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Optimising Fusion's Contribution to Economically Efficient Climate Change Mitigation

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Abstract

The context within which fusion development planning is undertaken is changing. Recent publications by the Stern Review (by the former Vice-President and Chief Economist of the World Bank) and by the Intergovernmental Panel on Climate Change have removed most of the residual uncertainties about the cost, reality, causation and pace of climate change. Governmental decisions, and demonstrations of public support, have displayed increasing commitment to mitigating climate-changing emissions. The ITER Treaty and the Broader Approach Agreement have removed much uncertainty relating to the near-term steps of fusion development. Concerns over energy security and diversity of supply have markedly increased. Thus, it has become reasonable to plan on the assumption that in twenty years time ITER and IFMIF will have been successful and the world will be eager for clean, secure energy supplies. Previously published 'fast track' scenario studies all assumed a sequential model of fusion development, severely constrained by funding. The present paper explores the economic justification for relaxing these assumptions, and the resulting potential for more rapid, but cost-effective, fusion deployment. This includes the acceptability of reduced targets for the internal cost performance of the first generation of power plants, and overlapping of development stages.

1. Introduction and Background

The context within which fusion development planning is undertaken is changing. Recent publications by the Stern Review [1] (by the former Vice-President and Chief Economist of the World Bank) and by the Intergovernmental Panel on Climate Change [2] have removed most of the residual uncertainties about the cost, reality, causation and pace of climate change. European and Governmental decisions, and demonstrations of public support, have displayed increasing commitment to mitigating climate-changing emissions. It is becoming more widely appreciated that during the second two-thirds of this century continued world economic development, and continued growth in energy consumption, must co-exist with the reduction of carbon emissions to very low levels, and that this will give rise to large political and economic forces. Concerns over energy security and diversity of supply have also markedly increased. The ratifications of the ITER Treaty and the Broader Approach Agreement have removed much uncertainty relating to the near-term steps of fusion development.

Thus, in these changed circumstances, it has become reasonable to plan on the assumption that in twenty years time ITER and IFMIF will have been successful and the world will be eager for clean, secure energy supplies, such as fusion. Previously published 'fast track' scenario proposals and studies [3-6] all assumed a sequential model of fusion development, severely constrained by funding. The present paper explores the economic justification for relaxing these assumptions, and the resulting potential for more rapid, but cost-effective, fusion deployment. This includes the consideration of the acceptability of reduced targets for the internal cost performance of an earlier first generation of power plants and overlapping of development stages, with risks controlled and options held open by broadening of the development stages, for example by several IFMIF and DEMO devices.

Section 2 outlines the essence of conventional, 'sequential, restricted-funding' fast track development scenarios and their expected economic outcomes. Section 3 discusses the implications of climate change mitigation. The implications of energy security considerations are briefly discussed in Section 4. The threads are drawn together in Section 5, and used to develop ideas for more rapid evolution of fusion power with less ambitious technical targets for the first generation of power plants: economic considerations suggest that this may be the optimal way for fusion to contribute to climate change mitigation. Conclusions are summarised in Section 6.

It must be stressed that all the development plans discussed, including the considerations advanced in this paper, fully preserve the major safety and environmental advantages of fusion power [7-13], which are key to securing social acceptance for it's widespread deployment.

2. Conventional Fusion Development Scenarios

The essence of conventional – 'funding-constrained, sequential' – fast track scenarios for the development of fusion [3, 4], is as follows:

- development and qualification of materials occurs on the same timescale as ITER;
- there is a single stage, DEMO(s), between the ITER/IFMIF stage and the launching of the first generation of power plants;
- each stage begins only when the previous stage is essentially complete.

An example [6] of a development of this concept is illustrated in Figure 1. Other plans [4,5,6,14], are broadly in agreement with Figure 1, though differing from one another in detail. An almost inevitable consequence of the sequential assumption, and of the time needed to construct and exploit large devices, is that demonstration of electricity production by fusion does not occur until up to about thirty years.

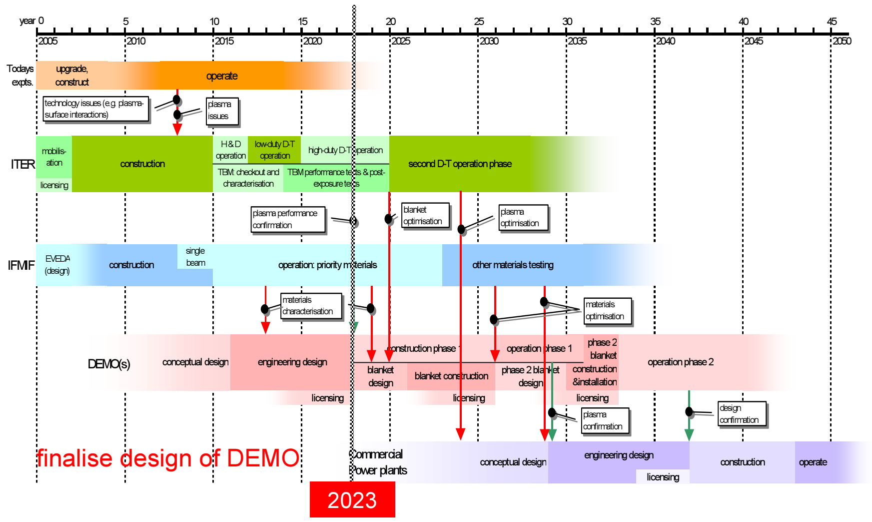

Figure 1. An example of a 'funding-constrained, sequential' fast track fusion development scenario (from [6]).

All these plans assumed – explicitly or tacitly – continuation of funding at about the present level. This level is low: the whole cost of developing fusion to fruition is equal to only a few days of world consumer spending on energy; the cost of constructing ITER is about the same as the cost of constructing a small European town (ten thousand households). As shown in Figure 2, there is a similar adverse picture for energy R&D as a whole: total world public sector energy R & D is about ten billion dollars annually, equal to about a day of consumer spending on energy – not much to solve a major global problem!

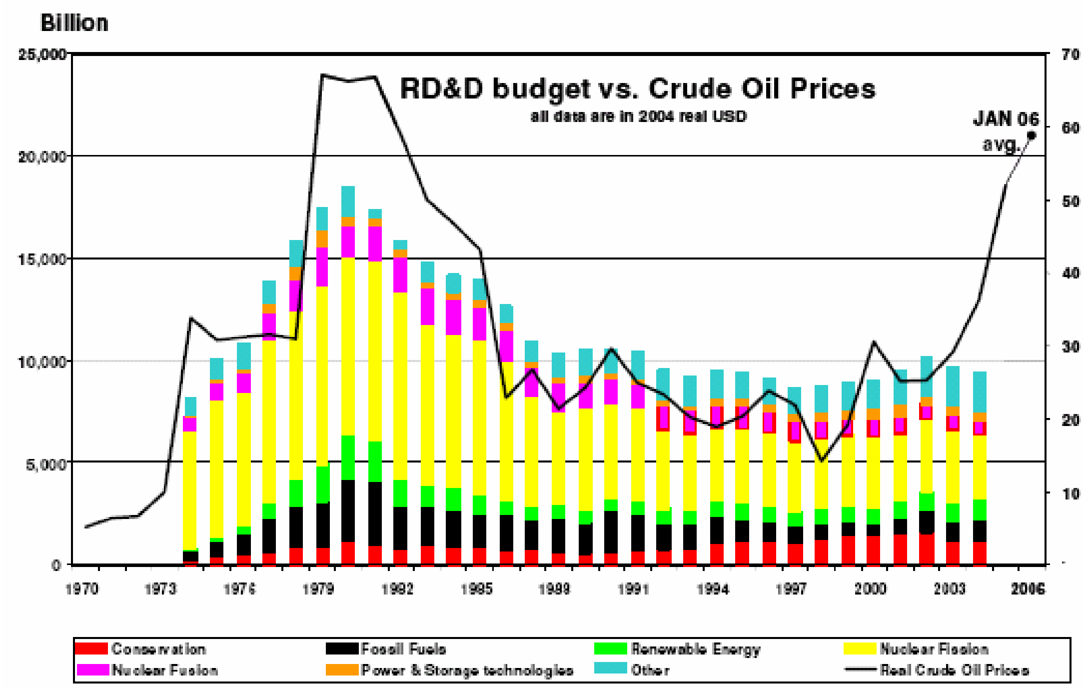

Figure 2. Annual world public sector spending on energy R&D (also shows crude oil prices) (IEA).

What are the likely economic characteristics of fusion power plants developed by programmes along the lines outlined above? A number of detailed studies have been made – see, for example, [7-9, 13, 15, 16-19] – that are broadly in agreement. Typical results for the estimated range of internal costs of electricity from fusion are shown in Figure 3, together with estimated ranges for projected internal costs of electricity from some other energy sources. ("Internal cost" means the conventional costs ignoring "external" costs associated with environmental and health effects stemming from emissions, accidents and so on – for fusion, these external costs are very small [7-9, 13, 15-16, 19], comparable with wind power.) In Figure 3, the ranges for the non-fusion sources are taken from an IEA publication [20] and the fusion ranges are taken from the European PPCS and follow-up work [7-9, 13, 19,21]. Note that wind is near term technology, but the numbers for wind do not include the costs for the standby or storage that would be necessary if it were to contribute on a large scale in the future. There are, of course, significant uncertainties associated with all such projections.

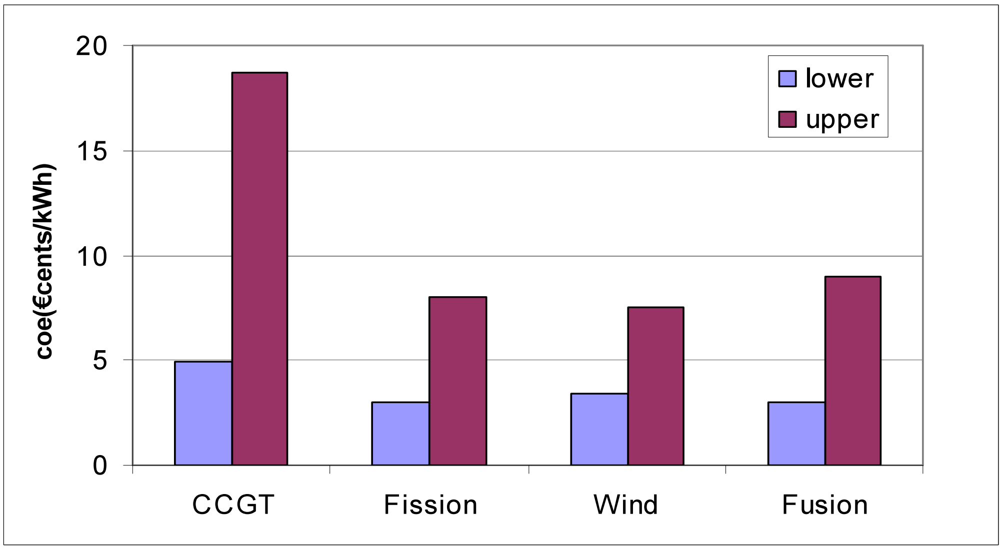

Figure 3. Ranges of projected costs of electricity from various energy sources.

Thus these 'fast track' fusion development scenarios, with rather measured pace dictated by severe funding constraints and characterised by risk aversion, result in a very good outcome – very safe and environmentally benign power plants with competitive internal costs of electricity. Until fairly recently, this would have been regarded as an entirely appropriate and defensible position. However, as emphasised in the Introduction, everything is changing! Does this mode of developing fusion power deliver its ***widespread*** deployment early enough to make an economically optimal contribution to mitigation of global climate change?

3. Mitigation of Climate Change and its Implications

Figures 4 – 7 illustrate the projected climatic consequences of various scenarios for greenhouse gas emissions (shown as equivalent amounts of CO_2 – in fact the effective contributions of the other greenhouse gases are small compared to that of CO_2). (These figures are taken from the Stern Report [1] – the information in the IPCC Reports [2] is essentially the same.) Figure 4 shows selected impacts of different global temperature rises. Information of this nature suggests that whilst a temperature rise of 2^oC might be acceptable, though not desirable, it would be dangerous to allow a rise of 3^oC or more. Figure 5 shows the uncertainties, arising from modelling uncertainties, in the relationship between postulated levels of stabilised greenhouse gas concentrations in the atmosphere and the calculated eventual resulting global temperature changes [1]. It is apparent that to have a good chance of staying below a rise of 3^oC, greenhouse gas concentrations need to be kept below 550 ppm CO_2e.

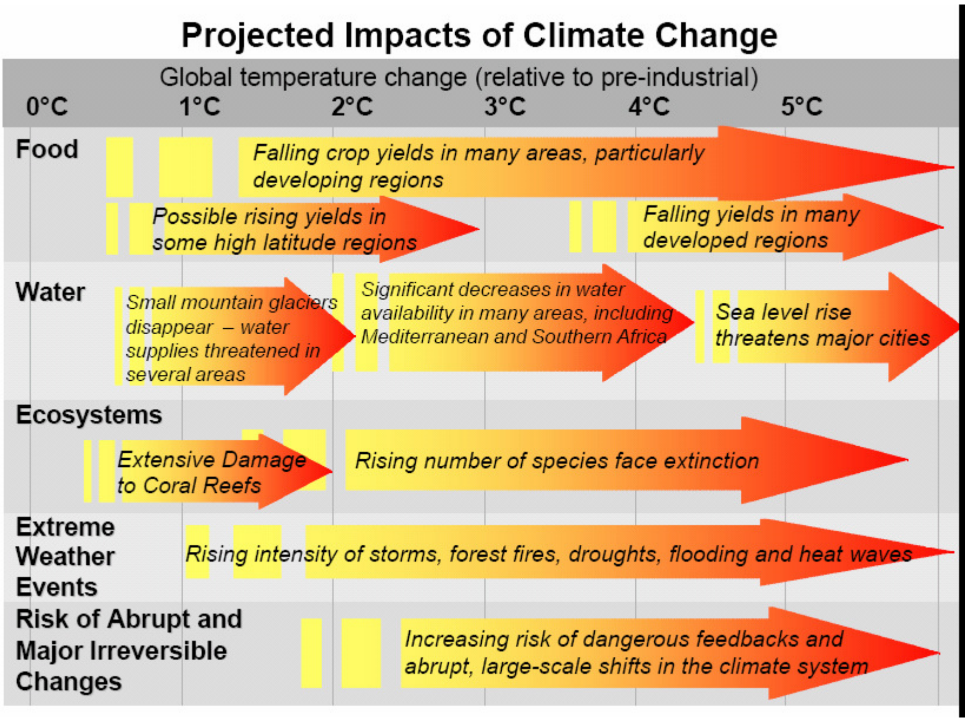

Figure 4. Selected projected impacts of climate change. A more complete picture can be found in the Stern Report [1].

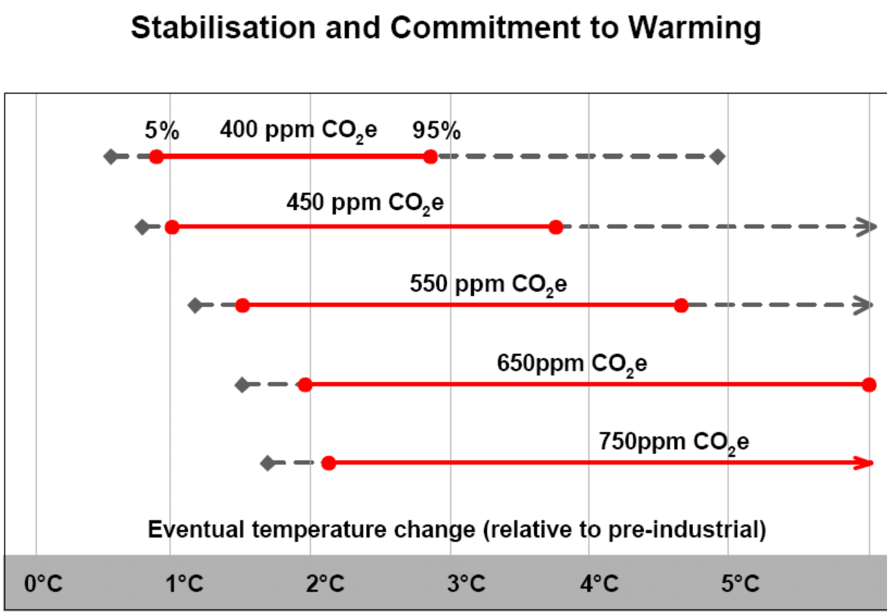

Figure 5. Uncertainties in the relationship between stabilised greenhouse gas content of the atmosphere and eventual temperature change [1].

Figures 6 and 7 show some typical emission scenarios [1]: an unconstrained 'Business as Usual' scenario, together with scenarios that stabilise atmospheric concentrations at 450 ppm CO_2e or 550 ppm CO_2e; a variety of emission paths all stabilising at 550 CO_2e but with differing lags before the adjustment is made. These scenarios illustrate well a point made forcefully by the authors of the recent comprehensive report 'Avoiding Dangerous Climate Change' [22]: *"In the first approximation, concentrations and temperature changes are a* *function of cumulative emissions. This implies that future global emissions trajectories have to curve through a maximum some time this century (during the next decade or two for stabilisation at relatively low levels of, say, 400-500 ppmv and a few decades later for high levels), and proceed to decline well below current levels towards the end of the century. This is a tall order from the current perspective……. What is more controversial, however, is whether now-known technologies can achieve this momentous global undertaking or whether fundamentally new options, such as fusion, that are still technically not feasible, might be required.*"

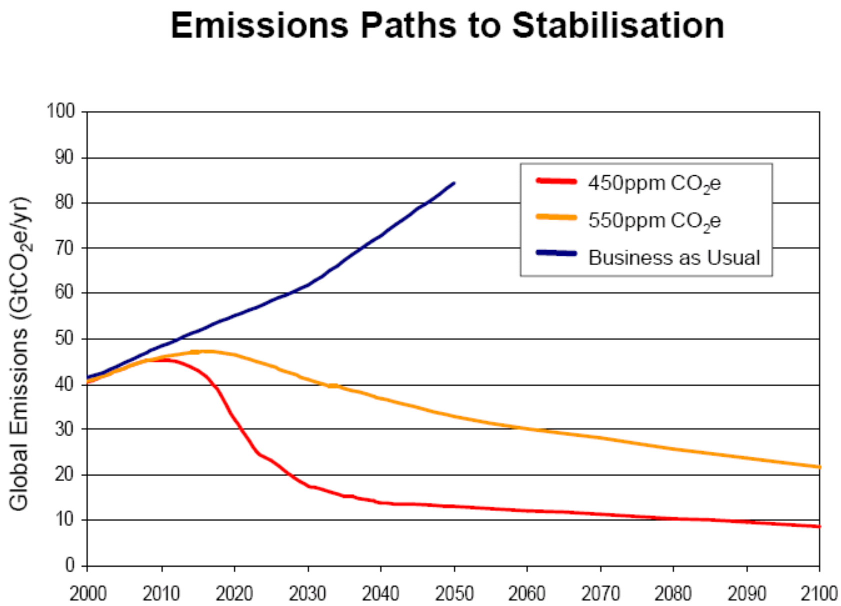

Figure 6. Typical emission scenarios: unconstrained, and constrained to stabilise end-of-century atmospheric concentrations [1].

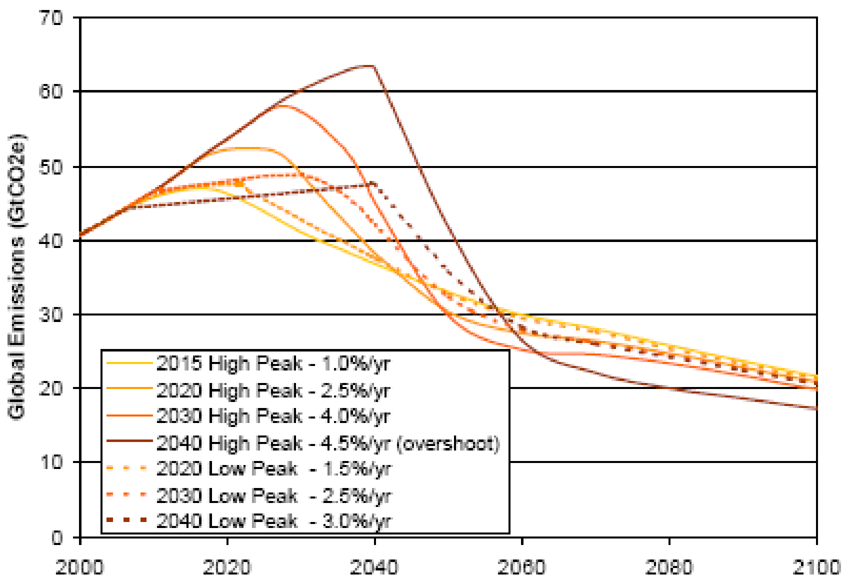

Figure 7. Illustrative emission paths to stabilise at 550 ppm CO_2e [1].

It is clear from all this that, during the second two-thirds of the century, the continuation of economic development in currently less-developed countries, co-existent with the reduction in emissions to low levels, will generate large political and economic forces and opportunities. In particular, it appears that the opportunities for fusion to contribute cost-effectively to climate change mitigation may be greatest if it can be deployed early enough, even in a non-ideal form, and that higher rates of fusion development expenditure would be amply justified from an economic perspective. These intuitions are supported by the pertinent economic analyses that have been performed. The Stern Review [1] found that the costs of climate change are far higher than the costs of measures that would mitigate it, and that economics mandates that investment in energy research and development should at least double, specifically citing fusion as one of the four priorities for scientific progress.

These conclusions were prefigured, and the role of fusion considered in detail, in seminal economic research, funded by the European fusion programme but performed by independent experts, a decade ago [23]. This work used a well-established detailed model (MARKAL) to simulate the evolution of the West European economy to the end of this century, determining the cheapest (discounted) way to supply the demand for energy subject to constraints such as a cap on atmospheric CO_2 – see [15,16,23] for further detail and discussion. The results shown in Figure 8 give the composition by source of West European electricity generation for a variety of constraints on atmospheric CO_2 concentration.

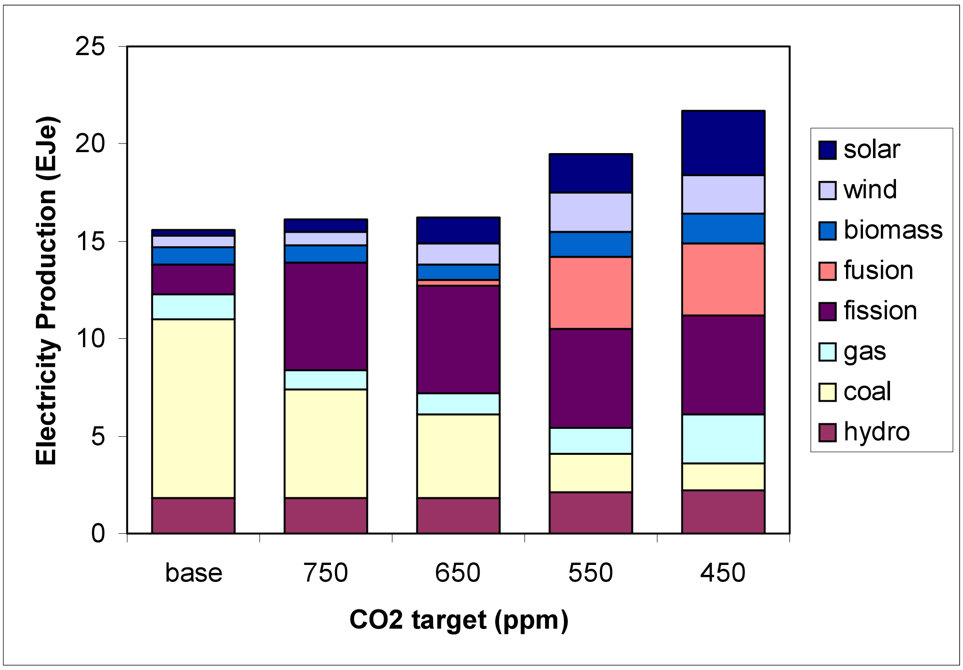

Figure 8. MARKAL results for the composition of West European electricity generation in 2100, for various constraints on atmospheric CO_2 concentration in 2100 ('base' means unconstrained) [23].

It can be seen that fusion captures about twenty percent of the market in the 450 ppm and 550 ppm cases (the critical cases identified earlier in this paper). A detailed examination of the results shows that fusion could not capture a larger share of the market because, on the assumptions made at that time (1997), it could not be deployed fast enough. It is important to realise that, in each column of Figure 8, each source shown is overall an economic source of electricity – otherwise the cost-minimising machinery in the code would have adjusted the proportional contributions – in the context of the constraint. Fusion was not forced into these scenarios, it was just made available and was sucked in by the cost-minimising mathematical machinery. Broadly similar conclusions were reached in a Japanese study using a world model [24]. In more recent, but still preliminary, European work using the EFDA-TIMES multi-regional world model, almost all of European electricity in 2100 is projected to have be supplied by non-carbon sources if CO_2 constraints are applied [25].

In all these cases, the sums involved are huge, dwarfing the costs of fusion development, amply justifying fusion development from the economic viewpoint and strongly suggesting that it would be more optimal economically to spend more on fusion development to produce fusion power earlier. Studies of the economic value of developing fusion at different speeds, taking into account the varying costs and resulting changes in the probabilities of failure, have been performed [26,21]. The economic value of developing fusion is substantially positive in all but the most pessimistic scenarios, and is highest for early deployment.

4. Energy Security and its Implications

Fusion has very abundant, accessible and widespread economically viable fuel resources (lithium, and deuterium from sea water): by far the largest of any energy source [21]. Thus it potentially can make a major contribution to the resolution of future energy security issues, as well as to global climate change mitigation. Energy security imperatives may inhibit the most cost-effective globalised deployment of some climate-change-mitigating energy sources, but this would not be a factor for the deployment of fusion.

5. More Optimal Development of Fusion

The considerations discussed in the previous sections suggest that:

- Higher levels of fusion development funding are economically justified, and could be used to break the ‘sequential’ assumption in fusion development planning.
- An earlier first generation of fusion power stations would be economically justified, even with reduced internal cost performance, and this may be the economically optimal scenario.

Conventional ways to somewhat accelerate, and reduce the risks of, fusion development were discussed in [6]. However, as emphasised elsewhere in these proceedings [14], a more decisive acceleration entails breaking the ‘sequential’ assumption. Consideration should be given to an early DEMO, beginning construction in ten years and demonstrating electricity production in twenty years, necessarily with relaxed requirements such as:

- Plasma performance similar to ITER, and moderate power density.
- Long-pulse operation, if steady-state is not available in time.
- A near-term, less efficient, blanket concept.
- A reduced lifetime-fluence target for the blanket structural steel.

See elsewhere in these proceedings [27] for a discussion of DEMO options. In particular, long pulse (about ten hours) fusion power output, with energy storage to produce steady net electric power, would probably incur an economic penalty of only about 20% - mainly from measures taken to reduce the effects of fatigue. For fixed net electric output, the size of a pulsed device is automatically larger [27] than a steady-state device, producing the following beneficial consequences, from the viewpoint of early development:

- Easier maintenance.
- Reduced load on the divertor.

- Reduced neutron flux to the first wall.

The economic considerations summarised in this paper suggest that an early generation of power plants, based directly on the above DEMO conceptions would be economically acceptable, but this requires more detailed study.

6. Summary of Conclusions

The new context of fusion development planning is

- greatly increased confidence in fusion,
- little doubt about the reality, causation, pace and cost of climate change, and sharply increased concerns over this issue,
- sharply increased concerns over energy security.

This motivates and justifies serious consideration of a radical change to the basis of fusion planning scenarios, involving *inter alia*:

- a reduced target for the internal cost of electricity from the first generation of fusion power plants;
- correspondingly reduced targets for the technical performance (e.g. plasma scenarios, materials endurance, blanket efficiency) of DEMO(s);
- demonstration of fusion electricity production in twenty years, leading to widespread deployment of fusion power earlier than in previous fast track scenarios.

7. Acknowledgements

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8. References

[1] N. Stern et al., 'Stern review: the economics of climate change'. UK Government Report, Cambridge University Press, January 2007, ISBN 0-521-70080-9, and www.sternreview.org.uk.

[2] Intergovernmental Panel on Climate Change, Reports: 'The physical science basis; 'Impacts, adaptation and vulnerability', (2007), www.ipcc.ch.

[3] European Council of Ministers, "Conclusions of the fusion fast track experts meeting held on 27 November 2001 on the initiative of Mr. De Donnea, President of the Research Council" (commonly called the King Report).

[4] "A Broader Approach to Fusion Power", Joint Report of the EU/JA Expert Group Meeting, 18/19 April 2004.

[5] K.Lackner et al., 'Long-term Fusion Strategy in Europe', J. Nucl. Mat. 307-311,10-20.

[6] I. Cook, N. Taylor, D. Ward, L. Baker and T. Hender, 'Accelerated Development of Fusion Power', UKAEA FUS 521, February 2005.

[7] D Maisonnier, I Cook, P Sardain, R Andreani, L Di Pace, R Forrest, L Giancarli, S Hermsmeyer, P Norajitra, N Taylor, D Ward, "A Conceptual Study of Commercial Fusion Power Plants: Final Report of the European Power Plant Conceptual Study". European Fusion Development Agreement Report EFDA-RP-RE-5.0, April 2005.

[8] I. Cook, D. Maisonnier, et al., “European Fusion Power Plant Studies”, Fusion Science and Technology 47, 384, April 2005.
[9] D. Maisonnier, I. Cook, et al., “The European Power Plant Conceptual Study”, Fusion Engineering and Design, 75-79, 1173, November 2005.
[10] J. Raeder, I. Cook, F.H. Morgenstern, E. Salpietro, R. Bunde and E. Ebert, “Safety and environmental assessment of fusion power (SEAFP)”, European Commission DGXII, Fusion Programme, report EUR-FUBRU XII-217/95, June 1995.
[11] I. Cook, G. Marbach, L. Di Pace, C. Girard, P. Rocco and N.P. Taylor, “Results, conclusions and implications of the SEAFP-2 programme”, Fusion Eng. Des. 51-52 (2000) 409-417.
[12] I. Cook, G. Marbach, L. Di Pace, C. Girard and N.P. Taylor, “Safety and environmental impact of fusion”, European Fusion Development Agreement report EFDA-S-RE-1, April 2001.
[13] I. Cook, ‘Economic, safety and environmental characteristics of commercial fusion power’, 1st IAEA technical meeting on first generation fusion power plants: design and technology, IAEA, Vienna, July 2005.
[14] D. Maisonnier and J. Hayward, ‘Technological and engineering challenges of fusion’, 2nd IAEA technical meeting on first generation fusion power plants: design and technology, IAEA, Vienna, 20-22 June 2007 (these proceedings).
[15] “Socio-economic aspects of fusion power”, EUR (01) CCE-FU 10/6.2.2, European Fusion Development Agreement Report, April 2001.
[16] I. Cook, R.L. Miller and D.J. Ward, “Prospects for economic fusion electricity”, Fusion Eng. Des. 63-64 (2002) 25-34.
[17] F. Najmabadi et al., ‘ARIES-AT: an Advanced Tokamak, Advanced Technology, Fusion Power Plant’, 18th IAEA Fusion Energy Conference, Sorrento, Oct. 2000.
[18] M. Kikuchi et al., “The Advanced SSTR”, Fusion Eng. Des. 48 (2002) 265.
[19] D.J. Ward, I. Cook, Y. Lechon, R.Saez, “The Economic Viability of Fusion Power”, Fusion Engineering and Design, 75-79, 1221, November 2005.
[20] International Energy Agency, ‘Projected costs of generating electricity’, IEA, Paris, 1998.
[21] D. J. Ward, ‘The contribution of fusion to sustainable development’, Proceedings of Symposium on Fusion Technology, Warsaw, September 2006, accepted for publication in Fusion Engineering and Design.
[22] H. J. Schellnhuber et al., ‘Technological Options’, in ‘Avoiding Dangerous Climate Change’, ed. ‘H. J. Schellnhuber et al., C.U.P, 2006.
[23] P. Lako, J.R. Ybema and A.J. Seebregts, “The Long-Term Potential of Fusion Power in Western Europe”, ECN-C-98-071, 1998.
[24] K. Tokimatsu et al., “Studies of Breakeven Prices and Electricity Supply Potentials of Nuclear Fusion by a Long-Term World Energy and Environmental Model”, Nuclear Fusion 42 (2002) 1289.
[25] D. Ward, private communication, May 2007.
[26] T. Bishop and D. Ward, ‘Assessing the Value of the Fast Track Fusion Programme’, UKAEA report SERF4/UKAEA/FESA/A3, Nov. 2004.
[27] D. Ward, ‘The benefits of different options for a European DEMO’, 2nd IAEA technical meeting on first generation fusion power plants: design and technology, IAEA, Vienna, 20-22 June 2007 (these proceedings).