Regarding the Assystem report on fusion power **Gordon Taylor** **2021-11-28**

I have been a Member since 1968, and a member of the Committee of the South Essex Area for many years. On 2021-06-09 I gave a presentation to the SEA 'The Futility of Fusion: A Dream Too Far'. This was based on the document with references 'The Case Against Nuclear Fusion Power'. These may be downloaded from: http://cms.energypolicy.co.uk/nuclear/348 The recording of my presentation is available via the IMechE Webinar Hub and on YouTube dated 17 June 2021, https://www.youtube.com/watch?v=Tukwoa1zLS8

According to PE, Issue 6, 2021, p 5, 'Fusion engineering company Assystem commissioned the IMechE's Engineering Policy Unit to investigate the sector's current state and future prospects and produce a report. 'Fusion Energy: A Global Effort, a UK Opportunity' examines the path to commercialisation, including the role for fusion in future energy systems, the cost drivers and potential for cost reduction, and the technical and non-technical challenges to developing fusion plants'.
The report 'Fusion Energy: A Global Effort, a UK Opportunity' is at:
https://www.imeche.org/docs/default-source/1-oscar/reports-policy-statements-and-documents/imeche-fusion-report-ao.pdf
Lead authors: Matt Rooney CEng MIMechE, Institution of Mechanical Engineers, Tony Roulstone CEng FIMechE, University of Cambridge, Prof Giorgio Locatelli CEng MIMechE FHEA, Politecnico di Milano and Prof Ben Lindley, AMIMechE, University of Wisconsin-Madison.
Page 8 includes:
'Key advantages of fusion power are its almost limitless supply of fuel, its inherent safety and low radioactive footprint. This provides the potential to access markets that are unavailable to fission due to political concerns about safety and radioactive waste'.

1) The Claims in the Assytem Report
1.1) Regarding the supply of fuel. The Deuterium-Tritium reaction requires a temperature far lower than the Deuterium-Deuterium reaction, so is seen as far more feasible. However, Tritium decays with a half-life of 12.3 years or 5.5% per year. Yet sufficient Tritium is required to sustain a Deuterium-Tritium reaction in the face of multiple Tritium loss mechanisms. This is usually expressed as the required 'Tritium Breeding Ratio', with values such as 1.5 for a Doubling Time of fusion power of 2 years, 1.25 for 5 years and 1.15 for 10 years. (2005-12-27 Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle, Sawan & Abdou, Fig. 2,
https://www.fusion.ucla.edu/abdou/abdou%20publications/2006/FED-v81-SawanPhysics.pdf).
I searched the report on 'Tritium', 'Breeding' and 'Breeding Ratio'. There was no mention of 'Breeding Ratio'.
I searched on 'Sawan', 'Abdou', 'Dittmar', 'Jassby' and 'Parkins' - none were found in the text or the references.
These are authors of reports and presentations critical of the prospects for fusion power, notably because of inadequate Tritium Breeding Ratios. Most of them have spent decades in fusion research, so their views must be respected.
This report provides no evidence that the Tritium Breeding Ratio would be sufficient to fuel even one fusion power plant, let alone for the fleet to grow. So the report has not shown that the fuel supply is almost limitless.

1.2) Regarding the inherent safety of fusion plants. Tritium is a very small molecule, and hence extremely prone to leakage. Moreover it is radioactive, both as a gas and as tritiated water, with a short half-life of 12.3 years and emitting Beta-particles. If inhaled or ingested, these are known to be injurious to humans, causing cancers, genetic defects and deaths.
Regarding nuclear harms to human health, the authors of the Assystem report appear to be unaware of this report:
2010 Recommendations of the ECRR, The Health Effects of Exposure to Low Doses of Ionizing Radiation, Regulators' Edition, Edited by Chris Busby with Rosalie Bertell, Inge Schmitz-Feuerhake, Molly Scott Cato and Alexey Yablokov, https://euradcom.eu/wp-content/uploads/2016/04/ecrr2010.pdf
This document of 258 pages acknowledges the assistance of 24 individuals, of whom 15 are Professors, and six PhD's.
Tritium is mentioned on pages 50, 53, 91, 103, 105, 106, and 108. Page 105 onwards includes: 'The isotope Tritium is a form of Hydrogen and the biochemical processes in living systems depend on the weak bonds called Hydrogen Bonds which bridge and support all enzyme systems and hold together the DNA helix. The sudden decay of such a Tritium atom to Helium (which is inert and does not support chemical bonds) may have a catastrophic effect on the activity and normal processing of such macromolecules. Hydrogen bonded in these systems is easily exchangeable and will exchange under equilibrium conditions with Tritium Oxide, or tritiated water, the normal form of this isotope in the environment'.
Thus the claim that fusion power is inherently safe is untrue.

1.3) Regarding the radioactive footprint of fusion power. The radioactive footprint of a fusion power plant of the magnetic confinement type, fuelled with Tritium, is not limited to operational and unforeseen releases of Tritium or tritiated water, but includes the in-vessel divertor and segmented walls of the tokamak. These require replacement about every two years. In a lifetime of say 25 years, these would total some 12 sets, all of which would require to be stored in a high-level repository.
Thus the claim that the radioactive footprint is low is untrue.

As all three claims (almost limitless supply of fuel, inherent safety and low radioactive footprint) made for fusion are untrue, the political concerns about safety and radioactive waste are not satisfied.

2) The Energy, Carbon and Money Costs of Fusion Power
These may be determined by Life Cycle Analysis. Energy costs have the advantage of being dependant on the conversion technologies, that change relatively slowly, while the carbon costs depend also on the carbon intensities of electricity, heat and materials, that vary between places (countries) and over time. Likewise, money costs depend on the money costs of electricity, heat and materials, that vary between places and over time.

2.1) The Costs of the Deuterium and Tritium fuels
Fusion on earth using the Deuterium-Tritium reaction requires achieving and containing temperatures of about 100 million C. The Lawson Criterion says that such temperatures are needed for terrestrial fusion, because it is not possible to create or contain on earth pressures comparable to those at the centre of the sun. The tokamak walls have multiple functions: vacuum tight containment, blanket (lithium 6/7) for breeding tritium, cooling (with water-steam, helium or molten salt) to limit material temperatures and to transport heat to the steam cycle. Yet they would be damaged by neutrons, and hence need periodic replacement. (e.g after two years). For this purpose, they are divided into multiple segments, so that they may be removed and replaced from inside the tokamak vessel by robots. These multiple requirements make the achievement of a Tritium Breeding Ratio sufficiently above 1 extremely difficult if not impossible.

While a fusion power plant requires relatively little deuterium and tritium per unit of electricity, these have high and very high carbon intensities. Deuterium is abundant (e.g. in the oceans), but the concentration is very low and separating it from protium (ordinary hydrogen) is energy intensive. ‘This very low value of the deuterium-to-hydrogen ratio in nature of about 150 ppm is the main factor responsible for the high cost of heavy water. It is necessary to process at least 8000 mols of feed per mol of product for all processes, and for the GS process the ratio of feed to product is nearly 40,000 to 1’.
‘Reactor grade heavy water is 99.75 mol% D2O. Thus, the overall concentration ratio from feed to product is about 3 x 10^6 . This means that hundreds of separative elements in series are needed to go from natural water to reactor grade heavy water. The combination of a very large feed flow and a very large number of separative elements means that heavy water plants are very large in relation to most other chemical plants. As a consequence heavy water is an extremely capital intensive product’. For the widely used GS process, ‘the energy required per kg D20 is 25 GJ of thermal energy and 700 kWh of electrical energy’. (See: 1977-12-16 Selecting Heavy Water Processes, https://pubs.acs.org/doi/pdf/10.1021/bk-1978-0068.ch001).

‘Normally in this process, water is enriched to 15–20% D2O. Further enrichment to "reactor-grade" heavy water (> 99% D2O) is done in another process, e.g. distillation’. (Girdler sulfide process, https://en.wikipedia.org/wiki/Girdler_sulfide_process).

‘Extracting this deuterium from seawater is a simple and well proven industrial process. "Heavy water", or D2O (water in which deuterium substitutes for hydrogen), is first separated from regular water by chemical exchange processes, and is then submitted to electrolysis in order to obtain deuterium gas’. (2011-03-11 Deuterium: a precious gift from the Big Bang, https://www.iter.org/newsline/167/631). (See Figure: LCA of Fusion Power, Box D).

As the requirement for deuterium is ongoing, some fraction of the cost of the separation plant must be added to that of the fusion power plant. (See Figure: LCA of Fusion Power, Box E).

Regarding the requirement for tritium, it is extremely expensive to separate it from ordinary water, with a typical cost of $ 80,000 to 120,000 per kg. Moreover, tritium is radioactive with a half-life of 12.3 years, so decays at 5.5% a year. While it may be necessary to purchase the initial charge (20 kg for ITER), the world supply of tritium would be insufficient for even one fusion power plant (e.g. 200 kg a year for a 1 GWe plant). So fusion power plants (using the D-T reaction) must be capable of breeding their own tritium. (See 1.1) above). Hence the failure of the Assytems report to mention the Tritium Breeding Ratio is inexcusable.

2.2) The Costs of a Fusion Power Plant
A tokamak fusion power plant would have an in-vessel divertor and segmented walls that are subject to neutron damage. These require replacement about every two years and, as the materials also become radioactive, they cannot be recycled. Then after a lifetime of maybe 25 years, the entire fusion plant would require expensive decommissioning. The plant and the many (e.g. 12 sets of) discarded walls would require storage as radioactive nuclear waste.

2.3) The Costs of Pulsed versus Continuous Operation
‘The tokamak is thus, at present, an inherently pulsed device, and both ITER and the proposed near-term European demonstration power plant are designed to operate as such with a dwell period in between the pulses allowing the recharge of the central solenoid. No other power generating technologies operate in an intentionally pulsed manner and this would certainly affect components such as steam turbines which are not generally designed for frequent cycling. Research, in partnership with industry, is presently under way to understand how to mitigate such risks and attempt to optimise efficiency in pulsed operation. With a sufficiently large central solenoid the pulse length could theoretically be as long as eight hours, requiring perhaps 15 minutes to recharge.

Another consideration is the profile of electricity output to the grid. The first one or two power plants are likely to be treated as special cases which will operate in close co-ordination with the electricity grid operator. They are likely to be of the order of 500 MWe and so not crucial to grid stability. Nevertheless, when a pulsed power plant is between fusion burns, the grid will need to compensate in some way, either using energy storage, or by rapidly ramping up spare capacity.
In addition, power is required to restart the fusion reactor. While there are many types of energy storage available, storing heat using molten salt might be particularly suited to a thermal power plant such as a fusion plant, providing temperatures of the order of 500ºC can be achieved. Molten salt energy storage is a well-developed technology, with solar plants in Spain equipped with storage capacity of 50 MWe for 7.5 hours. The need to transfer heat between water, which undergoes a phase change, and molten salt, which does not, poses substantial difficulties for integration into the Rankine cycle. This pinch point problem is discussed in the solar power literature 14. The problem is particularly acute if the steam both charges and discharges the salt. An alternative is for the salt to be heated directly by the primary coolant (perhaps helium), which eliminates one pinch point'. (See: 2013 Converting energy from fusion into useful forms, Page 17, https://arxiv.org/pdf/1401.4232).

'Continuous operation of a tokamak for fusion energy has clear engineering advantages but requires conditions beyond those sufficient for a burning plasma. The fusion reactions and external sources must support both the pressure and the current equilibrium without inductive current drive, leading to demands on stability, confinement, current drive, and plasma-wall interactions that exceed those for pulsed tokamaks. These conditions have been met individually, and significant progress has been made in the past decade to realize scenarios where the required conditions are obtained simultaneously. Tokamaks are operated routinely without disruptions near pressure limits, as needed for steady-state operation. Fully noninductive sustainment with more than half of the current from intrinsic currents has been obtained for a resistive time with normalized pressure and confinement approaching those needed for steady-state conditions. One remaining challenge is handling the heat and particle fluxes expected in a steady-state tokamak without compromising the core plasma performance'.
2011-03-25 Realizing steady-state tokamak operation for fusion energy, Abstract, https://aip.scitation.org/doi/10.1063/1.3551571 (See Figure: LCA of Fusion Power, Boxes F and G).

2.4) The Costs of Fusion Power
'A review of some of the DEMO reactors was conducted. It was shown that the highest aTBR in DEMO is less than 1.15 while rTBR is 1.475 at 0.5% fractional burn-up and 10 years doubling time. Furthermore, it was demonstrated that less than 3 years doubling time is required to prevent one DEMO reactor from consuming more tritium than it breeds after accounting for the 28% losses within the DEMO design restrictions like FW losses and EI losses. Not to mention, the external supply of tritium from sources like heavy water reactors is not only costly but also discrete. To conclude, fusion is currently at an immature stage that prevents one from accurately assessing the cost of fusion per kWh making it difficult to compare to renewable counterparts'.
2018-12-27 Assessment of DEMO Reactors for Fusion Power Utilization, Hatem Elserafy, Summary, http://www.tj.kyushu-u.ac.jp/evergreen/contents/EG2018-5_4_content/pdf/Pages_18-25.pdf

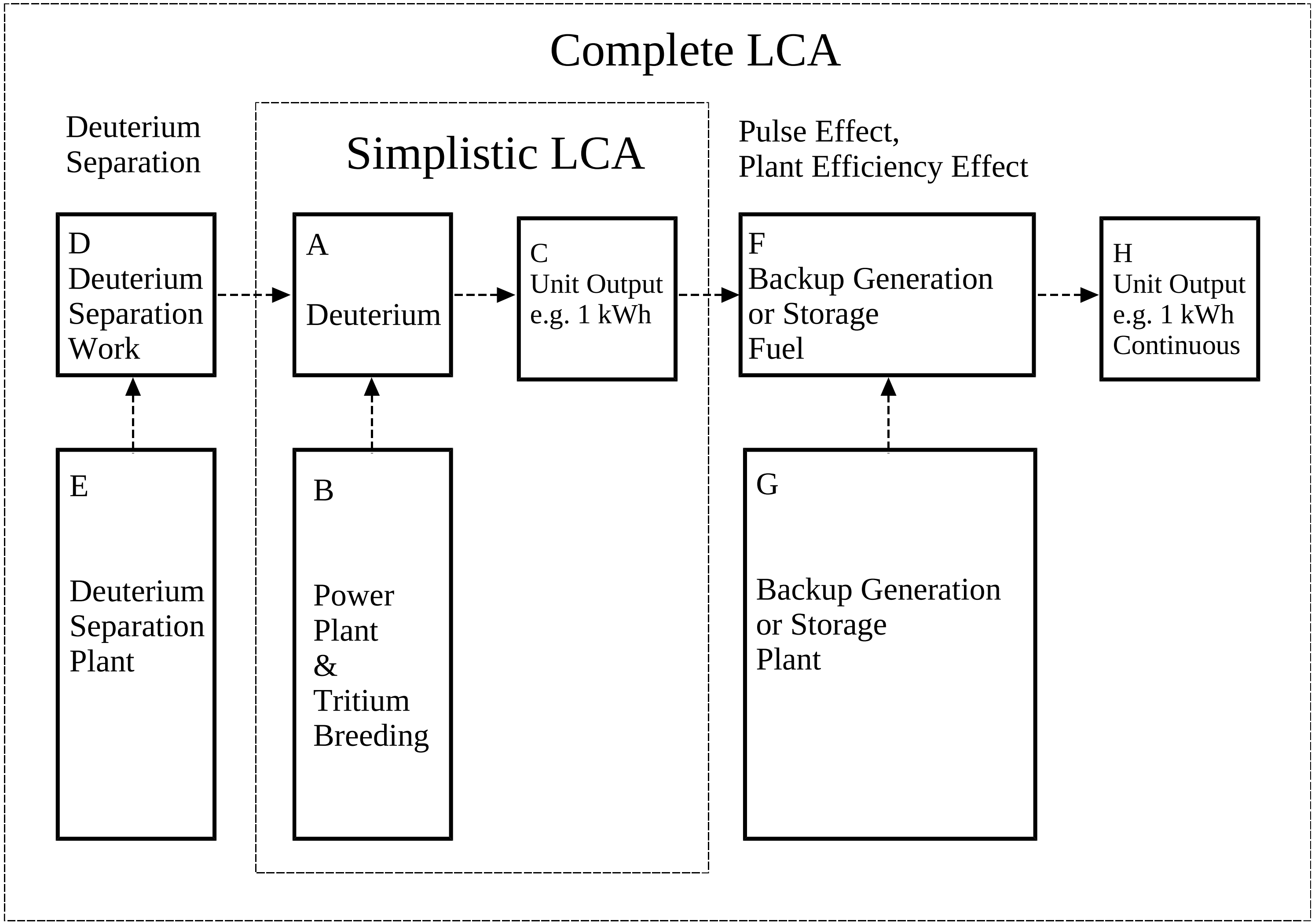
2.5) The Cost Implications of the Capacity Factor for Fusion Plants with High Recirculated Power
'The plant efficiency of a nuclear fusion power plant is considered. During nominal operation, the plant efficiency is determined by the thermodynamic efficiency and the recirculated power fraction. However, on average the reactor operates below the nominal power, even when the long shutdown periods for large maintenance are left outside the averaging. Hence, next to the recirculated power fraction the capacity factor must be factored in. An expression for the plant efficiency which incorporates both factors is given. It is shown that the combination of high recirculated power fraction and a low capacity factor, results in poor plant efficiency. This is due to the fact that in a fusion reactor the recirculated power remains high if it runs at reduced output power. It is argued that, at least for a first generation of power plants, this combination is likely to occur. Worked out example calculations are given for the models of the power plant conceptual study. Finally, the impact on the competitiveness of fusion on the energy market is discussed. This analysis stresses the importance of the development of plant designs with low recirculated power fraction'
See: 2021-03-17 Plant efficiency: a sensitivity analysis of the capacity factor for fusion power plants with high recirculated power, Mulder et al, Abstract, https://iopscience.iop.org/article/10.1088/1741-4326/abe68b/pdf
(See Figure: LCA of Fusion Power, Boxes F and G).

Page 6 of the Assystem report talks of ‘The need for dispatchable power’.
Nuclear fission exhibits negative learning, due to ever-increasing safety concerns, especially following disasters such as Chernobyl and Fukushima. (2010-09, The costs of the French nuclear scale-up: A case of negative learning by doing, A. Grubler, Fig. 13, https://www.sciencedirect.com/science/article/abs/pii/S0301421510003526).
Nuclear fusion has radioactive risks from releases of Tritium and from the tokamak walls, that require replacement every two years or so, and then storage in long-term repositories. Also, designs have yet to take full account of the radioactive hazards. (2017-11-17 Nuclear Fusion Reactors, IRSN Report 2017/199, https://www.irsn.fr/EN/Research/publicationsdocumentation/Scientific-books/Documents/ITER-VA_web_non_imprimable.pdf). So fusion power would probably also exhibit negative learning, with the cost rising over time.

2.6) There are physical limits to the rate at which new technologies can be deployed.
‘! There are physical limits to the rate at which new technologies can be deployed
! Governments need to design policies targeted at specific technologies to accelerate deployment
! More action is required on demand side to increase efficiency and curtail consumption’.
2009-12-02 No quick switch to low-carbon energy, Gert Jan Kramer and Martin Haigh, SUMMARY, https://www.landscapepartnership.org/maps-data/climate-context/cc-resources/ClimateSciPDFs/Nature09No%20quick%20way%20to%20low%20carbon.pdf/app-download-file/file/Nature09No%20quick%20way%20to%20low%20carbon.pdf

Slide 3 ‘Compare a ‘realistic’ scenario for the development of fusion with e.g. wind and solar: starting late and growing slowly’, GEN 2 (100 units) after 2100.
Slide 18 ‘Note that if fusion follows this universal development path, it will appear in the energy mix in 2070 or so’.
2015-02-28 Why we have solar panels but not yet fusion power, Lopes Cardozo + 2, http://newenergytimes.com/v2/sr/iter/public/Cardozo-2015.pdf
Thus the Assystem report has omitted several factors that could prevent fusion power from providing dispatchable power.

2.7) Dispatchable Power via Renewable Gas Storage.
However, dispatchable power could be supplied via renewable Power-to-Gas plants, gas storage in underground caverns, and recovered via Gas-to-Power plants. (See: 2013-10-09 Electricity from Wind and Storage, http://cms.energypolicy.co.uk/electricity/241)
In 100% renewable scenarios for true zero carbon, dispatchable power has a Capacity Factor of only about 15 to 20%. (2016-03-10 ‘Power-to-X – results from various projects on cross-sectoral energy storage and network coupling, Michael Sterner, Page 7, https://hugepdf.com/downloadFile/16-prof-michael-sterner-research-center-for_pdf).
Moreover, Solar PV power and Wind power exhibit positive learning, with the cost falling by 22 and 6 per cent per annum. (2018-02 The experience curve theory and its application in the field of electricity generation technologies, Samadi, Fig. 1, https://www.sciencedirect.com/science/article/abs/pii/S1364032117312224). Germany is over 10 years into phasing out nuclear power, due to end at end-2022, and expanding sustainable renewables. It is also the world leader in PtG conversion, with no barriers in sight to reaching true zero carbon by 2050.


Complete LCA
Deuterium Separation
Simplistic LCA
Pulse Effect,
Plant Efficiency Effect
D Deuterium Separation Work
A Deuterium
C Unit Output e.g. 1 kWh
F Backup Generation or Storage Fuel
H Unit Output e.g. 1 kWh Continuous
E Deuterium Separation Plant
B Power Plant & Tritium Breeding
G Backup Generation or Storage Plant