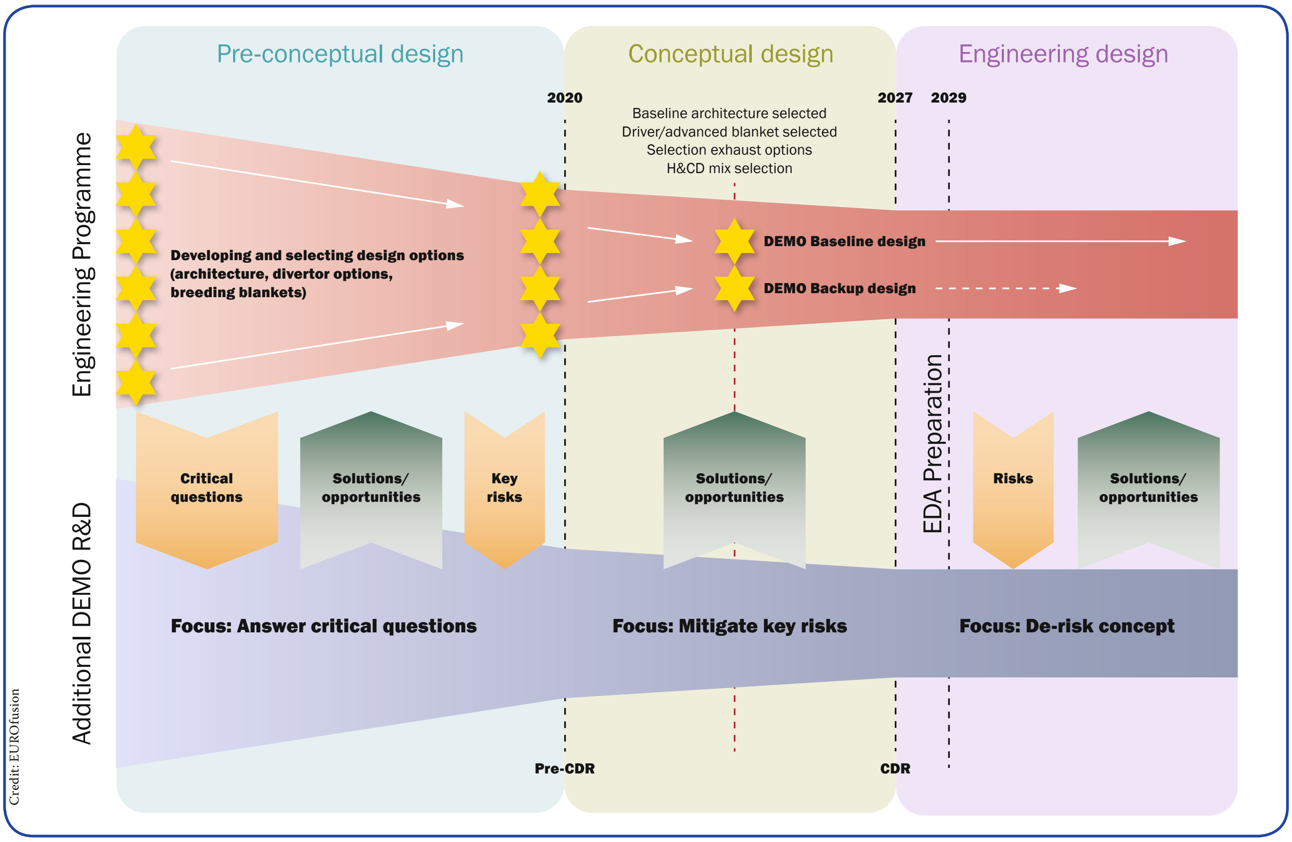

Figure 8: Flow diagram for the pre-conceptual, conceptual and engineering design of DEMO. The number of options (indicated by the yellow stars) and the timeline may need to be updated depending on the results obtained. The top funnel depicts the DEMO project, while the bottom funnel depicts part of the supporting prospective R&D Programme.

and further developed and compared. If possible a single concept and architecture (probably still with sub-variants) is selected in preparation for a concept design review.

- **Engineering design:** The selected DEMO architecture enters the engineering design phase where system level solutions are progressively selected and substantiated with detailed engineering assessments and technology R&D. This will also include prototype testing of the major components and systems to confirm and optimise their operational use. The selection of a site and the start of construction around 2040 linked to specific results from ITER is also envisioned in this phase.

- This strategy is based on several factors. First it is assumed that only one concept can be taken into the Engineering Design Activity phase. Secondly, is recognised that pursuing multiple fully-integrated concepts in parallel during the Conceptual Design Activity will not be easy. Furthermore, to meet the overall target of an electricity-generating DEMO early in the second half of the century, it is necessary to tightly focus the activities. Suitable accompanying activities can mitigate the risks that result from early decisions based on limited information, and where feasible, DEMO will be capable of testing some alternative concepts, such as advanced blanket modules. Finally, if the chosen concept encounters major unforeseen problems, it should be possible for the design team, by then highly experienced, to rapidly adopt an alternative approach, provided there has been focused R&D on these alternative concepts in parallel.

Missions 1-4 show there are several concepts and variants under consideration, and decisions are needed before data from ITER emerges. Two critical decisions which almost certainly cannot be made during the pre-Conceptual Design Activity are the main blanket and coolant, and the plasma exhaust concept. For the blanket, the proposal for the European TBMs developed for ITER is to pursue both ceramic and PbLi breeders, and both helium and water coolants. A present idea is that both would be implemented on DEMO, one as the main "driver" blanket, the other as an alternative or advanced option, for a small number of blanket modules, with a different coolant. A well-informed choice could be made in the mid-2020s based on performance analyses of the designs, targeted R&D and manufacturing assessments made jointly with the ITER TBM programme. Further blanket options could potentially be tested in port plugs later. For the exhaust the selection of an alternative concept is planned by the mid-2020s (see Mission 2). Since the experimental and modelling information on both conventional and alternate exhaust will only emerge later it may be necessary to keep both options open for longer.

Finally, while the DEMO device is the centre of the preparation for commercial power plants, it is not the only contributor. Some technologies and features can be part of a power plant without being included in DEMO, others can be developed in collaboration with DEMO-like facilities in other parties, and this is in mind for most missions.

The details of the DEMO design and development plan together with the description of the proposed systems engineering approach for the assessment of the design are described in ref.[42]; this encompasses defining the drivers and issues that need to be addressed in order to enable decision-making against a range of attributes. The plan shows due consideration to key external constraints (e.g., political constraints, availability of tritium, nature of the final ITER operational scenario(s), harnessing ITER competence and capitalising on ITER industry experience). Investigation and assessment of alternative plant concepts are given increased precedent in the pre-conceptual phase. Design variants are managed through a structured decision making process as part of the Systems Engineering approach. The framework should, in particular, give attention to design readiness and technology maturity, remote maintainability, industrial feasibility, costs, nuclear safety and licensing aspects. Increased involvement of industry in the design and monitoring process from the early stage to ensure that early attention is given to industrial feasibility, costs, nuclear safety and licensing aspects.

In particular, specific system development is required in some areas, and these are mostly already underway.

- In the area of **magnets**, the ITER technology of Nb_3Sn forms the basis for DEMO. More advanced cable solutions are being developed to avoid degradation of performance under cyclic operation and to reduce overall system cost. With the same cost objective, simplified magnet construction routes are also being investigated. New developments that could bring significant improvements for fusion power plants, such as high temperature superconductors, must be closely monitored, as they could influence the overall DEMO design.

- In the area of **heating and current-drive** systems:

  - In neutral beam systems, there is no foreseen need to increase energy above the ITER value of 1 MeV. Modularity could improve reliability. The ITER Neutral Beam Systems will give important input. Enhanced efficiency through energy recovery systems and improved neutralisation are being explored.

  - An increase in the frequency of electron cyclotron systems (up to ~240GHz) could be required together with step-tuneability (and/or remote steering) and broadband window development. Modularity is considered to be the right approach to high system reliability and can be ensured by moderate power units. Increase of source efficiency above present values (~50%) is under investigation mainly through energy recovery.

  - Ion cyclotron heating and current drive will be used on ITER, and possibly systems at the lower hybrid frequency. Application to DEMO is likely to need significant advances, for example to couple the power over longer distances between the antennas and the plasma.

[42]G. Federici et al., Revised DEMO Design and Development Plan (As part of the update of the EU Roadmap to Fusion Electricity) 2N2FJB).

Due to the engineering implications on the load assembly, improved concepts would need to be developed on smaller facilities before inclusion in the DEMO design.

- The development of the **remote maintenance** system for DEMO is driven by the need to maximise the overall plant availability, and therefore, minimise the plant down time for the foreseen maintenance operations. To achieve this:

  - Novel concepts, probably relying on vertical removal and replacement of large segments must be developed and validated, in particular, for the breeding blanket system. This requires that the design of the in-vessel components (Mission 2 and Mission 4) and their interfaces be optimised for reliable remote maintenance (RM) operations from the outset, and this is happening.

  - Validation of specific design concepts for maintenance aspects such as in-vessel attachments, remote maintenance transporters, servo manipulators, in-situ precision cutting and welding is needed and requires in-depth engineering studies and preliminary demonstration by using simplified mock-up and test facilities, which are underway. In the DEMO conceptual design phase, large-scale testing of proof-of-principle blanket maintenance in particular will be required.

  - Conceptual design of ex-vessel RM (near-vessel inside bio-shield), of some balance of plant components, of transport systems and of hot cell RM is required.

  - Although the designs are not directly transferrable, several important lessons will be learned from RM activities in ITER and in JET.

- In the area of vacuum and pumping because of the requirement to have a self-sufficient tritium fuel cycle and also operation for pulses of a few hours, systems based on continuously working pumps with an effective tritium separation and recycle function of the exhaust should be developed and tested, and low inventory designs are needed (significant advances already made compared with ITER).

- Due to the power plant environment, many present and even ITER **diagnostic technique**s will not be applicable in DEMO. Moreover, the number of measurement types and actuator available for plasma control will be significantly reduced. To reduce the chances of the situation becoming critical, it will be necessary to develop new diagnostic techniques that are DEMO-relevant. Specific activities to demonstrate the control of plasma regimes of operations with DEMO relevant systems are foreseen in Mission 1.

Above all, special emphasis will have to be given to the design integration, **maintainability, reliability** and licensability of components.

The choice of the **balance of plant** (BoP) has a number of consequences on the choice of blanket coolant and materials. BoP to match both water-cooled and helium-cooled blankets are being designed, modelled, analysed and evaluated using appropriate tools and the involvement of industrial experts. Basic test-bench R&D on some of the key issues specific to fusion (T-control in heat exchangers, response to cyclic operation, BoP component failure modes, etc.) will be needed.

Key decisions that are expected to be made in advance of the end of the conceptual design phase include: (i) Divertor configuration selection (see Mission 2) and first wall protection strategy; (ii) Breeding blanket concept and coolant selection; (iii) Plasma operating scenario selection; (iv) H&CD mix selection. These are needed to enable resources and activities to be focused on the preparation of a sound plant concept design in advance of the Concept Design Review.[43]

Mission 7 – Competitive cost of electricity

Fusion power plants must have attractive cost to play a significant role in the future energy supply. The ITER experience continues to underline the importance of low capital and construction cost; operational and decommissioning costs must also be as low as possible. Furthermore, it will be important to make fusion facilities and their operation as simple as reasonably possible.

DEMO is a development step and its own cost may not be representative of the cost of fusion deployment, but its cost must be minimised for many reasons. Cost should and will be a key driver for DEMO concept selection and optimisation, and for the ancillary systems incorporated. This is addressed via Mission 6, and will make DEMO a reference point as well as a rich source of ideas and realistic examples for cost reduction. Further reductions in cost will be needed for commercial power plants, both for the first of a kind, and also for series production which is when the biggest reductions will be sought. A programme of innovation and cost reduction can potentially make magnetic fusion devices significantly more attractive, most probably in the long-term. This is Mission 7, which is schematically depicted in Figure 9.

The capital and running costs of a fusion plant come from many elements, and the R&D costs and facilities should also be considered in the overall picture. Cost should be considered holistically, especially when there are so many direct and indirect interactions between different systems. Improved technical solutions in one area can lead to improvement elsewhere, but may also lead to more complexity and overall cost. An effective organisation is also critical for cost control and minimisation, and also plant simplification. Completing projects faster, including faster design cycles and avoiding late changes, usually reduces the overall costs. More widely, the total cost minimisation across the electricity grid could be considered, including the temporal and geographical interaction with distributed and intermittent renewable power sources (such as wind and solar) and energy storage.

Advances and research that are expected to lead to lower costs include the following:

[43] Revised DEMO Design and Development Plan (As part of the update of the EU Roadmap to Fusion Electricity) 2N2FJB.

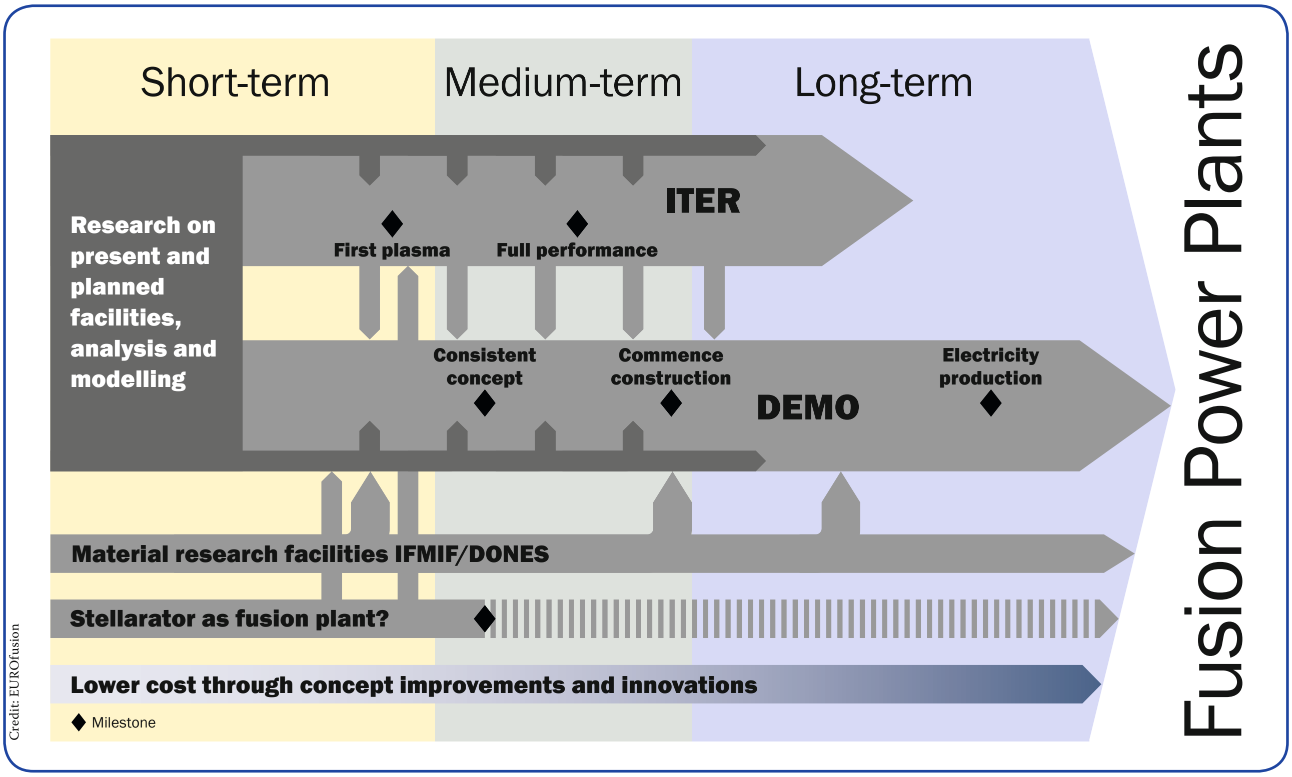

Figure 9: Mission 7 elements of the roadmap (coloured) involve work overlapping basically with all other Missions. It is depicted here as a single line, but in all aspects of the fusion roadmap an underlying aim is to find concept improvements and innovations that lead to lower costs and/or higher performance.

Higher performance plasma for higher Q or smaller devices: Improved scenarios with reduced turbulent transport could lead to higher power density in the plasma and could assist longer pulse or steady state operation, but they are not yet mature or reliable enough to be adopted and may lead to higher power density for the materials. New physics in higher temperature burning plasmas may reveal new options [Missions 1, 2, 3, 6].

Longer plasma duration including steady state: This would be attractive to the utilities, and could increase plant lifetime (fewer cycles). It would also reduce the requirements on on-site energy storage systems. Improved plasma scenarios, typically with higher power density, and high efficiency heating and current drive systems are needed to reduce the drain on the electrical output of the power plant. Stellarators can be intrinsically steady state [Missions 1, 6, 8].

Advanced higher field or higher temperature magnets: Higher field and/or higher temperature superconducting magnets can provide higher plasma performance and/or lower refrigerant power (stronger structural materials and/or thicker supports may be needed) [Missions 6, 7].

Higher thermal efficiency breeding blankets: The thermodynamic efficiency of the plant will increase if the blanket can operate at higher temperatures than allowed by EUROFER in contact with the primary coolant (heat transfer medium). Advanced steels have the potential to allow higher operation temperatures than EUROFER; they are presently expensive to produce and still limited in temperature range. Another option is for the primary coolant to be substantially hotter than the steel: Dual-Coolant Lithium Lead (DCLL) concepts use flowing PbLi as both breeder and heat transfer medium, with high pressure helium to cool the structures. The fusion neutrons heat the PbLi, and so advanced thermal insulation between the PbLi and the steel would allow the PbLi to be hotter. Such concepts might be tested in a DEMO-based on more conventional blankets [Missions 3, 4, 6].

Lower materials costs: Fusion-grade structural steels and other materials (including functional materials) are presently expensive because structural materials development is mainly driven by the high purification level requested to achieve reduced activation and waste level. However, there is scope for coupled improvements to the materials design and materials manufacturing process in particular for high heat flux and functional materials or ODS steels not yet produced at full industrial level [Mission 3].

Lower component manufacturing and assembly costs: Fusion components are traditionally costly; however, with improved designs and advanced manufacturing techniques, there are prospects for cost reduction and assembly simplification – this is a key area for economics of scale [Missions 6, 7].

Increased availability through improved remote maintenance: Operational costs/MW yr(e) can be cut by reducing down-time. Options include designs that are easier to handle as well as improved and more flexible remote maintenance systems [Mission 6].

Optimising the path from first to many of a kind: the series cost as well as the cost of the first plants will be critical to fusion's deployment, and experience can be gained from relevant industries and other organisations (such as space research and those industries involved in delivering ITER components). The rate of growth of power plant deployment also has to be assessed (what is feasible from the fusion industry, and what fits with the evolving energy market).

Several ideas to reduce overall costs are already embedded in the EUROfusion R&D programme. Some of the new ideas have emerged from the increased interaction with communities outside fusion (virtual engineering and additive manufacturing in particular). The avenues described here and other topics can be pursued within the main Missions and/or with special initiatives. New ideas will emerge, for example, from Enabling Research (Section 7). An early step would be to analyse the cost drivers, both technical and organisational.

Mission 8 – Stellarator

In order to bring the stellarator configuration to maturity as a possible long-term alternative to tokamaks, the European programme will focus primarily on the optimised stellarator Helias (Helical-Axis Advanced Stellarator) line, a stellarator optimisation approach based on modular field coils (see Figure 10). Work on other stellarator lines (e.g., Heliotrons and compact stellarators) will continue as part of the national programmes or in the frame of international collaborations. For the period 2014-2021, the main priority has been the first-phase completion and commissioning of the Wendelstein 7-X machine (achieved in 2015). Further plans include the final completion of the device as well as its scientific exploitation. The most important goals are to validate the energy and particle confinement of optimised stellarators, and to demonstrate the island divertor as a way to manage the heat and particle exhaust (Mission 2). Demonstration of high performance plasma scenarios under steady-state conditions will be achieved beyond 2020. These activities will also have an impact on the progress of the basic understanding of plasma physics in support of Mission 1 and 2, and specifically in support of the ITER preparation. One of the main reasons for pursuing the stellarator line arises from their not needing a large plasma current. This leads to an inherent steady-state capability and observation that there are no plasma disruptions, both of which are challenges for the tokamak. If Wendelstein 7-X confirms the good properties of optimised stellarators, a next-step HELIAS burning plasma experimental device may be required to address the specific dynamics of a stellarator burning plasma. The exact goal of such a device can be decided only after a proper assessment of the Wendelstein 7-X results and the likely **needs of a stellarator power plant**. In the long run, it is expected that this strategy, together with the technology results from a tokamak DEMO and developments of plasma exhaust and plasma facing components from Mission 2, could allow a stellarator fusion power plant to be built.

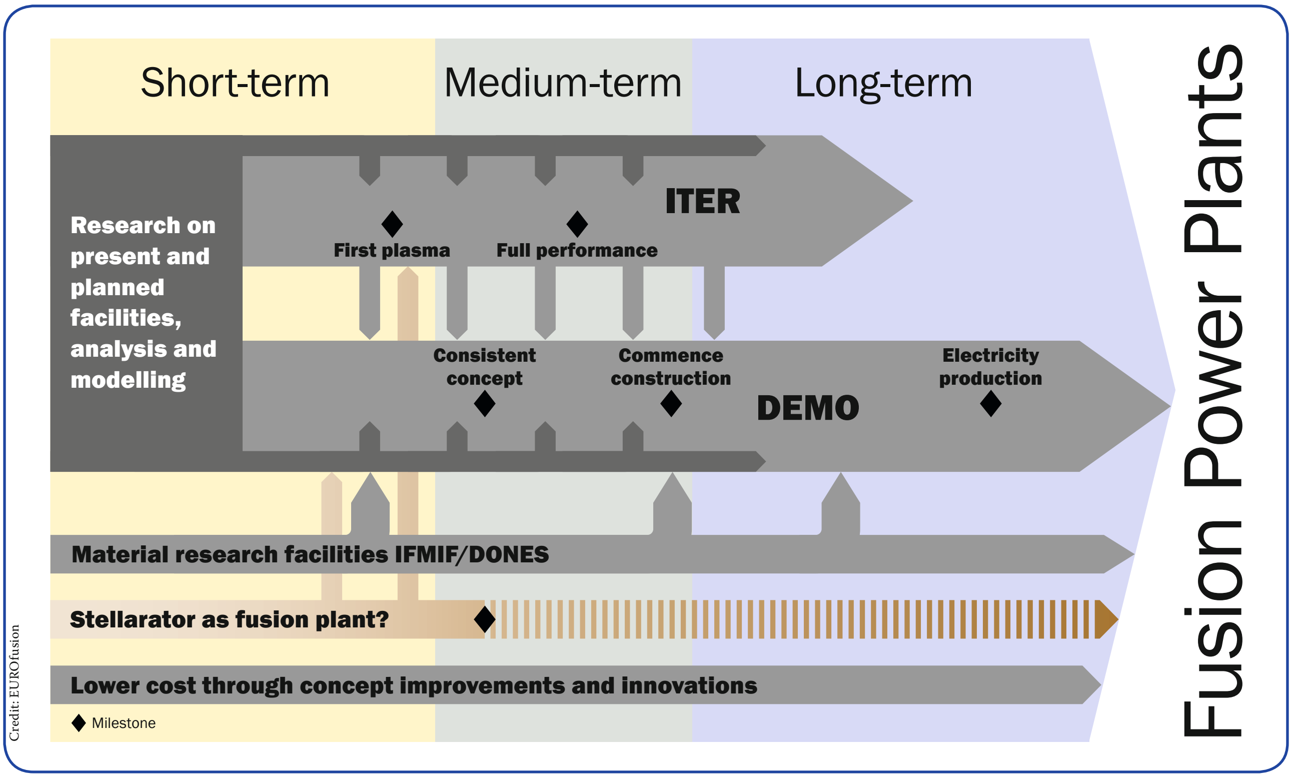

Figure 10: Mission 8 elements of the roadmap (coloured) involve exploitation of Wendelstein 7-X as well as pre-conceptual studies into a Helias-based fusion power plant.

5. Roadmap stages

Three different periods have been considered in the roadmap (See Section 1):

- First period: start ITER operation and complete DEMO conceptual design(s) (<2030);
- Second period: burning plasma on ITER and DEMO engineering design (2030-2040);
- Third period: plasma and technology optimisation on ITER and construct DEMO (>2040).

The diagram of the Fusion Roadmap (see Figure 1) shows how the work in the different missions combines towards the overall goals. In each stage, the progress made on each mission separately is considered, but all missions have to advance in concert due to the interactions. For example, the exhaust problem cannot be fully solved without knowing about the plasma core, and vice versa, DEMO cannot be designed without a solution for the tritium breeding, etc.

5.1 First period (up to 2030): Build ITER and Broader Approach projects; Secure ITER success; Lay the foundation of DEMO

The main facility milestones of this period are first the completion of ITER, the Broader Approach projects, especially JT-60SA, and the construction of a fusion neutron source IFMIF-DONES (wherever built), each with major EU commitments. Then their exploitation must be prepared and the first results towards the roadmap goals obtained. The procurement objectives are under the responsibility of F4E contracting with industries as well as European fusion laboratories. Alongside these, a conceptual design of DEMO is expected to be concluded leading to a complete integrated system design so that a Conceptual Design Review with detailed assessments of technical feasibility, safety, licensing and life-cycle costs can be undertaken as the initial step of the Engineering Design Phase.

Preparation for ITER exploitation and DEMO scenarios (Mission 1)

In the period after 2030, this phase includes the first plasma in ITER and then the pre-nuclear operation before the deuterium and then the deuterium-tritium operation towards Q=10. The primary goal is comprehensive preparation of ITER plasma scenarios and their operation so that ITER's goals can be reached as quickly as possible, especially given the earlier delays. Alongside this, the DEMO conceptual design requires a high confidence plasma scenario at its heart. Both of these will be based on combined experimental and theoretical research. The experimental programme will use JET (until it is phased out), the Medium-Size Tokamaks (MSTs) and JT-60SA as it becomes available. Substantial progress towards the major goal of a high fidelity numerical tokamak, important for ITER operation and for DEMO design is expected in this period. This was not considered feasible for this phase in the earlier Roadmap schedule. Many of the component models will be in use.

The main milestones related to ITER are focused on optimizing the the ITER Research Plan as well as to give input to the DEMO pre-conceptual and conceptual design phase. Actual milestones for ITER will be set by the evolving ITER Research Plan, but some indicative targets are given here. These include the preparation of the ITER regimes of operation (scenarios), taking account of the substantial effects of a metal wall. Results from JET, which has the same combination of plasma facing material as ITER, will be used, including results of JET's DT campaign. This is supported by specific studies on the medium-sized tokamaks, which bring important additional information. All this will be complemented by a comprehensive set of theory-based models. A strategy will be developed to transfer scenarios to ITER, using improved prediction and optimisation tools. These scenarios will be further optimised and exploited on ITER with the first results towards the end of the period. By the end of this period, reliable avoidance and mitigation methods for disruptions should have been demonstrated on JET and MSTs. Moreover, a strategy proposed for ITER based on a coordinated multi-machine experimental effort complemented by theory and model validation for extrapolation towards ITER and DEMO. The goal is the first experimental demonstration on ITER of ELM mitigation, suppression and, if possible, avoidance methods with high-confinement plasmas, backed up by theoretical understanding and modelling. Work on MSTs together with substantial theory and model validation effort will support this.

The main milestone for DEMO, specific to JT-60SA, will be the demonstration that baseline and advanced tokamak regimes (for very long pulses) can be reliably kept under control in conditions compatible with acceptable divertor/wall load preparing the transition to the full tungsten wall. The European involvement will focus on ITER and DEMO scenario development issues beyond the ITER Q=10 mission, notably on fast ion physics, management of off-normal events (i.e., disruptions and edge-localised modes), compatibility of radiative scenarios with high fusion performance (linked to Mission 2) and real time control of a non-inductive scenario at high beta with a minimum set of diagnostics and actuators. This complements the effort in the JET and MST programmes. These will provide crucial information for the design of DEMO, for the strategic decisions on ITER enhancements beyond the Q=10 milestone and on the feasibility of steady-state operation. By the end of the period, it is intended that JT-60SA will have a full tungsten wall, simulating the situation expected for DEMO. Europe expects to contribute to JT-60SA's full tungsten wall, and to enhancement of its heating and diagnostics systems.

By the time the ITER construction is complete, Europe will be ready to play a leading role in ITER operation (experiment, theory and modelling). High power long-pulse heating is essential for high plasma performance on ITER, and exploitation and optimisation of the Neutral Beam Test Facility will be a key part.

By the end of this period, there should be a coherent approach to the high power phase on ITER, developed with the other ITER parties. The second main goal is to develop one or more consistent integrated plasma scenarios for DEMO that meet the requirements, including fusion power, controllability, exhaust (Mission 2) and minimal disruptions, with the accompanying theory-based simulation tools. There will, however, be remaining uncertainties, but the aim is to ensure DEMO is designed with sufficient margin to accommodate discoveries on ITER (Mission 6).

Exhaust solutions (Mission 2)

This period sees the first tests of the ITER exhaust system, and the identification of coherent concepts for the design of the DEMO exhaust. A strategic programme has been defined to secure a viable solution to the problem of heat exhaust on ITER and DEMO ('Plasma Exhaust (PEX) strategy'). This programme considers conventional and advanced plasma facing units and conventional and advanced divertor configurations.

The ITER baseline strategy, which also underlies the baseline DEMO strategy, will be pursued in existing divertor devices, preferentially those with all metal plasma facing components, to design an acceptable ITER divertor operation in the detached regime. This subsequently needs to be further developed on ITER itself. Control schemes will be investigated and optimised to establish stable detached conditions and avoid damage to the ITER divertor target including slow transients. In order to optimise the radiated power, the injection of different impurity species will be tested together with control schemes to avoid excessive contamination of the plasma core. These activities will be supported by a strong modelling and validation effort. The goal by the end of the period is to demonstrate on ITER full control of detached conditions compatible with high confinement regimes. The step to DEMO for the reference strategy requires enhanced radiative losses from the main plasma (see Mission 1) to reduce the power entering the divertor. This is not foreseen on ITER in this phase. Consequently, the input to the DEMO conceptual design will be based mainly on results from European tokamaks and JT-60SA together with extensive use of existing and new models. Some uncertainty will remain about whether the reference exhaust strategy will meet the DEMO requirements. Regarding the plasma facing components (PFCs), the technological feasibility and performance of water-cooled divertor target concepts which extend the ITER design and technology, will be assessed for DEMO. The plasma and PFC performance will be combined into an integrated exhaust approach. Some uncertainty will remain about whether this will meet the DEMO requirements for the reference design. As in Mission 1, the aim will be to ensure that DEMO is designed with sufficient margin and, if not achievable, consider an alternative exhaust.

Alternative exhaust concepts based on innovative geometries/liquid metals should be designed for DEMO and it should be assessed whether they can be extrapolated to power plants. Additionally, proof-of-principle tests should be completed. Specific milestones are proof-of-principle tests of the physics of alternative divertor configurations and of liquid metal targets in a number of small/medium size tokamaks by the middle of the period. These would use enhancements of existing tokamaks and a portfolio of theory-based models, some of which need to be developed. Also, by the middle of the period, one or more integrated alternative exhaust concepts for DEMO would be taken into account of the various integration issues with the main plasma and the rest of the DEMO engineering integration. If a viable solution is identified, it would then need to be qualified for use in DEMO. This would require a dedicated new Divertor Test Tokamak (DTT) facility together with comprehensive theory-based models. This step would be started in this period and realised by the involvement of EUROfusion in the Italian I-DTT device, which has been approved for construction by the Italian Government.

R&D will be conducted on dedicated diagnostics related to ensuring efficient PFC operation (wall protection systems, fuel retention and dust diagnostics, etc.) and will include testing in existing tokamaks. Operational strategies to control/mitigate PFC erosion and damage/fuel retention/dust production will also be developed.

Taken together, by the end of this period, the detailed strategy for handling exhaust on ITER for the high power phase should be clear, and a consistent exhaust concept for DEMO that integrates plasma and engineering should have been identified for the Engineering Design Activity, probably with a back-up given the uncertainties likely to be remaining (Mission 6).

Materials (Mission 3)

In this period conservative design rules, mainly using already established design criteria for the **baseline structural and high heat flux materials** for DEMO shall be progressively complemented[45] with data on materials limits using a combination of data from Material Test Reactors (MTRs), ion beams and many test and analysis facilities. These will be combined with multi-scale (and multi-physics) models, using advanced computation techniques and High Performance Computers. This will enable more robust design approaches taking account of changes in materials properties under neutron irradiation.

Targeted irradiation data from IFMIF-DONES will be needed during the Engineering Design Activity in order to start the verification of the design criteria and limits developed by then. To achieve this, IFMIF-DONES will have to be constructed (in the EU or Japan), be commissioned and if possible operated in the period.

To support a sound engineering basis for DEMO, the programme shall ensure that a relevant comprehensive materials database is available in due time before the end of the DEMO conceptual design phase. The targets include data for structural steels at 20 dpa and for high-heat flux divertor materials (tungsten and copper alloys) at 10 dpa (Fe equivalent), including welded and jointed samples as far as they can be developed. In a second step, these developments must be verified and validated with 14 MeV irradiation data.

[45] By populating the relevant annexes on "Material design limit data" [called Appendix A in ITER SDC or RCC codes].

At the same time, a first set of codes and standards for the key safety important plasma-facing materials of DEMO should be issued in conjunction with International Codes & Standards organisations and other Missions.

In the early 2020s, an assessment can be made to establish if the **advanced/alternate materials** have sufficient proven advantages to be incorporated into the portfolio of baseline materials. Then a step-wise rigorous down selection can also be made to generate a prime candidate material list for structural, plasma-facing and high-heat flux zones of the breeding blanket and divertor areas of DEMO for prototyping, demonstration of welding and joining processes, and progressing towards industrialisation. Links with other advanced material programmes outside fusion shall be enhanced including international links (e.g., Japan and US for high heat flux materials) at whatever level possible, potentially resulting in accelerated development. Specific progress with industry on large-scale production of materials (and lower cost options) will have been made by the end of the period.

Similar activities will be completed for **functional materials,** in cooperation with Mission 4 for breeding materials, tritium barriers and corrosion protection, and with Mission 6 for diagnostic windows, mirrors, fibres, insulators and other materials for heating and current drive systems.

Tritium production and management (Mission 4)

Substantial R&D on the breeding blanket and fuel cycle will be pursued in this period. Most of the R&D will be in support of the two blanket concepts to be tested as part of the ITER TBM programme (i.e., HCPB and WCLL) and to address all the design integration issues and R&D issues of the corresponding concepts for DEMO. The return of experience of the TBM programme at this stage (design, R&D, procurement and qualification), is expected to strongly contribute to the DEMO blanket concept selection during the Conceptual Design Activity. This is planned around the middle of the period by taking into account design and R&D input obtained not only in the area of blanket and TBM, but also safety, materials, Balance of Plant, remote maintenance, etc.

Additional milestones include: (1) the initial demonstration of the performance and durability of permeation barriers on candidate materials for the different blanket concepts, and operating conditions, (2) the extraction of tritium from PbLi at high temperature through a gas-liquid interface, permeation into vacuum, etc., while having little or no impact on the fluid's power conversion, and full demonstration of applicability of pumps for the fuel cycle that would enable the Direct Internal Recycling concept. This will lead to two continuously recycling loops in addition to an outer loop with classical isotope separation and tritium plant exhaust detritiation technologies.

Safety (Mission 5)

The analysis of the critical aspects will be completed for the licensing of DEMO on the basis of the ITER experience. In the area of radioactive waste management, R&D to identify efficient detritiation systems from solid waste should be well underway, and in advance of a possible test on ITER components. Feasibility studies of **waste recycling** and proof-of-principle demonstration of related technology should also be undertaken. Detritiation and recycling options could influence materials and design choices for DEMO.

Accident scenarios that can affect the plant or potentially the personnel will be identified and ranked, leading to a focus on avoiding the initiating events. This can be by design, by the operational regime and its control (notably avoiding significant plasma disruptions), and by monitoring the state of the plant and components. Approaches will be identified for monitoring or estimating the state of internal components and materials to judge their condition and remaining life.

Integrated DEMO design (Mission 6)

The pre-concept phase will run until 2020, and transform into to the Conceptual Design Activity which then will lead to a conceptual design review timed so that the Engineering Design Activity can start at the end of the period.

Pre-Conceptual Design Activity: Modest, targeted investments in the DEMO integrated design and system development (Mission 6) and analysis of cost minimisation strategies (Mission 7) are expected. The main targets are: (1) the definition of the optimum overall DEMO configuration(s), (2) the balance of plant (using results of Missions 3 and 4), (3) advanced low-temperature superconducting cables, (4) definition of remote maintenance schemes and key elements on H&CD, and (5) vacuum and pumping systems. The pre-Conceptual Design Activity should narrow down from several alternative DEMO plant concepts based on the knowledge available at the time. It should assess and integrate different designs of the breeding blanket and divertor concepts to be developed in Mission 4 and Mission 2, respectively, and culminate in the selection of one or more plant concepts (with some limited sub-variants) by the end of 2020. The selected concept(s) should have the highest likelihood of success, to cover the two blanket options and probably two exhaust options. In addition, an alternative concept should be selected for backup and or to allow for exploitation of enabling technologies.

At the end of this phase, a gate review shall be carried out with particular focus on assessing the progress and status of device feasibility, risks, key design decisions and integration aspects. Industry will be engaged in various ways, in particular in project management, systems engineering and the gate review process itself.

Conceptual Design Activity: The selected architectures developed for DEMO during the pre-conceptual design phase are taken in the Conceptual Design Activity and further developed. This is then compared, with, if possible, a single architecture (still with sub-variants) that is selected early in the second half of the period in preparation for the concept design review. Probably two exhaust concepts will need to be retained, depending on the results of the underlying physics performance and engineering investigations. The goal is a complete integrated system where feasibility, safety and licensing issues and costs, including development cost and times to be expected during the subsequent engineering design phase can be determined. The architecture(s) of the DEMO plant should be selected two to three years in advance of the Conceptual Design Review. This stage includes improving design solutions and technology to increase the design maturity, including interfaces between the system and its intended environment; a comprehensive evaluation and minimisation of the cost and safety and feasibility assessments. R&D is predominantly to establish sufficient confidence that most of the design and technology solutions adopted are feasible. Some initial manufacturing tests or system component performance tests are required at prototype scale even during the Conceptual Design Activity phase. As there are strong implications on the overall power plant design, it is important that the proposed remote maintenance strategy is confirmed through test-rig and trial demonstrations. The DEMO architecture depends on system level solutions. These solutions should be validated as far as possible during the Conceptual Design Activity to keep any overhaul in the Engineering Design Activity at the lowest possible level. For the case of an alternative exhaust approach there may still be open questions at the Conceptional Design Review. It is critical to get the requirements and the initial design and analysis right at the very beginning of the Engineering Design Activity to avoid costly corrections later.

Lower cost (Mission 7):

The portfolio of options described in Section 4 will be pursued, mostly within the other missions, with progress integrated into the design and cost estimates for the DEMO Conceptional Design Review. A first scoping will be made of the drivers for the cost reduction due to learning and improved processes and designs as fusion plants are progressively deployed, including savings from many-of-a-kind. It is expected that first outlines of possible power plants will be developed to clarify where innovations and improvements are needed to make them commercially attractive.

Stellarators (Mission 8)

The installation of fully actively cooled components on Wendelstein 7-X is the main milestone for the end of Horizon 2020. Demonstration of high performance steady state plasmas will then be developed on Wendelstein 7-X. The first scenario options for a burning plasma stellarator will be defined, consistent with a pre-conceptual engineering design developed in parallel. A decision on how to progress with a next-step stellarator device (such as a burning-plasma experiment) should be taken towards the end of the period in the light of first outlines of a stellarator power plant also developed in this period.

5.2 Second period (2031-2040): Exploit ITER up to its maximum performance and prepare DEMO construction

Plasma scenarios (Mission 1): Here the main milestone[46] is the demonstration of the production of high fusion gain regimes (Q=10) in ITER (i.e., the accomplishment of the key part of Mission 1 for inductive tokamak regimes). Intermediate milestones are described in the ITER Research Plan. During this period ITER will be the leading facility, and EUROfusion with the European laboratories will focus their effort on its exploitation and are expected to be major contributors to all the ITER performance milestones. At the same time, the development of fully steady state regimes of operation will continue on JT-60SA with a metal wall. High-beta, inductive and non-inductive operation will be demonstrated on JT-60SA with metal plasma-facing components, probably with high radiation fraction (Mission 2), for the following reasons: (1) in preparation for similar studies on ITER (which may need significant upgrades), (2) for DEMO Engineering Design Activity optimisation and DEMO operation and (3) for the wider science and technology base for power plants. The goal of a full numerical tokamak will be pursued further, in particular to provide greater confidence by increasing the fidelity of the constituent models with more powerful computational techniques. The models will be used for JT-60SA, ITER and DEMO, and can be extensively tested and improved with the high-performance plasma on ITER and JT-60SA. Developing scenarios along with control techniques will aim at operational simplicity.

Reliable heat exhaust (Mission 2): Solutions for DEMO will have to be resolved during this period. In the case of the baseline strategy, by around the middle of the period, ITER should have explored the divertor situation, including materials, for power plant relevant exhaust power loads, albeit with some distance from the DEMO requirements on integrated exhaust. To assess the situation for the integrated exhaust, ITER scenarios will be needed that, when combined with modelling, will provide enough confidence for a DEMO construction decision. This may need a range of dedicated ITER scenarios including ones with high radiation fraction (Mission 1). In the case of an alternate exhaust strategy the situation will depend on the state of the concept design for DEMO (e.g., design margin), the level of experimental test and the confidence in the modelling, especially of the integration with the core plasma (Mission 1). In the case of a suitable alternate concept, full exploitation of the I-DTT for the purposes of Mission 2 will be done in this period.

The advances in the integrated exhaust options (plasma and components) will balance the plasma and first wall design, in particular so that the power conducted and radiated to the first wall does not lead to armour design incompatible with the rest of the blanket design and goals. ITER will demonstrate the suitability of actively cooled W divertor targets in an operational environment. This will include demonstration of PFC related diagnostics and operational strategies to control/mitigate PFC erosion and damage/fuel retention/dust production. These results can then be extrapolated to a full W-wall DEMO, using results from smaller full W-wall tokamaks (including JT-60SA) and modelling. If the R&D on advanced tungsten materials including W-alloys and composites is successful, elements could be tested on DEMO (Mission 3). The optimal selection of the DEMO divertor and first wall materials, the plasma scenario and operational strategy will then be made based on comprehensive integrated exhaust solutions for the baseline and alternative options.

[46]Many of these milestones are not purely the responsibility of Europe, but they effect the European Fusion Roadmap as such and are therefore mentioned here.

Materials (Mission 3): During this period of time, IFMIF-DONES must be used in various campaigns to produce as much as possible 14 MeV irradiation data to support DEMO design and licensing. The updated portfolio of DEMO baseline materials shall be taken to ~50 dpa in IFMIF-DONES. This will allow the engineering design limits to be updated (or respectively complemented by new criteria) to determine the revised operating range/lifetime of the baseline DEMO blanket and other components under the combined loads expected in operations. To support this, intensive use will be made of various models. Some advanced materials, the result of the down-selection process in the 2020s, shall now be irradiated to extended neutron fluence with the target to define design limits and adapt design criteria. Functional materials, that during the previous decade's material and design activities and design selection process are considered most important, shall be further tested and optimised in support of the DEMO Engineering Design Activity.

DEMO design (Missions 4-6): The Engineering Design Activity for DEMO will be carried out during this period in close cooperation with industry as a partner. The activity will include a preliminary licensing discussion (Mission 5 and 6). Integrated safety analysis will be performed to enable the start of licensing (e.g., safety analysis report including comprehensive identification of hazards, identification of safety functions and the corresponding safety credit to be given to systems, structures and components). Final technology demonstration R&D and prototype testing of various components and systems will be conducted. Major design developments, fabrication, and tests are expected during the engineering design phase to: (i) validate the technologies incorporated in the DEMO design; (ii) confirm the manufacturing techniques and quality assurance; and (iii) support the manufacturing cost estimates for important cost drivers. These are expected to be supported by advanced in-silico design and simulation tools. The design is not expected to be frozen but to evolve and adapt to the results of the R&D and the evolving plasma knowledge (especially from ITER). A planning schedule for the various stages of supply, construction, assembly, tests and commissioning together with a corresponding plan for human and financial resources requirements will be produced. Materials recycling strategies should be developed based on trials of example processes (Mission 5). The results of the TBM programme during DT operation are expected to provide essential input and to strongly contribute to validate the function and enable the calibration of predictive modelling tools prior to start of construction of DEMO (Mission 4). It is expected that adequate information on the TBM for the construction decision will emerge at about the same time as the critical information on the plasma from the Q=10 operation. If facilities such as CFETR are proceeding, or other DEMO-class design studies, then strong collaborations will have been sought, for example to develop technical solutions of interest for commercial power plants and not included in the European DEMO (e.g., alternative advanced breeding blankets).

Reduced cost (Mission 7): By this stage there should be a programme of cost optimisation within the DEMO design and outside for materials, components and systems that would be options for commercial power plants. Possible first power plant designs will be explored in greater detail in collaboration with industry. Further special projects may be needed to explore ideas, such as advanced design and manufacturing techniques which would have the greatest impact on the lifecycle costs. This will have included industry and other big science research.

Stellarators (Mission 8): The scope of Mission 8 in this period will depend on the development of Wendelstein 7-X and the decision taken in the previous period on a next-step stellarator. There will anyway be further high performance long pulse studies on Wendelstein 7-X, focused on specific issues for stellarators, work on a next step device, and stellarator power plant issues. It is likely that a similar range of issues will emerge on the plasma scenarios and technology as for tokamaks, and the programme will be adapted accordingly. There will be scenario and exhaust issues for the power plant environment which will build on the knowledge and experience gained in Missions 1 and 2, including an assessment of different wall materials and the upgrade of divertor configurations in Wendelstein 7-X. The materials and technology will share many features with the tokamak DEMO, although these are different in the application (notably magnet and remote maintenance design). Concepts of stellarator power plants will start to include integration aspects (in cooperation with Mission 6 and 7 work for tokamaks).

5.3 Third period (beyond 2040): Complete the ITER exploitation; IFMIF upgrade; Construct and operate DEMO; Lay the foundation for fusion power plants

This third stage can only be rather coarsely outlined at the moment.

Plasma scenarios (Missions 1 and 2): The construction, commissioning and operation of DEMO will take place in this period. Moreover, the JT-60SA and ITER research programmes will address and resolve specific DEMO operation issues for the core plasma. ITER will successfully demonstrate the integrated control of the burning plasma state with dominant alpha-heating over long-duration and/or in steady state conditions. In addition, it is intended that ITER will be able to approach highly radiative plasmas to inform the fine tuning of DEMO systems and then operation, for whichever exhaust option is chosen. If DEMO has a conventional divertor configuration, this information will be more complete. If not, DEMO will make greater use of other facilities, such as the I-DTT, and comprehensive modelling (the numerical tokamak should have very high fidelity by this stage). All these, and other facilities, together with the numerical tokamak tools, will also inform the design of the first commercial tokamak-based power plants, where operational simplicity is likely to be a major requirement.

Materials (Mission 3): The focus in this period is on DEMO operating limits and rules, component lifetime, replacement blankets and test blankets on DEMO and on the design of the first fusion power plants. To accumulate data for this range of objectives, it becomes mandatory that the 14 MeV irradiation facilities are enhanced. The simplest option is that IFMIF-DONES is upgraded with a second beam, if not done earlier, to reach the full IFMIF specifications and to be able to irradiate more material samples (including different welds, joints, coatings, etc.) at higher neutron fluence per year. For DEMO: to reduce the list of materials and compounds with an insufficient data base and hence unnecessary conservatism in operation limits of installed equipment and design assumptions for improved replacements and alternative test blanket modules. For fusion power plants: the target fluence should be able to qualify the materials of interest at higher dpa than DEMO, including reference and advanced structural materials as well as different types of functional materials.

DEMO: It is envisaged that DEMO will operate in two phases, progressively testing and using improved technologies in preparation for first-of-a-kind commercial power plants, and also developing and demonstrating high reliability and availability of systems and the whole plant. This period will implement the strategy that DEMO will have a "starter" blanket with EUROFER structure, a nominal 20 dpa damage limit and conservative design margins, probably with one advanced or back-up concept in a subset of modules. This will then switch to a second set of blankets with a nominal 50 dpa damage limit with a more optimised design, and if available, improved structural materials. Both the actual lifetime and usage period will be determined by progressive data from IFMIF-DONES and other sources (Mission 3) and stakeholder views. More advanced breeding blanket concept(s) having the potential to be deployed in a first-of-a-kind power plant will be tested in ports or segments. These replacement and advanced blanket modules will be implemented in this period (some may have been designed earlier), noting that the balance of plant will not be replaced so that the coolant(s) for the main breeding blanket will remain unchanged. The test of advanced blankets will be done using an experimental cooling loop (that can be independent and different from the main one) that could be decoupled or only partially integrated in the main power system. The overall tritium production of driver and advanced breeding blankets must ensure the DEMO tritium self-sufficiency. All blankets must have designs compatible with the remote maintenance system.

Preparation for development of commercial fusion power plants: By this stage there will be strong industry engagement in fusion because of DEMO's construction, and it will be an appropriate time to seriously address any extra R&D needed for the wider deployment of fusion (in Europe and beyond). It will be the time to explore further avenues for bringing the capital, operating and decommissioning costs down. It is hoped that an integrated concept design of a power plant can start, akin to the Mission 6 activities for DEMO, bringing together all of Missions 1-6.

Stellarators (Mission 8): Assuming the stellarator continues to show the promise perceived today, it is expected that a combination of further experiments/facilities and conceptual or engineering design activities for stellarator power plants will be pursued with industry engagement in view of possible deployment. It is expected that similar approaches to those for the tokamak DEMO will be pursued for blankets and other technologies, sharing solutions. The integrated design approaches developed under Mission 6 can be translated to the stellarator with strong industry partnership.

6. Form “Generation ITER” and “Generation DEMO” – training, education and knowledge management

The evolution of the fusion programme requires a shift "from pure research to designing, building and operating future facilities like ITER and DEMO", as recognised by the Panel on Strategic Orientations of the Fusion Programme.[23] This transition requires strengthening the available engineering resources, with a marked change from non-nuclear to nuclear technologies, and has to be facilitated by specific measures in support of training, development and education. A new cadre of leaders and pioneers capable of operating in complex and multi-disciplinary environments will be needed.

As implemented by other industries in comparable stages of maturity of technological development, these specific measures should mainly deal with the important issue of knowledge management: "an integrated, systematic approach to identifying, acquiring, transforming, developing, disseminating, using, and preserving knowledge, relevant to achieving specified objectives".[47] Here, knowledge must include "tacit, implicit and explicit knowledge, meaning it encompasses everything from technical information laid down on paper or in electronic media to insights or capabilities and skills embodied in people. Knowledge then clearly extends beyond just information. It includes the expertise required to turn raw data or information into understanding (i.e., the ability to find a meaningful interpretation of relevant issues using information). Knowledge Management consists of three fundamental components: "people, processes and tools".[48]

More specifically, in the fusion programme Knowledge Management should deal with all knowledge that is being built up through the different, but deeply connected current and future fusion projects, e.g., the lessons learned during design, construction and assembly of ITER. It should encompass not only data and document storage, but also human resources (experts, talents) management and supporting policies and processes (e.g., education and training). Focusing on the latter, fusion laboratories and universities play a key role in providing general training and education in fusion science and technology by selecting and forming "Generation ITER", through theoretical and experimental work on relevant science and engineering facilities, including designing and building complex equipment. Their objective should be that of ensuring adequate access of their scientists and engineers to the leading facilities and teams. These include JET, which represents an intermediate step towards ITER operation because of its large size, representative complexity, tritium capability, use of remote handling and of beryllium and is therefore the best place for training scientists and engineers for ITER operation. "Generation DEMO" will have a stronger focus on engineering, industrial approaches and economic drivers. The engineering and technology skills for the design and construction of DEMO need to be further consolidated through training of young engineers and project managers in the large devices currently under construction or planned (ITER, JT-60SA and possibly I-DTT), on major enhancements and on specific facilities such as IFMIF-DONES. ITER will break new ground in fusion science and the best young scientists should be encouraged to participate in the ITER programme and its operations team at an early stage of their career. DEMO and commercial fusion power plants will need innovative approaches and techniques to the technology. The future staff should be prepared for this during their education.

The role of fusion laboratories and universities in training and education should be explicitly recognised by specific support at the under-graduate and PhD level, in particular programmes with a strong international component. This should be followed by next-step training and development schemes such as the EUROfusion Researcher and Engineering Grants. Training in critical qualifications should be reviewed with industry, ITER and F4E, and should be encouraged. Existing international Master and PhD programmes, the present post-doctoral programmes and past training programmes under EFDA such as the European Fusion Research Fellowship and the Goal-Oriented Training programmes have been very effective, as well over 75% of the participants stayed in fusion.[49] This may be due to the strong network the fellows have created with the corresponding opportunities. A similar high percentage is expected from the grant programmes set up under EUROfusion.

The existing training schemes should be enlarged to involve industry through in-company training of engineers involved in fusion-related tasks. Specific training of professionals and technicians, already specialised in fusion should be considered on technologies and standards associated with the transition of fusion to a fully nuclear technology.

A healthy and stable European fusion programme system needs as a minimum about 55 PhD students as well as approximately 55 engineers per year (either PhD students or trainees), with an appropriate spread over topics in fusion engineering and physics, nuclear science and, increasingly, large scale computation and big data.[48] These numbers are for the 'Business as Usual' scenario in which the number of engineers and scientists stays constant and only the people that leave the programme due to retirement or job mutations need to be replenished. It also assumes that the various educational programmes that have been set up in the last decade will continue.

These education and training activities must be supplemented in the medium term by a Knowledge Management approach that will strive to systematically manage all knowledge that is being built up through the different, but deeply connected current and future fusion projects. Here, a coherent activity dealing with people, processes and tools and that is agreed on by all main actors in the fusion programme is needed.

While this activity is focused on building and maintaining the teams for the future, individuals trained in fusion activities have been shown to be highly attractive to industry and

[47] See https://www.iaea.org/km/documents/NKM-Glossary.pdf

[48] See http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1494_web.pdf, IAEA Nuclear Energy Series, Comparative Analysis of Methods and Tools for Nuclear Knowledge Preservation.

[49] A.J.H. Donné, L.G. Eriksson, C. Ibbott, J.-M. Noterdaeme and C. Schönfelder, Review of Human Resources in the European Fusion Landscape (2016).

other fields. So this activity will generate a steady stream of highly competent individuals for the wider technical and industrial community providing an immediate benefit of the fusion programme.

7. Breaking new frontiers, bridging the gaps – enabling research and theory

Innovation is an important ingredient over the full width of the Fusion Roadmap in order to strive for effective fusion plants with low costs of electricity (cf Mission 7). Therefore, it plays a central role in all Work Packages that are implemented under EUROfusion, and receives explicit stimulation. Additionally, a vigorous underlying enabling research programme should be continued in the participating countries to provide a path to bring new ideas and techniques into the programme in ways not easily achievable within the strongly goal-oriented missions. Such a programme has been set up, distinct from the project-oriented programme in the eight missions, but it still remains focused on the roadmap goals. It stimulates modest-sized projects which are selected based on excellence and innovation. These can be "curiosity driven" and should usually have a theory element to create understanding. But purely technological or computational innovations of near-term application area also encouraged.

Theory and modelling: The future steps in fusion, ITER and DEMO, are far from the present facilities in many respects, and also distinct from each other. For the **plasma**, it is known that projections into new parameter regimes based only on empirical data can be misleading (e.g., the underlying physics mechanisms change, sometimes radically). Yet reliable predictions are needed to design experiments on ITER and to optimise ITER's performance including real-time plasma control (Mission 1), and the DEMO design depends critically on accurate estimates of the plasma performance and behaviour, and also on optimising it to increase performance margins. This is especially true in the area of **plasma exhaust** (Mission 2) where the performance is critical and can have fundamental impact on the design of DEMO, but the predictive capability is presently very limited. Also, in the field of **stellarators** (Mission 8) reliable predictions are needed to accurately extrapolate from experiments on present devices, in particular Wendelstein 7-X, to a burning plasma stellarator, or even a Helias-based fusion power plant. Many tools and capabilities are common to tokamaks and stellarator allowing synergistic efforts, but some will need to be developed specifically for stellarators.

For the **materials**, DEMO has to be designed with only limited data on the effects of long-term exposure to high neutron flux (see Missions 3, 4, 6). Yet the materials engineering performance and limits are needed to guide the design, in particular to estimate reasonable design margins. For both of these areas, advanced models are needed based as far as possible on the first principles theory. These models are generally large scale and need to be implemented on high performance computers using advanced numerical techniques continually adapted to the latest technology. Furthermore, big data techniques will become increasingly important. Hence, there is increasing emphasis in this area, and it is likely some new initiatives will be required (it is not appropriate to rely on bottom-up enabling research projects).

Finally, the **engineering** design of DEMO is highly complex, and many multi-physics tools are needed to develop and evaluate designs – for example, calculations of the tritium breeding using neutron transport codes are compelling but need to be very accurate, and the design needs to be optimised to maximise the breeding. Models for the mechanical and thermo-mechanical performance and optimisation of large and complex structures are also needed, likewise for the evolving thermo-mechanical performance of composite plasma facing units subject to radiation damage. There are many other examples. There are thus potentially very large benefits of advanced in-silico design and analysis tools, in improving the design, handling interactions between systems and components, and also reducing the design cycle time and potentially optimising the choice of engineering prototypes.

8. Industrial involvement – From provider of high-tech components to driver of fusion development

Lessons learnt from comparable projects have highlighted the importance of involving industry during the early phases of the design development – especially for complex nuclear infrastructures. For instance, Gen IV programmes have leveraged impressive industry support, and engaged with industry as a partner from the outset.

European industrial involvement in ITER already represents, during the 10-year period until 2020, a turnover of about 6 billion euros and involves ~5,000 full-time equivalent staff. DEMO will move the development of fusion from science-driven research to an industry- and technology-driven programme.

Industry must be able to take the main responsibility for the commercial fusion power plant after successful DEMO operation. For this reason, DEMO cannot be defined and designed by research laboratories alone, but requires deep involvement of industry in all technological and systems aspects of the design. This will also ensure that the various technologies and systems are developed to an adequate level of maturity for implementation. Industrial capability needs to be developed in specific areas (e.g., fabrication of EUROFER and ODS steels and plasma-facing components, breeder material and pellet manufacture, tritium barriers).

Early engagement of industry in the DEMO design activities, allows the possibility to build a familiarity within industry of the particular challenges associated with DEMO. Furthermore, it provides some continuity for industrial suppliers in the interim period following the completion of ITER procurements – but prior to the launch of major DEMO procurements – to maintain interest and engagement in fusion. It also provides an opportunity for industry to steer the design direction, and encourages industry to participate not only as a supplier but also as an important stakeholder within the project.

Specific areas where industry involvement is considered critical in the early phase of the DEMO design are:

- Industrial Project Management;
- Plant architect engineering, systems engineering and design integration;
- Plant engineering tools, modelling and simulation;
- Design for robustness and manufacturing of critical components/systems, including design simplification and reduction of fabrication costs;
- Standardisation of parts and components;
- Balance of plant design and integration;
- Materials development must include strong emphasis on the industrialisation of the candidate materials;
- Cost, risk, safety and RAMI analyses for DEMO, and ways to embed their continuous control into the project;
- Technology Readiness Level (TRL) assessments, evaluation and selection of design alternatives;
- Definition, together with the research laboratories, of the priorities in the technology development;
- Development of design codes and standards.

In addition to the above list, a controlled plasma scenario for the fusion power plant that is simple to operate needs to be developed by the research community (this is very much the output of Missions 1 and 2). Subsequently, a specific approach should be developed so that industry can design and operate power plants. A similar situation exists for materials science – here there are examples from other fields where industry interacts effectively with the scientific community.

Industry needs to be convinced that fusion can be converted into commercially viable electricity plants. A policy is needed to develop and maintain industrial competence in fusion-specific areas after the completion of the ITER construction. Without specific provisions the know-how accumulated during the ITER construction phase could rapidly disappear. The launch of the DEMO Engineering Design Activity around 2030, only a few years after ITER comes into operation, will facilitate maintaining these competences. This requires a dedicated knowledge management system (section 6) and a review of the legal aspects related with the know-how management. An adequate technology transfer from fusion laboratories to industry and vice versa must be established in order to keep on track and optimise the development of the required industrial competences. Transfer of relevant know-how is needed in particular. This can well be achieved by industry and fusion laboratories working closely together from the early DEMO designs phases onwards.

9. Exploit the opportunities from international collaboration

To demonstrate fusion electricity as early as possible and prepare for subsequent deployment, Europe requires comprehensive coverage of all the science and technology needed for DEMO, and also further options and innovations for the deployment phase. Importantly, fusion is a global challenge, and so Europe should seek all the opportunities for international collaborations for mutual benefit from the intellectual diversity of the whole fusion community and from the sharing of resources and facilities. Some of the ITER parties have similar roadmaps and have a very aggressive programme in fusion, and there would be mutual benefit from Europe's participation in the design, construction and operation of their facilities. Already the Broader Approach (BA) agreement with Japan is a good example of a positive collaboration that can give further advantages through the time periods considered here, such as the collaboration in the design rules for DEMO.

Specific for the ITER preparation all ITER parties work intensively together in the International Tokamak Physics Activity (ITPA). Within this framework, they are joining efforts in the so-called IEA-ITPA joint experiments that are carried out under the umbrella of one of the Technical Coordination Programmes of the International Energy Agency (IEA)(specifically the Coordinated Tokamak Programme). This involves participation of Europeans in the tokamak programmes of other parties and vice versa non-European scientists are involved in experiments on JET and the medium-sized tokamaks. Similar Technical Coordination Programmes are also the basis for international collaboration in the field of stellarators, spherical tokamaks and plasma-wall interaction.

In addition to the ITER exploitation, the following are areas and opportunities for international collaboration:

- The exploitation of JT-60SA in collaboration with Japan for the preparation of ITER and for DEMO;
- The construction of IFMIF-DONES for material irradiation in collaboration with Japan within the post IFMIF-EVEDA phase;
- The collaboration on DEMO R&D with Japan (for example, making use of the materials research infrastructure developed during the Broader Approach for that purpose as well as the collaboration in the design rules for DEMO);
- The participation in the design of the CFETR facility with China or next step facilities in the other ITER parties;
- Possible sharing of know-how on the Test Blanket Module (TBM) programme with other ITER parties whenever mutual benefit is expected;
- The use of non-European fission research reactors for irradiation studies;
- Use of dedicated technology test beds (e.g., PISCES, MAPLE in the US, etc.);
- The collaboration on long pulse tokamak facilities besides JT-60SA and on stellarator lines other than the Helias (i.e., Heliotron and compact stellarator).

The above list certainly does not cover all international collaborations. Examples of joint development of facilities already in place include the US hardware investment and involvement along with ITER in the exploitation of Shattered Pellet Injector at JET for disruption mitigation and in diagnostics for the Wendelstein 7-X stellarator (following earlier contributions to the magnetic field optimisation system). Also the teams in the individual facilities, particularly the medium-sized tokamaks and WEST, spend much effort to internationalise their devices with in-kind components delivered by several non-European parties, which are also involved in the exploitation.

Finally there are and will continue to be many scientific collaborations on materials and plasma theory and modelling; as mentioned in many places in the roadmap, theory and modelling will become increasingly important.

10. A living document: Roadmap reviews and decision points

In the original fusion roadmap, published in 2012, it was already indicated that most likely a first review of the roadmap needed to be undertaken by 2015, albeit for reasons different from those that actually triggered it.

The present roadmap relies on the assumption that adequate resources will be made available, both by the European Commission and the national research programmes. The decisions within Europe with the largest impact on the proposed programme (especially until ITER comes into operation) are:

- The decision on any extension of JET beyond 2020;
- The decision on the next step on alternative tokamak exhaust configurations in the early-mid 2020s and the nature of the subsequent involvement of EUROfusion in the Italian Divertor Test Tokamak;
- The decision to extend and possibly enlarge the scope of Broader Approach activities to be undertaken with Japan; and
- The decision on the Early Neutron Source (IFMIF-DONES).

This document has to be seen as a living document, with updates and reviews to be performed at appropriate times, based on strategic events. Reviews that are considered mandatory are listed below.

A review of the roadmap should be undertaken in the first half of the next decade, this mainly to assess (1) the progress in the ITER project, (2) the situation on alternative exhaust configurations, (3) the outcome of the pre-Conceptual Design Activity of DEMO, including R&D results, (4) the status and the plans of the Early Neutron Source. Connected to this, it would be timely to have another facility review to decide on the most important supporting facilities once ITER is in operation.

Near the end of the next decade, the situation on ITER should be much advanced with the first results emerging. In parallel, it should be decided if there are enough elements to progress towards the Engineering Design Activity for DEMO and to assess the costs involved. This review should involve utilities and vendors as for the Gen IV fission programme to ensure that before launching engineering design activities, there is wide acceptance of the proposal by these stakeholders.

A review around the mid-2030s will be necessary to assess the progress of the DEMO Engineering Design Activity as well as of the ITER exploitation.

A review near the end of the 2030s, after ITER has achieved Q=10 operation, is needed to assess the readiness for DEMO construction. The working assumption is that Europe should have by 2040 all the know-how necessary to build a DEMO demonstration power plant.

Although approximate dates are given above for the time of future roadmap reviews, it is important to remark that any reviews and possible updates should be driven by strategic events (which could be both external as well as internal to the programme) rather than by given dates.

11. Progress along the Fusion Roadmap since 2012

From 2014 onwards, under EUROfusion, funding has been strictly aligned with the priorities of the Fusion Roadmap. Work under EUROfusion is organised into 35 Work Packages most of which are led by Project Leaders and Task Force Leaders (for organising the experimental campaigns on JET and on the medium-sized tokamaks).[50]

11.1 Progress in tokamak physics for ITER and DEMO

The central activity of the experimental programme is the scientific exploitation of JET, medium-sized tokamaks (ASDEX Upgrade, MAST Upgrade and TCV) and Plasma Facing Material and Component test facilities (GLADIS, JUDITH, Magnum-PSI, Pilot-PSI, PSI-2 and WEST) in support of Missions 1 and 2. EUROfusion has seized the unique opportunity to develop an integrated scientific programme including experiments and modelling on devices with different sizes, i.e., on medium-sized tokamaks and on JET to provide a step-ladder approach for extrapolations to JT-60SA, ITER and DEMO. Strong synergy in the programme of the various European devices has been pursued for instance in the fields of plasma wall interactions, pedestal and confinement optimisation with metallic walls and in disruption control. First results on these topics tackle the scientific uncertainties identified in the ITER research plan, and will also guide the optimisation of ITER's performance and identify suitable scenarios for DEMO.

A limited number of highlights, demonstrating the progress along the fusion roadmap Missions 1, and 2, along with the contributions made to preparing the optimisation of ITER performance, and to the DEMO physics basis are briefly summarised below.

Progress along Mission 1:

- The EU programme has addressed operational issues of tokamaks with metallic wall for an efficient preparation of ITER, DEMO and the commercial fusion power plant. It is found that plasma performance can be significantly affected when plasma boundary conditions are modified. The performance has been largely recovered by scenario optimisation but this will affect the approach taken to achieve Q_{DT}=10 on ITER. This was discovered after the original roadmap was published, and it will take significant time to adapt the reference ITER scenarios (designed from carbon wall results), however it should save time when ITER starts.

- Some of the changes in behaviour between carbon and metallic walls appears to be due to detailed changes in the edge pedestal observed on ASDEX Upgrade and JET linked to the gas fuelling used. First models have been developed to describe the effect and potentially guide the approach on ITER.

- ITER and DEMO plasma performance will be strongly affected by fast particle dynamics Encouraging discoveries have been made on the role of fast ions to reduce core transport, leading to a virtuous core and pedestal feedback loop at high beta. These findings, recently simulated in sophisticated integrated modelling coupled with first principles codes, underline the need for improved understanding, and expand beyond empirical scaling. They will affect approaches to performance optimisation and may allow better performance than expected earlier.

- The European Transport Simulator used for integrated plasma modelling has undergone major development and has been released; this will be a key tool for performance optimisation on JET, ITER and DEMO. It will allow the large qualitative change in modelling of turbulent transport in recent years to be exploited; gyrokinetic turbulence simulation codes are nowadays capable of reproducing the experimental particle and power fluxes in certain plasma regimes.

- ITER and DEMO need effective disruption mitigation tools, which depend on the dynamics of disruption and runaway electron beam formation which are found to be significantly different in the presence of metallic wall compared to a carbon wall. First principle simulations of an intentionally triggered disruption have been performed with a 3-D non-linear MHD code (JOREK).

- ITER (and DEMO) need edge pedestals (H-mode) if the fusion power is to be high enough. Formation of the pedestal needs a certain power (P_{LH}) deposited in the plasma, and providing this is costly and technically demanding. A global reduction of P_{LH} by 25% has been observed with metallic walls compared to the previous carbon wall. It has also been found that when the plasma in JET is changed from hydrogen to deuterium a lower power is required to access H-mode operation while the high confinement could be sustained over a broader range of densities. These results will clearly be beneficial for ITER if they transfer.

- ITER will have a preparatory non-active phase in hydrogen and helium, and it is important that the preparation is relevant for the deuterium and DT phases. In support of this, ELM mitigation has been established in ASDEX Upgrade in helium discharges using the methods developed for deuterium.

- ITER will have ICRH heating which needs to be made as efficient as possible. A new and efficient ICRH absorption scheme (the so-called three-ion ICRH scenarios) in multi-ion plasmas has been proposed and recently tested in European experiments. Additionally, a novel three-strap ICRF antenna was successfully developed and tested in ASDEX Upgrade which makes ICRF operation compatible with high-Z plasma facing components. These could both help ITER.

- The lifetime of ITER divertor components is shortened by ELMs, and it is important to know how well ELMs

[50] References to the many publications summarised in this section are not included to avoid diluting the text to much with footnotes, except for the case when figures are used.

need to be mitigated to allow sufficient lifetime. ELM mitigation and sometimes even suppression has been demonstrated on both ASDEX Upgrade and MAST, with good progress in theoretical understanding (and hence predictive capability for ITER). A new multi-machine scaling of the type-I ELM divertor energy flux density parallel to magnetic field lines has been proposed. First principle predictions from the non-linear MHD JOREK code for the JET–ILW discharges and ITER peak ELM energy density are in agreement. An extensive set of transient heat load experiments on multiple PFC test facilities has provided a physics basis for their impact on W plasma facing materials and guides the target for ELM mitigation on ITER. Progress was made in the MST devices and within international collaborations on the compatibility of small, no- or suppressed ELM regimes with ITER and DEMO requirements on confinement, heat and particle loads.

- ITER needs precise calibration of the neutron detectors and good information on the dose rates around the machine. A new accurate calibration procedure of neutron detectors at 14-MeV neutron energy has been developed and tested on JET in collaboration with ITER. The measured D-D neutron fluence and gamma dose rates have been successfully compared with simulations performed with the codes used for ITER nuclear safety analyses.

Progress along Mission 2:

- ITER (and DEMO) need very low levels of tritium retention and dust inside the vessel. Deuterium retention studies (post-mortem analysis of retrieved PFCs and gas balance studies) in metallic wall tokamaks have demonstrated a significant reduction (by factor of 10-15) of the deuterium fuel retention with metallic first walls as compared to the previously used carbon-based first walls. The dust levels have been reduced by two orders of magnitude compared with the carbon wall. Extrapolation towards ITER has been performed, and this provided vital input to the decision made by ITER for a full W divertor in the first phase of ITER operation.

- ITER needs to be able to operate even when the metal wall components have some melted areas. Melt experiments in tokamaks with full-metal walls have shown that these tokamaks can be operated effectively after some surface melting and they indicate tolerable consequences also for ITER operation. This result was also crucial for the decision made to use tungsten for the first divertor.

- The ITER first wall components need to survive erosion for long periods before they are replaced, and in any case their expected lifetime has to be known. Material migration codes have been validated on metallic wall experiments and have been used to predict the number and type of full power ITER DT plasmas that can be run before erosion becomes too severe.

- For the preparation of ITER non-active operation in helium, the feasibility of using Ion Cyclotron Wall Conditioning in He plasmas was demonstrated and the physics basis for the conditioning was extended.

- To protect the plasma facing components in ITER and DEMO, the divertor has to operate in partial or full detachment, and on DEMO the radiative losses from seed impurities in the main plasma need to be high. Radiative scenarios with detached plasmas have been demonstrated on different tokamaks and the effect of extrinsic impurity seeding in the core plasma explored with W divertors in different scenarios and machine sizes.

- ITER and DEMO divertor behaviour and lifetime depends critically on a wide enough scrape-off layer width which is narrow in H-mode. A multi-machine scaling for the H-mode scrape-off layer power fall-off length was proposed and applied to ITER and DEMO. Major progress was also made in understanding filamentary transport across the Scrape-Off-Layer (SOL) in view of determining the power loads to the divertor and first wall of the machine (e.g., the role of effective collisionality and detachment conditions in the broadening of the far-SOL density profile).

- A credible exhaust solution for DEMO requires new experimental data and models. Following an extensive gap analysis in the field of plasma exhaust physics and technology, a number of upgrades of existing devices to study alternative power exhaust solutions (both alternative divertor geometries and materials) were initiated.

11.2 Progress in stellarator physics and technology

A few highlights of the progress along the fusion roadmap Mission 8, along with contributions made to the advancement of the stellarator as an alternative for fusion power plants, are given below.

- The major achievement in Mission 8 is the completion of the Wendelstein 7-X construction phase in 2014, the start of the operation in December 2015 (after the operating permit was granted) and successful completion of the first (March 2016) and second (December 2017) operational phases.

- The successful start of the scientific exploitation of Wendelstein 7-X, verifying the quality of magnetic flux surfaces and the closeness between the real and the designed magnetic structure validating the assembly of the entire device, is a first step towards bringing the stellarator line to maturity as foreseen in the EU Roadmap. Plasmas with 30 s duration were quickly achieved. During its second campaign, Wendelstein 7-X already set a new world record for the triple product ($nT\tau_E$) on a stellarator.

- A first optimisation of the power plant configuration of the HELIAS line has been performed. Configurations with reduced bootstrap current and good confinement of fast particles were obtained.

11.3 Progress in power plant physics and technology

Progress along Mission 3:

DEMO requires the development, qualification and validation of (blanket) **structural materials** that are neutron tolerant and that can withstand 20 – 50 dpa with acceptable loss of performance. Similarly, there is a need for **new materials** that can withstand high heat fluxes for long periods in divertor/limiter components as well as **functional materials** to match the requirements of heating and diagnostic systems. Materials development, qualification and validation is an effort that requires long lead times. Typically, two or three decades are required to develop new materials from scratch, improve performance and attain commercial large-scale readiness. This requires appropriate test facilities such as Materials Test Reactors and a dedicated 14 MeV neutron source such as IFMIF-DONES. Substantial advances on this long path have been made.

- **Neutron irradiation:** Irradiation campaigns are underway for the baseline materials EUROFER97, tungsten and copper alloys in European and US high flux materials test reactors to obtain design relevant (engineering) data and load limits.

- **Design rules:** "New" structural design criteria are being developed for operating conditions and lifetimes appropriate for DEMO breeding blanket structural materials along with "adaption" and "re-writing" of existing rules from RCC-MRx[51] and ITER-Structural Design Criteria (SDC).

- **Material database:** The first EUROfusion (DEMO) Material Property Handbook has been released.

- **Advanced Steels:**
  ■ for "EUROFER"-type materials, after having specified and cast at industrial level more than 30 new alloys since 2014, options have been developed with a significant improvement of EUROFER-HT mechanical properties equivalent to an enlargement of the temperature window by approximately 50-70K; a process to select from these options has started;

  ■ for Oxide Dispersion Strengthened (ODS) steels, industrialization technological readiness was improved in two directions by fabricating batches in the order of 100 kg of ODS steel with subsequent hot and cold rolling to obtain large thin plates of square metres size and by developing "direct fabrication" without the mechanical alloying processes.

- **High Heat Flux Materials:** Significant progress was made in both the maturity of newly developed fabrication technologies as well as in a growing database from detailed mechanical, thermo-physical and high heat flux characterization, including:

  ■ plasma facing materials: particle and fibre reinforced W materials fabricated by technologies without the final deformation step;

  ■ heat sink materials: particle and fibre reinforced Cu-based materials;

  ■ W-laminates which are options for both plasma facing as well as heat sink materials;

  ■ joining technologies (W/Cu or W/CuCrZr, W/steel) and interfaces for alternative concepts (W/Cu functionally graded materials, thermal barriers).

- **Functional Materials** addressing insulators and optical reference materials:

  ■ Radiation stability of metallic mirrors was tested at higher doses in ion irradiation including He effects for down-selection of materials and fabrication options;

  ■ Surface dielectric properties of commercial diamond windows were characterised using different surface treatments, resulting in down-selection to three remaining options;

  ■ Neutron irradiation campaigns at three fluences are underway including twenty different candidate material options for H&CD and diagnostics application to study potential saturation effects.

- **Irradiation modelling:** Predictive capabilities were achieved in certain areas of fusion materials modelling, notably neutron transport, density functional calculations of point defect properties, ion penetration depth profiles, and sputtering by energetic ions in the physical sputtering regime. These were done in preparation to approach the key issue of providing a set of multiscale predictive models for simulating changes of physical and mechanical properties due to exposure to neutrons under fusion power plant relevant conditions.

- **Early Neutron Source:** The IFMIF-DONES Preliminary Engineering Design Report was released, demonstrating that the facility is ready from the technical point of view for a site decision. This comprehensive document describes the complete facility: accelerator design, target design, building, operation, and all the safety and RAMI aspects.

Progress along Mission 4:

For Mission 4 (**Tritium Self-Sufficiency**) the most attractive design options for the DEMO breeding blanket have been identified and four concepts were investigated until the end of 2017. Following the recommendations of a Review Pan-

[51] Design and construction rules for mechanical components of nuclear installations: High temperature, research and fusion reactors

el involving independent experts[52] in all relevant technical fields, a Working Group was established in 2017. Its goal was to streamline the European Fusion Programme on Breeding Blankets (BB) and the project for the European Test Blanket Modules (TBM) in ITER to ensure the full coherency of the two programmes. From 2018, efforts are being made for the design and validation of the driver blanket for DEMO focus on the Helium Cooled Pebble Bed (HCPB) and Water Cooled Lithium Lead (WCLL) concepts. Accordingly, a HCPB concept and a WCLL concept should be tested by Europe in ITER (replacing one of the two ITER TBM concepts cooled by helium with a concept cooled by water). This strategy will enable testing both high temperature/high pressure coolants (helium and water) and both breeder/neutron multiplier materials combinations (PbLi and ceramics/Be). The strategy has been perceived to be the best one to consolidate the design for the driver breeding blanket for DEMO, which is expected by about 2024. The DEMO breeding blanket design and integration work conducted to date shows clearly that some technical features of the breeding blanket (the type of coolant, the type of breeder, the type of neutron multiplier) impact not only the design of the breeding blanket itself but also the design of the interfacing systems and, as a consequence, of the overall tokamak layout. A great deal of attention is being given in this phase to design aspects of the breeding blanket that affect (i) the tritium breeding capability due to penetrations of the Heating and Current Drive (HCD) systems, and deployment of protection of the first-wall (i.e., limiters) against plasma transients; (ii) the integration and safety of large cooling systems for the case with helium and with water as coolants (e.g., Primary Heat Transfer System, vacuum vessel pressure suppression system) to understand the impact on the overall plant architecture and remote maintenance; (iii) mechanisms of tritium permeation to the coolant to identify adequate design and technological measures, to minimise it and to size a technologically feasible Coolant Purification system. Novel manufacturing techniques (i.e., Selective Laser Sintering (SLS) and Electron Beam welded to conventionally manufactured parts) have been further developed and representative specimens/ mock-ups were fabricated. They could lead to significant design simplifications and minimisation of manufacturing costs. The work carried out on all those aspects makes clear that the selection of the breeding blanket for DEMO must not be solely based on performance criteria of the breeding blanket. It should also account for the interfacing systems, the tokamak integration and the safety approach. Moreover, the return of experience from all the phases of the EU TBM programme for ITER will provide fundamental inputs. It is indeed recognised that some operational experience of the TBM in ITER in the nuclear phase will be essential in order to collect nuclear data for validating the tritium production and transport modelling tools, which are used for the design of the DEMO breeding blanket.

Progress along Mission 5:

For Mission 5 **(Safety and Environment)** initial safety analyses are in progress to evaluate the response of the DEMO systems to abnormal events, and to guide the design to minimise potential accident consequences. As safety also plays an important role in the ultimate selection of plant design choices and operating conditions (e.g., choice of materials, coolants), safety analyses must be constantly updated to match the evolution of the DEMO design. Preliminary assessments of radioactive waste have also been performed, focused on the influence of design options on the quantity and classification of waste. An R&D plan is in place to develop further techniques for detritiation of solid waste, and confirm the feasibility of recycling, together with industrial partners.

Progress along Mission 6-7:

In accordance with the strategy and ambition of the Roadmap, key features of the European DEMO stage design and R&D approach include: (i) a strong philosophy of 'systems thinking' and emphasis on developing and evaluating system designs in the context of the wider **integrated plant design**; (ii) targeted technology R&D and system design studies that are driven by the requirements of the DEMO plant concept and focus on design feasibility and integration issues; (iii) where possible, modest extrapolations from the ITER physics and technology basis; (iv) evaluation of multiple design options and parallel investigations for improved systems and/ or technologies which currently have high technical risk or novelty (e.g., the choice of breeding blanket technology and coolant, power exhaust solution and configuration, power conversion systems, etc.). Important design integration achievements of PPPT encompassing Missions 4-7 are summarised as follows:

- The high-level DEMO requirements have been defined following interaction with an external stakeholder group composed of experts from industry, utilities, grids, safety, licensing, etc. This has led to a further substantiation and cascading of functions and requirements to sub-systems.
- A close contact has been established with Gen IV fission and ITER to learn from their project execution experience.
- An integrated design philosophy has been established with a traceable decision making process, and a more systems-oriented approach has brought clarity to a number of critical design issues.
- The methodology to determine DEMO design points has been improved by using systems codes. This involved improved consistency of physics and technology models and assumptions and identification of main design parameter drivers.
- Sensitivity studies have been performed to determine the impact of uncertainties of underlying physics and engineering/technology assumptions on machine parameters.
- Design trade-off studies have been carried out to understand the impact of key design assumptions on plasma performance, integration, maintenance, etc. Most notable are the aspect ratio, plasma elongation and the re-

[52] M. Gasparotto, et al., Review of the TBM/DEMO Breeding Blanket programmes by the Review Panel, Final Report, Sept. 2017

duction of the thickness of the outboard breeding blanket and the number of TF coils.

- Issues related to the development of a reliable DEMO scenario have been identified, including Heating and Current Drive Systems requirements and Plasma Diagnostics and Control requirements.

- A first DEMO plant layout has been designed in collaboration with industry for the two options of using either water or helium to remove the heat from the breeding blanket. This preliminary layout serves to identify system integration issues and to develop a technically feasible, operable and a maintainable and safe plant design. It enables the identification of areas in which there are significant technical uncertainties and to provide a clear basis for safety and cost analysis as well as further improvements.

- Preliminary safety assessments were performed, including assessment of alternative design and technology options.

- The integrated schedule and deliverables for a Staged Design Approach to arrive to a DEMO Concept Design Review around 2027 have been defined. This places strong emphasis on development of requirements, examination of systems integration aspects, traceable concept down-selection and assessment of design and project maturity through the implementation of a formal Gate Review Process at the end of the pre-concept design phase in 2020.

- The key design integration issues that affect the whole DEMO nuclear plant architecture and layout have been identified and studied. The emphasis is on design integration of all components, engineering/operational aspects of power conversion, technology feasibility, safety, licensing and remote maintenance.

- An initial exploration was made of design integration and engineering issues (i.e., nuclear shielding and structural performance, superconductor coil design and integration, remote maintainability, etc.) related to a number of alternative divertor configurations (e.g., double-null divertor, snowflake divertor, a long-leg Super-X divertor) as well as a flexible pulsed/steady-state operation device, etc., to evaluate their DEMO reactor relevance and engineering development needs.

- Initial relationships with industry have been built up and industry experience has been embedded in the design to ensure that licensing, manufacturing and operational aspects are considered. This ensures that early attention is given to industrial feasibility, cost, nuclear safety and licensing.

For the Projects under **Missions 6 and 7**:

- **Balance of Plant:** Work is ongoing, with industrial support, to develop feasible technical solutions for a Balance of Plant design for DEMO for both options of helium and water as coolants of the breeding blanket. This includes a Primary Heat Transfer System, an Intermediate Heat Transfer System equipped with an Energy Storage System using Molten Salt as heat transfer fluid, to mitigate the impact of plasma pulsing on the steam turbines, other Power Conversion System equipment and the electrical grid. This work is useful to establish layout requirements and evaluate integration implications with other systems. Additionally, it enables the identification of technical feasibility issues; commercial availability and R&D needs. Recently, work has also started, with a strong support of relevant industry, to develop a conceptual design of a plant option directly coupling the Primary Heat Transfer System to Power Conversion System, which addresses the feasibility of an alternative (hopefully simple) Balance of Plant option.

- **Diagnostics and control:** Work is underway to develop a conceptual design of a control system that ensures machine operation in compliance with nuclear safety requirements, avoids machine damage, and achieves high plant availability and an optimised fusion performance.

- **Divertor:** A number of small scale mock-ups were successfully manufactured by means of tailored joining methods, inspected by dedicated non-destructive test methods such as ultrasonic testing and infrared thermography and high-heat-flux tested for a large number of cycles. In the first phase HHF testing campaign, the mock-ups of five concepts withstood 300 loading cycles and those of three concepts even up to 500 cycles without any discernible damage (technologies that survive 500 cycles often have a good chance of long lifetimes). In addition, 3D CFD analysis verified that the cooling scheme assured required power exhaust capability with a reasonable thermohydraulic performance and acceptable operation temperature range for the structural materials.

- **H&CD systems:** Pre-conceptual designs for neutral beams (NBI), electron cyclotron heating (ECH) and ion cyclotron heating (ICH) systems for DEMO have been developed and integration studies are underway. Other achievements are outlined below. For ECH, a coaxial high power short pulse gyrotron was assembled and is being tested. For step tuneable gyrotron, first diamond disks of 180mm diameter were produced, as part of a medium term part project in collaboration with industry. For NBI, proof-of principle of the photo-neutralisation at reduced scale was performed.

- **Magnets:** Work is focused on the design, development, and testing of improved concepts of superconducting cables with better performance and resistance to degradation due to cyclic loads, based on three different alternative winding packs, all based on Nb_3Sn technology and Cable-in-Conduit Conductors. Short samples manufactured the following (i) a layer-wound configuration and a react & wind cabling technique and (ii) a double-layer winding and a wind & react cabling approach have been tested at different temperatures and magnetic fields in the SULTAN and EDIPO facilities at EPFL (Switzerland).

Results show no degradation with electromagnetic cycles and an effective strain of -0.35%. Additional work include conceptual design of DEMO magnet systems (i.e., toroidal and poloidal field superconducting coils, including the central solenoid), supported by thermo-hydraulic and mechanical analyses and design and testing of fusion-relevant high-temperature superconductor cables.

- **Remote maintenance:** Remote maintenance is a design defining driver for DEMO, i.e., it is very important for the reactor architecture as a whole and must be substantiated early. Design and R&D focuses on aspects with highest risk to the feasibility of the strategy, including precision placement of large in-vessel components and pipe joining technology. Highlights of achievements include the conceptual design of a solution to the blanket handling requirements using a low-mass actuator to manipulate high-mass objects, the release for manufacture of proof-of-principle laser pipe cutting and welding tools deployed in-bore and the integration of in-vessel and ex-vessel maintenance equipment concepts with the evolving component designs and plant layout.
- **Tritium fuelling and vacuum:** A novel and innovative fuel cycle architecture has been developed, driven by the need to reduce the tritium inventory to an absolute minimum. This consists of changing from discontinuous cryopumping (as in ITER) to mercury based continuous vacuum pumping with zero demand on cryoplant power, and the introduction of thermal cycling ab- and adsorption processes for isotope separation in the tritium plant instead of large cryogenic distillation columns with tritiated liquid hold-ups. To further reduce inventory, the well-known approach to route all exhaust gas through the tritium plant has been abandoned in favour of a three-loop architecture. There, super-permeable metal foils are introduced in the divertor ports to separate a pure DT stream which is then immediately recycled to feed the pellet injection systems. To increase the core fuelling efficiency, optimisation potentials in the design of the high field side pellet guiding tube systems are being exploited.

Competitive costs of electricity (Mission 7) has focused on reliability and availability (major overall factors in the costs of electricity), notably effective remote maintenance strategies, and early work on reducing costs of components by suitable design (e.g., the magnets). A wider scope is planned for the coming years as described above.

11.4 Progress in other areas

- EUROfusion has awarded in its first 5 years[53] a total of 61 EUROfusion Researcher Grants (ERG), which are highly competitive two-year post-doc positions granted on the basis of scientific excellence. Additionally, 77 EUROfusion Engineering Grants (EEG) for three-year engineering positions were granted. The EEG programme is a follow up of the Goal Oriented Training Programme. In contrast to the ERG programme where candidates can propose any subject as long as it is aligned to the Fusion Roadmap, candidates for an EEG grant draft proposals based on job descriptions which are related to the most urgent technology and engineering fields. The job descriptions are partly drafted by project leaders and are partly set up to cover the urgent skills needs of Fusion for Energy. The 2015 Human Resources Survey concluded that 80-85% of the grantees stay in fusion for a long time after their grant is finished.
- EUROfusion is funding the PhD programmes of its members, and FuseNet conducted a quality assessment of the fusion related elements in the PhD programmes in the various European countries. Overall the assessment was very positive, however, there were clear recommendations to involve PhD students from countries that have only limited training possibilities in fusion (e.g., simply because it is a relatively minor activity in some countries) into European training networks.
- EUROfusion spent during the period 2014-2018 an amount of about 35 MEuros in support of Enabling Research projects (see Section 7). The first round in 2014 was for 1-year projects only; the second round in 2015, for projects up to 3-years duration; and the third round in 2017 for 2 years. A total of 91 projects have been launched. The selection of the Enabling Research Projects is done by the Scientific and Technical Advisory Committee (STAC) of EUROfusion with involvement of external referees.

[53]Calls were annually in the period 2013-2017.

12. Glossary

Advanced tokamak operation
The baseline operating regime for ITER is the H-mode, which is characterised by strong ELM activity. Advanced regimes represent a step beyond this baseline regime in which the energy confinement is further improved, relative to that expected in H-mode. An important characteristic of the advanced regime is that it has a high self-driven current fraction, which minimises the need for external current drive methods, and makes it more suited to continuous operation of a power plant.

Balance of Plant
The “balance of plant” of a system is the components not included in the primary system itself, including blowers, compressors and pumps, and other necessary but not primary components.

Blanket
In a fusion power plant, the blanket is the system surrounding the plasma used to slow down the neutrons produced, so that the heat released can be used for electricity generation. The blanket is also used to synthesise tritium (from the neutrons and a lithium compound) to use as fuel.

Broader Approach
The Broader Approach agreement, concluded between the European Atomic Energy Community (Euratom) and Japan, consists of activities which complement the ITER project and to accelerate the realisation of fusion energy through R&D and advanced technologies for future demonstration fusion power plant prototypes (DEMO).

CFETR
Chinese Fusion Engineering Test Reactor with the aim of demonstrating the full cycle of fusion energy in long pulse or steady-state operation, with tritium self-sufficiency.

DEMO
Demonstration power plant prototype(s) envisaged to follow ITER.

Disruption
A complex phenomenon involving plasma instabilities which results in rapid heat loss and termination of a tokamak discharge. Plasma control may be lost, in which the apparatus may be damaged, particularly in large machines. This phenomenon places a limit on the maximum density, pressure and current in a tokamak.

Divertor
A magnetic field configuration affecting the edge of the plasma confinement region, designed to divert impurities/helium ash to a target chamber (this chamber is also often called the ‘divertor’). This is an alternative to using a limiter to define the plasma edge.

Dpa (displacements per atom)
In irradiation damage the conventional unit of neutron fluence is displacements per atom (dpa). This measure of damage is a calculated value, derived from neutron transport calculations and a model of scattering recoils. Fusion structural materials designed for future power plant must withstand many 10s of dpa over their lifetime. For example, at 100 dpa each atom has on average been displaced from its lattice site one hundred times, and more than 99,99% of the atoms in the crystal structure have recombined at a proper lattice site.

Edge Localised Mode (ELM)
An instability that often occurs in short periodic bursts during H-mode in divertor tokamaks. It causes transient heat and particle loss into the divertor which can be damaging.

Energy confinement time
The energy confinement time is the average time taken for the energy to escape the plasma, usually defined by the ratio of the energy stored and the power loss.

EUROFER
Ferritic-martensitic (9% Chrome) steel with special properties: it is the reference steel for the development of components in fusion power plants, with, compared to austenitic steels, very much reduced irradiation induced swelling and susceptibility to the production of helium under neutron bombardment, and can be made with chemical compositions to achieve reduced activation and waste.

EUROfusion
Consortium of 30 national fusion research institutes in 26 European Union countries plus Switzerland and Ukraine performing Research and Developments in the field of fusion research.

EVEDA
Engineering Validation and Engineering Design Activity for IFMIF.

Ferritic-Martensitic steels
Magnetic alloys which, when modified to improve their ductility, represent the most promising structural material for the first generation of fusion power plants. In microscopic terms they have a body centred cubic lattice structure; such structures are thought to have the highest resistance to embrittlement under irradiation, inherently yield strength, however limited ductility and fracture resistance at lower temperature following neutron irradiation.

Fusion gain
Ratio between the power produced by the fusion reactions and the external power required to sustain them. A fusion power plant requires a fusion gain (Q) between Q=10 and 50.

Fusion Material Neutron Source
To test and validate materials and components for DEMO and the commercial fusion power plant, materials need to be tested under a 14 MeV neutron load. The ideal source would be IFMIF or its lighter variants IFMIF-DONES and A-FNS (see below).

H-mode
The H-mode is a high confinement regime that has been observed in tokamak plasmas. It develops when the plasma is heated above a characteristic power threshold, which varies with density, magnetic field and machine size. The H-mode is characterised by a sharp temperature gradient near the

edge and typically a doubling of the energy confinement time compared to the normal L-mode. ELMs are often observed in this regime.

Helias
A helical advanced stellarator, using an optimised modular coil set designed to simultaneously achieve high plasma, low Pfirsch–Schlüter currents and good confinement of energetic particles; i.e., alpha particles. The Wendelstein 7-X device is based on a five field-period Helias configuration.

IFMIF-DONES and A-FNS
The International Fusion Materials Irradiation Facility (IFMIF) is a proposed device that shall test and validate the structural integrity of fusion power plant materials under appropriate neutron spectrum and fusion irradiation damage conditions. The detailed design and prototyping are being undertaken by Europe and Japan as a Broader Approach project. DONES (DEMO oriented Neutron Source) and A-FNS (Advanced Fusion Neutron Source), are rather similar, reduced-scope fusion materials test facilities with the potential to be upgraded to “full” IFMIF.

Inductive regimes of operation
Tokamak operation regime, where most of the toroidal plasma current required for plasma confinement is driven inductively by the magnetic flux swing produced by the transformer. This regime is characterised by a limit in the pulse duration, leading to pulsed operation of the tokamak; in contrast to steady state tokamak operation that requires the current to be driven non-inductively.

Liquid metals as plasma facing components
The concept of replacing solid tokamak plasma facing components with liquid components, might increase the quasi-stationary heat fluxes removal capability, avoiding the melting, cracking and other damages that occur in solid components.

Medium-sized tokamaks (MSTs)
EUROfusion exploits the tokamaks ASDEX Upgrade (Germany), MAST Upgrade (United Kingdom) and TCV (Switzerland). These three tokamaks are referred to as the medium-sized tokamaks.

ODS steels
Oxide dispersion strengthened alloys are intended to be used for high temperature, high n-fluence applications and have potential against helium embrittlement. The development of suitable low activation ODS steels would allow the operation of the fusion power plants at higher temperature, resulting in a higher thermodynamic efficiency and increased lifetime of plasma near components.

Plasma operation scenario
A plasma operation scenario is a recipe for how to run a plasma discharge in a tokamak or stellarator. It defines the point(s) in operational space that are desired as well as the most suitable path(s) to reach these points.

RAMI
RAMI stands for Reliability, Availability, Maintainability and Inspectability. It describes a process whose primary purpose is to make sure that all the systems of a machine will be reliable during the operation phase and maintain their performance under operational conditions with the best possible availability.

Snowflake divertor
Divertor configuration which makes use of a second-order null of the poloidal field (poloidal field and poloidal field variation equals to zero) to improve performance; by the larger flux-expansion near the poloidal field null, increased connection length allowing radiative cooling before the plasma reaches the target.

Steady-state regimes of operation
Steady State tokamak operation that requires the plasma current to be driven non-inductively.

Stellarator
A stellarator is a magnetic confinement device in which the poloidal magnetic field is generated by external helical coils, in contrast to the tokamak in which the poloidal magnetic field is generated by an externally driven plasma current. The stellarator is, engineering-wise more complicated as the tokamak, but has as advantage that it is in principle steady state and additionally it is not prone to some of the plasma instabilities that affect tokamak plasmas.

Super-X divertor
A divertor design in which the power per unit area striking material surfaces is reduced greatly. It requires a set of divertor coils that extends and controls a long plume of exhaust plasma. The length of the plume allows high radiative cooling before the plasma reaches the target. Also, the radius of the target is higher than in other designs, which increases the target area.

TBM programme
The Test Blanket Module (TBM) Programme is a specific programme for the development of blanket modules for application in fusion power plants. ITER will test a number of concepts through the implementation of the Test Blanket Module Programme under the ITER agreement.

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In drafting this updated Fusion Roadmap the authors had many interactions with Project Leaders, Task Force Leaders and other experts. Via these groups we had input from the Beneficiaries.

In 2018 the European Fusion Community finalised the 'European Research Roadmap to the Realisation of Fusion Energy' which outlines the steps to the realisation of fusion electricity. The same year the EUROfusion General Assembly approved the document. Additionally, the Euratom Scientific and Technical Committee reviewed the roadmap and supported it with a positive opinion paper. This document can be downloaded on www.euro-fusion.org/eurofusion/roadmap.

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[54] F. Romanelli, P. Barabaschi, D. Borba, G. Federici, L. Horton, R. Neu, D. Stork and H. Zohm, Fusion Electricity: a roadmap to the realisation of fusion energy, EFDA (2012) ISBN 978-3-00-040720-8.

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Integration Group


Credit: EUROfusion

Tony Donné, EUROfusion


Credit: UKAEA

William Morris, CCFE

Mission 1


Credit: EUROfusion

Xavier Litaudon, EUROfusion


Credit: CIEMAT

Carlos Hidalgo, CIEMAT

With involvement of Wolfgang Biel, Flavio Crisanti, Gloria Falchetto, Daniela Farina, Gerardo Giruzzi, Per Helander, Emmanuel Joffrin, Arne Kallenbach, Richard Kamendje, Alberto Loarte (ITER), Joelle Mailloux, Piero Martin, Marie-Line Mayoral, Hendrik Meyer, Isabel Nunes, Michele Romanelli, Henry Weisen, Ronald Wenninger

Mission 2


Credit: UKAEA

Darren McDonald, EUROfusion


Credit: IPP, Silke Winkler

Hartmut Zohm, IPP

With involvement of Raffaele Albanese, Wolfgang Biel, Sebastijan Brezinsek, Stefano Coda, David Coster, Thomas Eich, Gloria Falchetto, Antti Hakola, Karl Krieger, Giuseppe Mazzitelli, Hendrik Meyer, Gerald Pintsuk, Jens Juul Rasmussen, Holger Reimerdes, Paolo Ricci, Emmanuelle Tsitrone, Ronald Wenninger, Sven Wiesen, Marco Wischmeier, Jeong-Ha You

Mission 3

Eberhard Diegele, EUROfusion

Anton Möslang, KIT

Kai Nordlund, University of Helsinki

With involvement of Angel Ibarra, Michael Rieth and Gerald Pintsuk

Mission 4-7

Gianfranco Federici, EUROfusion

Piergiorgio Sonato, Consorzio RFX

Chris Waldon, CCFE

With involvement of John Anthony, Wolfgang Biel, Lorenzo Boccaccini, Richard Brown, Matti Coleman, Christian Day, Robert Ellis, Maurizio Gasparotto, Marco Grattarola, Angel Ibarra, Tony Loving, Neill Taylor, Derek Stork, Ming Quang Tran, David Ward, Jeong-Ha You, Louis Zani

Mission 8

Duarte Borba, EUROfusion

Per Helander, IPP

With involvement of Francisco Castejón, Andreas Dinklage, José Manuel García-Regaña

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Programme Management Unit
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contact@euro-fusion.org

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National Center for Scientific
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SLOVENIA

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