The Case Against Nuclear Fusion Power **Gordon Taylor** **2021-06-09**

Summary
a) Fusion power would use deuterium and tritium – both isotopes of hydrogen. Tritium has a radioactive half-life of 12.3 years, so has to be produced as required, often in fission reactors for small amounts. So any feasible fusion reactor must breed it's own tritium, with a significant excess over that burnt to cover several loss mechanisms. But this may not be possible.

b) A segmented tokomak reactor would work at a pressure of up to two atmospheres and a temperature of around one hundred million degrees, but living things cannot distinguish between (radioactive) tritium and (stable) hydrogen. So any tritium leakage would result in the cells of plants and animals incorporating radioactive tritium, which releases beta particles, damaging DNA, and causing genetic harms, such as malformations, cancers, deaths and sterility.

c) Fusion power cannot help to achieve 'net zero' by 2050. Even building and operating fusion test plants, such as ITER, DEMO, and PROTO, would consume huge amounts of materials and energy, all with significant carbon footprints.

d) The capital charges of fusion power (e.g. 36 US c/kWh) and the 'limit sales price' (of 175 $/MWh [17.5 c/kWh]) are far higher than the operating costs of '9 €-cents/kW-hour for early near-term (water cooled steel) model', and even more so the '5 €-cents/kW-hour for early advanced (Li-Pb cooled SiC composite) model'.

e) The segmented walls of the tokomak reactor would require replacement (e.g. every two years), with the discards being radioactive for at least 100 years. 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. With these costs included, fusion power would be far more expensive than energy savings and renewables.

f) Particularly in recent years, there have been several very telling well-informed criticisms of fusion power.

g) Compared with central power plants, end use appliances take far less time and energy to develop and deploy at scale. This has been well-demonstrated by LED lighting, which is already saving significant amounts of electricity. Further savings could come from high efficiency refrigerators and central heating pumps, which run more or less full-time.

h) 'Zero by 2050' could be achieved by energy savings, energy efficiency, and renewables such as solar PV and wind power, that are already proven at multi-GW scale. So the finite resources of time, money, energy, carbon and human talent should be transferred from fission and fusion to these proven zero-carbon energy services.

2) **The ITER tokamak fusion reactor**
The ITER tokamak fusion reactor being built in France is huge and costly at over 20 billion Euros. However, it will run only in short bursts, so has limited cooling, and will generate no electric power. Following this line, a fusion power plant would be even bigger, and could have at least three times the thermal output, to produce around 1 GWe.

3) **The Physics of Fusion**
Fusion on Earth is often described as like the Sun and other stars, but the nuclear physics is completely different. The Sun uses the so-called Proton-Proton reaction, wherein hydrogen nuclei are converted to helium nuclei via several intermediates.
This involves temperatures around 15 million degrees, but Sun-like pressures cannot be achieved on Earth (using magnetic confinement). The Lawson paper of 1955 considered the Deuterium-Deuterium reaction, with around 700 million degrees, and the Deuterium-Tritium reaction with around 100 million degrees.

Fusion obeys Einstein's famous equation $E=mc^2$, whereby mass (m) is transmuted into energy (E). The temperatures and pressures near the centre of the sun achieve fusion with the Proton-Proton reaction. This occurs with a pressure of 10 billion bar and a temperature of about 15 million C. (Energy and Environment in the 21 century, 6 Lectures June 2013, ETH/CERN Michael Dittmar, ETH Zurich, p 8, http://ihp-lx2.ethz.ch/energy21/energyjune2013_3.pdf).
Fusion on earth with the Deuterium-Deuterium (D-D) and Deuterium-Tritium (D-T) reactions was discussed in: ('Some Criteria for a Power Producing Thermonuclear Reactor', J.D. Lawson, 1955, (https://www.euro-fusion.org/wpcms/wp-content/uploads/2012/10/dec05-aere-gpr1807.pdf).
This is extended in: (Lawson Criterion, https://en.wikipedia.org/wiki/Lawson_criterion)
For fusion on earth, the D-D reaction would require around 700 million C but the D-T reaction far less at about 100 million C. (See: Fusion Power Plants, Garry McCracken, Peter Stott, in Fusion, 2005, https://www.sciencedirect.com/science/article/pii/B9780124818514500135).

4) **The Triple Product**
• *Lawson showed that fusion power requires a product of Plasma density, Temperature & Time*
• *With magnetic confinement, the pressure is a 'good vacuum', so the others must be higher*
• *Fusion temperatures have been achieved, so one remaining challenge is the confinement time*
• *For plasmas in strong magnetic fields, these are limited by instabilities, less so for large reactors*

5) Fusion was achieved with Deuterium-Tritium by the JET reactor in 1997, but the thermal energy output was only 67% of breakeven, and for only a few seconds. (See: Participation in the Joint European Torus JET, https://www.ipp.mpg.de/16701/jet)
Llewellyn Smith 2010 talked of progress, but there had been none towards energy breakeven at JET or elsewhere.
Even so, he strongly supported the building of ITER, of GigaWatt (thermal) scale.

6) A fusion power plant would have a wall temperature of less than 550 C, probably using a primary coolant such as helium or molten salt. This would power a steam cycle with a top temperature of around 400 C, giving a thermal (First Law) efficiency of maybe 30%.
With a reactor temperature of 100 million degrees, the exergetic (Second Law) efficiency would be miniscule.

7) **Nuclear Dangers - 1**
Because D-D requires about 700 million degrees, but D-T only about 100 million degrees, fusion power would most likely use Tritium. However, this is a radioactive isotope of the smallest molecule in the universe, and much lighter than air, so may well leak and be lost from the plant.
Living things may ingest Tritium or tritiated water, releasing beta particles internally, causing harms such as cancers, deaths and genetic damage.
The liability of nuclear operators is carried by e.g. the UK Nuclear Installations Act of 1965.
This liability is described as ‘unquantifiable’, which means an unlimited charge on the taxpayers.
However, the operator is liable for the costs of decommissioning and waste storage, as part of the Cost Of Electricity.

8) **Nuclear Dangers - 2**
The tokamak vacuum vessel would contain an inner wall (First Wall), backed by a blanket containing Lithium for the production of Tritium, and channels for the primary coolant.

‘A fusion-based power plant must also convert energy from the neutrons into heat that drives a turbine. Future reactor designs make the conversion in a region surrounding the fusion core called the blanket. Although the chance is small that a given neutron will hit any single atomic nucleus in a blanket, a blanket thick enough and made from the right material—a few meters’ worth of steel, perhaps—will capture nearly all the neutrons passing through. These collisions heat the blanket, and a liquid coolant such as molten salt draws that heat out of the reactor. The hot salt is then used to boil water, and as in any other generator, this steam spins a turbine to generate electricity.

Except it is not so simple. The blanket has another job, one just as critical to the ultimate success of the reactor as extracting energy. The blanket has to make the fuel that will eventually go back into the reactor.

Although deuterium is cheap and abundant, tritium is exceptionally rare and must be harvested from nuclear reactions. An ordinary nuclear power plant can make between two to three kilograms of it in a year, at an estimated cost of between $80 million and $120 million a kilogram. Unfortunately, a magnetic fusion plant will consume about a kilogram of tritium a week. “The fusion needs are way, way beyond what fission can supply,” says Mohamed Abdou, director of the Fusion Science and Technology Center at the University of California, Los Angeles.

For a fusion plant to generate its own tritium, it has to borrow some of the neutrons that would otherwise be used for energy. Inside the blanket channels of lithium, a soft, highly reactive metal, would capture energetic neutrons to make helium and tritium. The tritium would escape out through the channels, get captured by the reactor and be reinjected into the plasma.

When you get to the fine print, though, the accounting becomes precarious. Every fusion reaction devours exactly one tritium ion and produces exactly one neutron. So every neutron coming out of the reactor must make at least one tritium ion, or else the reactor will soon run a tritium deficit—consuming more than it creates. Avoiding this obstacle is possible only if scientists manage to induce a complicated cascade of reactions. First, a neutron hits a lithium 7 isotope, which, although it consumes energy, produces both a tritium ion and a neutron. Then this second neutron goes on to hit a lithium 6 isotope and produce a second tritium ion.

Moreover, all this tritium has to be collected and reintroduced to the plasma with near 100 percent efficiency. “In this chain reaction you cannot lose a single neutron, otherwise the reaction stops,” says Michael Dittmar, a particle physicist at the Swiss Federal Institute for Technology in Zurich. “The first thing one should do [before building a reactor] is to show that the tritium production can function. It is pretty obvious that this is completely out of the question.”’
(See: Fusion's False Dawn, Michael Moyer, Scientific American, March 2010,
https://www.scientificamerican.com/article/fusions-false-dawn/

The tokamak vacuum vessel would contain an inner wall (First Wall), backed by a blanket containing Lithium for the production of Tritium, and channels for the primary coolant.
As the blanket is subject to radiation damage, it would be divided into segments, so that they can removed and replaced by robot about every two years. While ITER has 440 segments, power plants would have far fewer to speed the changeover. However, they would be much larger and heavier, bringing many challenges in handling and processing.

(See: 2017-11-17 Nuclear Fusion Reactors, IRSN Report 2017/199, https://www.irsn.fr/EN/Research/publications-documentation/Scientific-books/Documents/ITER-VA_web_non_imprimable.pdf)

Those segments removed would be radioactive waste, requiring secure long term storage.
Fusion is often claimed to be safe because it would produce less radioactive waste than nuclear fission, but this is not zero !

Fusion would most likely use radioactive tritium as a fuel. Moreover, the Tokomak wall is subjected to intense neutron bombardment, making its' materials radioactive, and requiring it to be changed about every two years. The wall includes a blanket using materials such as lithium 7 and lithium 6 to 'breed' additional neutrons and produce enough tritium to fuel the fusion cycle. A Tokomak reactor vessel must be segmented to enable periodic changing of the inner walls and blankets. It would work at a pressure of up to two atmospheres and a temperature of around 100 million degrees. Under operational and disaster conditions, these radioactive materials could escape with serious consequences – especially in the worst cases. The harm done by past nuclear releases from nuclear weapons and fuel plants, nuclear weapons and nuclear power plants is becoming ever more apparent in injuries (e.g. cancers, deformities, sterility) and deaths, including in later generations. (See: 2017-09-12 Internal radiation exposure and genetic effects on birth outcomes..., C. Busby, http://www.greenaudit.org/wp-content/uploads/2017/10/LondonBEIS2017C.pptx).

Living things cannot distinguish tritium from hydrogen and if tritiated water was ingested, it would release radioactive beta particles internally. (See: 2020-01 Tritium, https://hps.org/documents/tritium_fact_sheet.pdf P 1). So tritium releases would cause losses of safe land and drinking water, and – as with other nuclear disasters - the fusion plants would have to shut down. Thus they would be like fission plants in respect of the risks to humans and other life-forms, as well as to their owners.

The liability of nuclear fission plant operators for radioactive releases at home or reaching other countries was limited in time and amount by the Paris Convention on Third Party Liability in the Field of Nuclear Energy of 1960 and the Vienna Convention on Liability for Nuclear Damage of 1963. Thus the risks have been carried by nuclear states under e.g. the Nuclear Installations Act of 1965 in the UK. The UK Government has accepted 'unquantifiable contingent liabilities' including 'Incidents/Accidents Insurance claims for exposure to ionising radiation pursued outside the existing UKAEA insurance scheme'. (See e.g. 2010-07-26 Department for Business, Innovation and Skills resource accounts 2009-10: including the consolidated resource accounts for the year ended 31 March 2010, http://www.bis.gov.uk/assets/biscore/corporate/docs/b/10-p102-bis-resource-accounts-2009-10.pdf P 171). So apart from the limited liability carried by the operators, that carried by the taxpayers is unlimited.

The segmented walls of the tokomak reactor would require replacement (e.g. every two years), with the discards being radioactive for at least 100 years. 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. (See also: 2016 BLANKET PERFORMANCE AND RADIOACTIVE WASTE OF FUSION REACTORS: A NEUTRONICS APPROACH, Bethany R. Colling, https://eprints.lancs.ac.uk/id/eprint/137882/1/2016collingphd.pdf p 29).

With these costs included, fusion power would be far more expensive than energy savings and renewables.

9) **Tritium Balance and Supply - 1**
• *Deuterium is a stable isotope of hydrogen but Tritium is radioactive, with a half-life of 12.3 y*
• *Tritium can be produced by nuclear fission plants especially Heavy Water Reactors, such as CANDU*
There are only a few CANDU fission plants worldwide. That at Darlington, Canada, is specially equipped, and produces most of the world's Tritium, but is due to close in 2025. Thereafter the world inventory will decline at about 5.5 % a year.
• *But the world inventory is small - e.g. 30 kg – and the price extremely high – e.g. $ 80-120 million/kg*
So an initial charge of 20 kg could cost $ 2 billion !
• *Yet a hypothetical fusion plant of 3000 MWth (1 GWe) would consume Tritium of about 200 kg/y*

Deuterium is a naturally-occurring isotope and stable, but Tritium is radioactive, with a half-life of 12.3 y. At present, most of the world's supply of tritium comes from one Canadian heavy water fission reactor (at Darlington) which is due to shut down in 2025. There is a certain amount in stock, but this decays by one half every 12.3 years. There may not be sufficient tritium available even to fuel ITER, which is only an experimental device – far short of a fusion power plant.
(See 2018 GLOBAL SUPPLY OF TRITIUM FOR FUSION R&D FROM HEAVY WATER REACTORS, https://pdfs.semanticscholar.org/3a3c/3b76859550ce98dc127082f1e5b5381c8b96.pdf)

'Running a hypothetical 3000 MW(thermal) reactor "burns" about 200 Kg of Tritium/year. External tritium sources can provide only a few kg per year (world inventory 2027 at best about 30 kg)'.
(See: Energy and Environment in the 21 century, 8 Lectures April/May 2017, Lecture III: (May 2.) Some Nuclear Energy basics and Nuclear Energy today?, ETH/CERN, Michael Dittmar, http://ihp-lx2.ethz.ch/energy21/energyapril_may2017_3.pdf Slide 38-43).

10) **Tritium Balance and Supply - 2**
Hence any D-T fusion power plant must ‘breed’ Tritium.
• *A D-T plasma emits neutrons that heat the walls cooled by e.g. molten salt for a steam power cycle*
• *The walls also include a ‘blanket’ of lithium wherein some of the neutrons produce Tritium*
• *A neutron hits Li7, creating a Tritium ion and a 2nd neutron, which hits Li6 and creates a 2nd Tritium ion*
• *Sawan & Abdou 2005 show a required Tritium Breeding Ratio of e.g. 1.5 for a Doubling Time of 2 years, 1.25 for 5 years and 1.15 for 10 years*
Another circuit outside the tokamak captures the Tritium, and together with streams from the primary coolant and from the plasma chamber, this is purified before use as fuel.
The Tritium supply must suffice not only for the plant in question, but also any deployed in future years.
So the Doubling Time is a crucial parameter, and largely determines the required Tritium Breeding Ratio.

Fusion power plants must be designed to breed tritium in a surrounding blanket. It’s thickness is a compromise between:
- thicker to increase the neutron capture and thus heat flow to the power cycle, and also to increase the tritium breeding.
- thinner to keep down the running cost due to the periodic replacement of the wall and blanket.
(See e.g.: 2005-12-27 ‘Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle’, M. E. Sawan, M. A. Abdou, http://www.fusion.ucla.edu/abdou/abdou%20publications/2006/FED-v81-SawanPhysics.pdf).
Simulations of state-of-the-art blankets have shown a maximum Tritium Breeding Ratio (TBR) of 1.15, but 1.5 may be required to cover the various losses. (See: 2018-12-27 Assessment of DEMO Reactors for Fusion Power Utilization, Hatem Elserafy, http://www.tj.kyushu-u.ac.jp/evergreen/contents/EG2018-5_4_content/pdf/Pages_18-25.pdf).

While fusion power plants may be designed to be self-sufficient, each new one requires an initial charge of about 20 kg. So tritium production would be a constraint on the growth rate (MW/year) or Doubling Time of fusion power.

11) **Installed Effective Power - 1**
This figure is from Lopes Cardoso 2019. (See: 2019-02-04 Economic aspects of the deployment of fusion energy, N. J. Lopes Cardozo, Abstract, https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2017.0444).
It has taken a worldwide consortium to build ITER (so far), which will not demonstrate D-T fusion before about 2037.
So there is no chance of following the red dotted line ‘C’. Even the blue dotted line ‘B’ is too optimistic.
Abdou 2019 says that the likely TBR is 1.05 – 1.15. This could drive the Doubling Time to e.g. 10 years.
So 10 Doublings could take 100 years to approach 1 TW and make a significant contribution to world energy supply.

Even the chief proponent - Sir Chris Llewellyn Smith, FRS – has said: ‘‘Commercial’ fusion power ~ middle of the century’.
(See: 2010-03-04 The energy challenge and the case for fusion, Slide 35,
https://energy.stanford.edu/sites/g/files/sbiybj9971/f/energy_challenge_and_the_case_for_fusion.pdf).

‘Fusion is at the start of the exponential growth phase, while still having significant uncertainties concerning its technical feasibility. In comparison to e.g. solar PV and wind, fusion is ‘late’, lagging by some 50 years. To follow the same rate of development that fission, wind and PV have shown, fusion will need to have 3 DEMO reactors operational in the early 2050s, followed by 10 generation one (GEN1) plants in the early 2060s and 100 GEN2 plants in the early 2070s’.
(2015-09-19 Fusion: Expensive and Taking Forever?, Abstract and Fig. 2, https://core.ac.uk/download/pdf/81699571.pdf).
This has been confirmed recently:
‘It is concluded that, within the mainstream scenario—a few DEMO reactors towards 2060 followed by generations of relatively large reactors—there is no realistic path to an appreciable contribution to the energy mix in the twenty-first century if economic constraints are applied. In other words, fusion will not contribute to the energy transition in the time frame of the Paris climate agreement’.
(See: 2019-02-04 Economic aspects of the deployment of fusion energy, N. J. Lopes Cardozo, Abstract,
https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2017.0444 and
https://research.tue.nl/files/123942756/RS.LopesCardozo.FutureofFusion.lastauthorversion_2_.pdf).

So fusion power cannot deliver any significant electricity by 2050, the date for net zero carbon to meet the Paris objectives.
But building and operating fusion test plants, such as ITER, DEMO, and PROTO, would consume huge amounts of materials and energy, all with significant carbon footprints.

12) **Installed Effective Power - 2**
In this figure, the net energy is negative for the period (Construction Time + Energy Payback Time).
So avoiding negative net energy could drive the Doubling Time to over 10 years,

13) **Timeline for Fusion Power - 1**
• *Compared with wind and solar PV, fusion lags by more than 50 years, so cannot contribute by 2050*
• *But ITER and DEMO etc would require huge amounts of materials and energy - hence GHG*
• *Assuming the unit size is 1 GWe and the target capacity is 1 TWe, the number of doublings is ~ 10*
• *If the Doubling Time < (Construction Time + EPT), then during the exponential growth period, the Net Energy Production & the ROI are negative*
This applies to both the Energy Return on Investment and the money Return on Investment. A positive money ROI requires that the EROI is greater than one, with a margin for non-energy outlays, such as wages and salaries.

14) **Timeline for Fusion Power - 2**
Compared with ITER (e.g. 500 MWth) and DEMO (e.g. 500 MWe), Tokamak Energy argues that a smaller unit size (e.g. 100 MWe) would enable quicker and cheaper development of the technology. They say that this becomes possible by using a spherical tokamak vessel and High Temperature Superconductors (HTS) for the magnets that constrain the plasma.
'Spherical tokamak + HTS ⇒ the possibility of small modular fusion reactors of ~100MWe → Rapid, affordable, development' (2017-02-21 A Faster Way to Fusion, Slide 32,
https://indico.cern.ch/event/614256/attachments/1428727%2F2193411/Tokamak_Energy_20170221.pdf).

'The third scenario (C) in Fig.2 explores the most optimistic case of 'acceleration of fusion power' by bringing forward the DEMO point to 2030 (which assumes that a much smaller DEMO can be built, with the consequence that its fusion power is smaller, too), and following this up with the fast exponential growth with a 2.5 year doubling time.
The smaller DEMO has two advantages over the mainstream scenarios:
• The valley of death can be crossed at a level of risk-carrying investment that is 1-2 orders lower
• The shorter construction time allows a more effective innovation cycle, which makes it more realistic to aim for a fast exponential growth
The big question here is, of course, whether it is actually possible – from a physics and technology perspective - to realise a smaller, faster-to-build and cheaper DEMO. Within the frame of the established fusion science, the ITER design was the answer to the question what the smallest and cheapest Q=10 machine would be. Any claim for a significantly smaller DEMO solution will have to be based on new developments or insights, be they in physics, technology, or in design concept. It is interesting that there are a number of developments in fields not directly related to fusion that are seeing great progress. Examples are high temperature superconductors, allowing higher magnetic fields; developments in materials science, including additive manufacturing; robotics, and of course the power of computational science.

We stress that also in the optimistic assumption that a smaller DEMO can indeed be developed, Fig.2 shows that fusion will not become a big factor in the energy mix overnight. But it is clear that the smaller, modular approach to introducing fusion power in the system would in principle allow for a significant acceleration.
More importantly, it could bring fusion back in the time horizon of energy policy makers.
We do not, in this paper, intend to say anything about the scientific and technical feasibility of smaller tokamak reactors. Also, smaller machine may not be the best solution in terms of efficiency. But if feasible, they do offer the possibility of crossing the valley of death at lower financial risk level. And they do offer, crucially, the possibility of an innovation cycle which is compatible with fast exponential growth'.
(See: 2019-02-04 Economic aspects of the deployment of fusion energy,
https://research.tue.nl/files/123942756/RS.LopesCardozo.FutureofFusion.lastauthorversion_2_.pdf).

Smaller units of ~ 100 MWe may speed development, but much larger units of 1 GWe or more give a much lower Cost of Electricity (COE).
'The power plant study shows that the cost of fusion-generated electricity decreases with the electrical power output (Pe) approximately as P−0.4e [$P^{-0.4}$]. It was assumed that the maximum output acceptable to the grid would be 1.5 GW'.
(2010-03-13 The path to fusion power, Appendix A, https://royalsocietypublishing.org/doi/10.1098/rsta.2009.0216).
So the COE from a plant of 100 MWe would be about three times that from a plant of 1.5 GWe.

Smaller fusion plants of e.g. 100 MWe might demonstrate Q=10 sooner, but unless the TBR > 1.25 and the COE is competitive, they too would be futile.

15) **Cost Of Electricity - 1**
• *The 'Power Plant Study' gave a COE, for a 10th of a kind water-cooled steel fusion plant, & 6% real interest rate, of 9 €-cents/kWh*
• *Scaling of the Bechtel estimates gave a plant cost of $ 15 billion, or $ 15,000/kWe of rated power*
• *At a plant factor of 0.8 and annual charges of 17% the capital charges alone would be 36 cents/kWh*
• *The COE range is ~ 9-36 ¢/kWh i.e. $ 90-360/MWh*

'As with all systems, the absolute value of the internal cost of electricity depends on the level of maturity of the technology. For an early implementation of these power plant models, characteristic of a tenth of a kind plant, the cost range of the PPCS plant models is calculated to be 5 to 9 Eurocents/kWh. In a mature technology in which technological learning has progressed,

the costs are expected to fall in the range 3 to 5 Eurocents/kWh. For all the Models, the internal cost of electricity is in the range of estimates, in the literature, for future costs from other sources. Both the near-term Models have acceptable competitive internal costs'.
(See: 2005-04-13 A CONCEPTUAL STUDY OF COMMERCIAL FUSION POWER PLANTS, Page 28, https://www.euro-fusion.org/wpcms/wp-content/uploads/2012/01/PPCS_overall_report_final.pdf).

'European Power Plant Conceptual Study published last year
Give encouraging range for the expected cost of fusion generated electricity
9 €-cents/kW-hour for early near-term (water cooled steel) model
5 €-cents/kW-hour for early advanced (Li-Pb cooled SiC composite) model
– costs will fall with maturity'
(See: 2006-07-05 The Path to Fusion Power and ITER, Slide 18, 0^^Path^to^fusion^^ITER^-^Llewellyn^Smith.pdf)
The latter is highly improbable as the use of molten metal as the coolant was never solved for 'fast' nuclear fission reactors.

Furthermore, the cost of electricity from solar PV is expected to continue to fall, from $ 0.085/kWh for projects commissioned in 2018, to $ 0.048 in 2019, $ 0.02-0.08 by 2030 and $ 0.01-0.05 by 2050.
(See: 2019-11-13 IRENA predicts LCOE of solar will drop to $0.01-0.05 by mid century, https://www.pv-magazine.com/2019/11/13/irena-predicts-lcoe-of-solar-will-drop-to-0-01-0-05-by-mid-century
And: 2019-11 Future of Solar Photovoltaic, IRENA, https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf).
The latter includes: 'This report's findings are summarised as follows:
n ## Accelerated deployment of renewables, combined with deep electrification and increased energy efficiency, can achieve over 90% of the energy-related carbon dioxide (CO2) reduction needed by 2050 to set the world on a path towards meeting the Paris climate targets. Among all low-carbon technology options, accelerated deployment of solar PV alone can lead to significant emission reductions of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector.
n ## Achieving the Paris climate goals would require significant acceleration across a range of sectors and technologies. By 2050 solar PV would represent the second-largest power generation source, just behind wind power and lead the way for the transformation of the global electricity sector. Solar PV would generate a quarter (25%) of total electricity needs globally, becoming one of prominent generations source by 2050'.

Nth Of A Kind, Projects commissioning in 2025, in real 2018 prices.
The levelised costs in 2025, in £2018) per megawatt, are Offshore wind 57, Onshore wind 46, Large-scale solar 44, Gas 85, Gas+CCS 85
(2020-08-24 'BEIS electricity generation cost report (2020)', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911817/electricity-generation-cost-report-2020.pdf
The levelised costs in 2040, in £(2018) per megawatt-hour, are Offshore wind 51-63, Onshore wind 39-52, Large solar 39-51, Gas 84-87, Gas+CCS 80-90, and Nuclear 91-132.
(2020-08-27 'Electricity generated from wind and solar is 30-50% cheaper than previously thought, according to newly published UK government figures, https://www.carbonbrief.org/wind-and-solar-are-30-50-cheaper-than-thought-admits-uk-government).

An internal cost of fusion power of '9 €-cents/kW-hour for early near-term (water cooled steel) model' (90 €/MWh), not before 2050, would be far more than the levelised costs of Offshore wind, Onshore wind, and Large solar in 2040, and comparable to those of Gas+CCS in 2040, and Nuclear in 2030.

'Scaling of the construction costs from the Bechtel estimates suggests a total plant cost on the order of $15 billion, or $15,000/kWe of plant rating. At a plant factor of 0.8 and total annual charges of 17% against the capital investment, these capital charges alone would contribute 36 cents to the cost of generating each kilowatt hour. This is far outside the competitive price range'.
(See: 2006 Fusion Power: Will It Ever Come?, by William Parkins, http://fire.pppl.gov/fusion_science_parkins_031006.pdf).

For fusion power, the capital charges alone (e.g. 36 US c/kWh, 360 $/MWh) are far higher than the internal cost of electricity of '9 €-cents/kW-hour for early near-term (water cooled steel) model', and even more so the '5 €-cents/kW-hour for early advanced (Li-Pb cooled SiC composite) model'. This implies costs of at least 90 + 360 = 450 and 50 + 360 = 410 $/MWh.

16) **Nuclear – Negative Learning**
Grubler 2010 showed that the capital cost of nuclear fission power increased strongly over time in both the US and France. Yet these countries had the largest fleets, mostly of standardised designs. One reason for the increase was 'legislative creep' resulting from concerns about nuclear safety. Indeed, after Chernobyl in 1986, the capital costs sky-rocketed.

A disadvantage of the large unit size (~ 1 GWe) and the long construction time (e.g. 10 years) is that the 'learning rate' is low.

In fact, it is more likely to be negative, as for nuclear fission power plants.
(See: 2010-05-02 The costs of the French nuclear scale-up: A case of negative learning by doing, Arnulf Grubler, https://www.sciencedirect.com/science/article/pii/S0301421510003526).

The above fusion power plants (DEMO and PROTO) were designed before the IRSN report on the safety considerations for fusion power plants, so it is unlikely that the cost implications of these have been included.
P 48. Safety and radiation protection issues...
Residual heat removal.
P 52. Ionising radiation exposure risks (to operators and in operation) due to the large quantity of tritium. (e.g. 10s of kg).
P 54. Types of accidents to consider.
(See: 2017-11-17 Nuclear Fusion Reactors, //safety and radiation protection considerations for demonstration reactors that follow the ITER facility, https://www.irsn.fr/EN/Research/publications-documentation/Scientific-books/Documents/ITER-VA_web_non_imprimable.pdf).

With the costs to mitigate such risks included, fusion power would be far more expensive than energy savings and renewables.

17) **Solar PV, Wind – Positive Learning**
Samadi 2018 showed positive experience or learning curves for the cost per peak Watt of solar PV and onshore wind.
So their advantage in COE increases with time compared with the negative learning of fission – and probably fusion plants.
At 22% per annum, the learning rate for solar PV is particularly large, due to strong competition, and both reduced cost and increased efficiency per unit area. Both PV and wind power also benefit from their small unit size, which eases financing.
(See: 2018 The experience curve theory and its application in the field of electricity generation technologies, Samadi, https://epub.wupperinst.org/frontdoor/deliver/index/docId/6806/file/6806_Samadi.pdf Fig. 1)

18) **Cost of Electricity - 2**
• *Large unit size (~ 1 GWe) and long construction times (~ 10 y) imply a low 'learning rate'*
• *Indeed, Grubler found the learning rate of nuclear fission power plants in France & US to be negative*
• *Yet the COE from solar PV is expected to fall from 8.5 ¢/kWh in 2018 to 2-8 ¢/kWh in 2030*
• *The levelised COE in 2025, in £(2018)/MWh, are Large Solar PV 44, Onshore Wind 46, Offshore Wind 57, and Gas 85 (BEIS, 2020)*

19) **Critics of Fusion Power**
Particularly in recent years, there have been several very telling well-informed criticisms of fusion power.
Most of those below have retired after decades in fusion research. Michael Dittmar works in adjacent physics fields.

a) William Parkins of Rockwell International. (See: 2006-03-10 Fusion Power: Will It Ever Come?, http://fire.pppl.gov/fusion_science_parkins_031006.pdf).
This includes: 'Even if a practical means of generating a sustained, net power-producing fusion reaction were found, prospects of excessive plant cost per unit of electric output, requirement for reactor vessel replacement, and need for remote maintenance for ensuring vessel vacuum integrity lie ahead. What executive would invest in a fusion power plant if faced with any one of these obstacles? It's time to sell fusion for physics, not power'.

b) Daniel Jassby of PPPL (Princeton Lab). (See: 2017-04-19 Fusion reactors: Not what they're cracked up to be, https://thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be).
This includes: 'To sum up, fusion reactors face some unique problems: a lack of a natural fuel supply (tritium), and large and irreducible electrical energy drains to offset. Because 80 percent of the energy in any reactor fueled by deuterium and tritium appears in the form of neutron streams, it is inescapable that such reactors share many of the drawbacks of fission reactors—including the production of large masses of radioactive waste and serious radiation damage to reactor components. These problems are endemic to any type of fusion reactor fueled with deuterium-tritium, so abandoning tokamaks for some other confinement concept can provide no relief.
If reactors can be made to operate using only deuterium fuel, then the tritium replenishment issue vanishes and neutron radiation damage is alleviated. But the other drawbacks remain—and reactors requiring only deuterium fueling will have greatly enhanced nuclear weapons proliferation potential.
These impediments—together with the colossal capital outlay and several additional disadvantages shared with fission reactors—will make fusion reactors more demanding to construct and operate, or reach economic practicality, than any other type of electrical energy generator'.

And: (2018-02-14 ITER is a showcase … for the drawbacks of fusion energy, https://thebulletin.org/2018/02/iter-is-a-showcase-for-the-drawbacks-of-fusion-energy).
This includes: 'The underlying problem is that all nuclear energy facilities—whether fission or fusion—are extraordinarily complex and exorbitantly expensive.
A second invaluable role of ITER will be its definitive influence on energy-supply planning. If successful, ITER may allow physicists to study long-lived, high-temperature fusioning plasmas. But viewed as a prototypical energy producer, ITER will

be, manifestly, a havoc-wreaking neutron source fueled by tritium produced in fission reactors, powered by hundreds of megawatts of electricity from the regional electric grid, and demanding unprecedented cooling water resources. Neutron damage will be intensified while the other characteristics will endure in any subsequent fusion reactor that attempts to generate enough electricity to exceed all the energy sinks identified herein.
When confronted by this reality, even the most starry-eyed energy planners may abandon fusion. Rather than heralding the dawn of a new energy era, it's likely instead that ITER will perform a role analogous to that of the fission fast breeder reactor, whose blatant drawbacks mortally wounded another professed source of "limitless energy" and enabled the continued dominance of light-water reactors in the nuclear arena'.

c) Michael Dittmar of IPP, ETH. (See: 2009-11-13 The Future of Nuclear Energy: Facts and Fiction, Chapter IV: Energy from Breeder Reactors and from Fusion?, https://arxiv.org/pdf/0911.2628).
The Abstract includes: 'We further conclude that, no matter how far into the future we may look, nuclear fusion as an energy source is even less probable than large-scale breeder reactors, for the accumulated knowledge on this subject is already sufficient to say that commercial fusion power will never become a reality'.

And: (2019-07-10 Status and Prospects of the ITER Plasma Physics Experiment. Is it time to terminate the project? Part I, https://www.gruene-bundestag.de/fileadmin/media/gruenebundestag_de/themen_az/atomausstieg/PDF/iter-project-2019-part-1.pdf).
This includes: 'However, only a few years after the project received the green light in 2007, the estimated construction cost began to explode and the ITER management had to admit that the original plans could not be realised. The latest 2018 estimates, which include a drastically downscaled experimental program, show that the construction will cost at least some 20 billion Euros. Furthermore, the first basic plasma experiments are also not expected to begin before the end of 2025. It has also been admitted that the ability to demonstrate significant few-minute deuterium-tritium fusion energy release can not be expected before the year 2040.
As those deuterium-tritium results are "Go/ No-Go" criteria for the realisation of nuclear fusion for electric energy production, and for a realistic initial design of a "demonstration reactor", DEMO, which has to be at least three times larger than the ITER, cannot begin before the year 2040.
To summarise, the experience gained during the 30 years design and construction process of the ITER Tokamak, demonstrates that Tokamaks are not the technology which leads to commercially competitive energy production'.

Mohamed Abdou of UCLA.
2020-11-23 Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency, Abdou et al, https://iopscience.iop.org/article/10.1088/1741-4326/abbf35/pdf
The Abstract includes:
'We focus in particular on components, issues and R&D necessary to satisfy three 'principal requirements': (1) achieving tritium self-suffciency within the fusion system, (2) providing a tritium inventory for the initial start-up of a fusion facility, and (3) managing the safety and biological hazards of tritium. A primary conclusion is that the physics and technology state-of-the-art will not enable DEMO and future power plants to satisfy these principal requirements'.

2020-12-16 Lessons Learned from 40 Years of Fusion Science and Technology Research, M. Abdou, https://www.fusion.ucla.edu/abdou/abdou%20presentations/2020/Abdou_FPA2020_201217.pdf
Slide 10 includes:
'The physics and technology state-of-the-art will not enable DEMO and future power plants to satisfy the Principal Requirements of T self-sufficiency and Providing the initial start-up tritium inventory of a fusion facility'.

2021-04-28 Physics and technology considerations for the D-T fuel cycle and conditions for tritium fuel self-sufficiency, Abdou, https://www.fusion.ucla.edu/abdou/abdou%20presentations/2021/Abdou_MIT_Virtual_Seminar_4-28-2021_Tritium_Fuel_Cycle.pdf
Slide 2 includes:
'In D-T Fusion Systems, Tritium plays a Dominant Role
Major Areas of highest importance:

1. Tritium Inventories and Startup Inventory
Accurate calculations of time-dependent tritium flow rates and inventories in a fusion plant are critical for determining:
a) Required initial inventory for startup of DEMO and future fusion devices beyond ITER
b) Conditions Required to attain Tritium Self-Sufficiency in DEMO and future Power Plants
c) Impact on Safety

2. Tritium Self-Sufficiency
⏶ Absolutely required for D-T Fusion Energy Systems to be feasible
⏶ Complex dependence on many plasma physics and fusion technology parameters/ conditions
⏶ The required TBR and the achievable TBR have very different dependence on fusion system physics and technology

3. Safety
-Tritium Inventories, permeation and release are key aspects of safety analysis
Calculations/Analysis for all these 3 areas require detailed Dynamic Modelling of the T fuel Cycle'.

Slide 31 includes:
'The state-of-the-art for fb, ηf, tp is not acceptable because it:
1) Results in too large T startup inventory that cannot be provided from any tritium-producing non-fusion sources
2) Makes it unlikely (or cause low-confidence) in achieving tritium self-sufficiency
3) Denies fusion the opportunity to have short doubling time (e.g. ~1yr) in the critical stage from demonstration to initial commercialization'.

In addition, Niek Lopes Cardoso of TU Eindhoven has criticised fusion as being too late. (See above, under 11)).

20) **Energy Efficiency and Savings - 1**
According to the findings of Cullen, Allwood and Borgstein, 2010 and 2011, energy demand can be reduced by up to 85%. This would also reduce the need for energy storage and increase resilience in a world subject to climate change and a still-growing population, expecting higher living standards.

21) **Energy Efficiency and Savings - 2**
There is huge scope for increased efficiency from known technologies, which deserve much wider deployment.
• *Compared with incandescent lights, LEDs save 85%*
• *Much electricity drives pumps and fans - 'cube law' devices - in homes, commerce and industry*
  Electronic drives enable annual savings of 50-80%
• *'Inverter drives' can also be used in fridges, air conditioners and heat pumps, with similar savings*
• *Delivering these savings at scale and speed is possible because these are all made in factories*

The potential demand-side energy reductions are estimated in two major papers by Cullen and Allwood et al.:
(2010-03-05 Theoretical efficiency limits for energy conversion devices, Cullen and Allwood, https://www.sciencedirect.com/science/article/abs/pii/S0360544210000265).
The Abstract includes: 'global demand for energy could be reduced by almost 90 per cent if all energy conversion devices were operated at their theoretical maximum efficiency'.
I argue that all energy conversion devices should be able to operate at about half their theoretical maximum efficiency – as is the case for internal combustion engines. If so, the global demand for energy could be reduced by about 45%.
(2011-01-12 Reducing Energy Demand: What Are the Practical Limits ?, Cullen, Allwood and Borgstein, https://pubs.acs.org/doi/pdf/10.1021/es102641n).

The Abstract includes: 'The result demonstrates that 73% of global energy use could be saved by practically achievable design changes to passive systems'.
Hence by combining energy conversion devices at about half their theoretical efficiency (saving 45%) with the practical passive system changes (saving 73%), the global energy saving could be 100 - (100-45)*(100-73) = 85%.

• *Compared with incandescent lights, LEDs save 85%*
In the USA, lighting accounts for 22% of electricity, i.e. 8% of energy, and solid state lighting (i.e. LEDs) is expected to save 50% by 2027. (See: 2015-10-29 Impact of LED lighting on Worldwide Energy Saving and Role of Optical Metrology, Slide 3, https://www.nist.gov/document-18427). This implies LEDs saving 11% of electricity, i.e. 4% of energy, by 2027.
• *Much electricity drives pumps and fans - 'cube law' devices - in homes, commerce and industry. Electronic drives enable annual savings of 50-80%*
• *'Inverter drives' can also be used in fridges, air conditioners and heat pumps, with similar savings*
Compared with central power plants, end use appliances take far less time and energy to develop and produce in quantity.

22) **Global Potentials of Renewables**
This table shows that, after increased savings and efficiency, a world energy demand of less than 30 TW could easily be met widely by solar PV and wind, and locally by hydro and maybe sustainable biomass.

Wind
2004 On the Global and Regional Potential of Renewable Energy Sources, Hoogwijk, Monique, http://dspace.library.uu.nl/bitstream/handle/1874/782/full.pdf (Wind 10.9 TW, with offshore 15.3 TW)

2005 Evaluation of Global Wind Power, Archer, C. L. & Jacobson, M. Z. http://www.stanford.edu/group/efmh/winds/2004jd005462.pdf (72 TW of which 20% is 14.4 TW)

2011-06-29 GLOBAL WIND POWER POTENTIAL, physical and technological limits, De Castro, https://www.sciencedirect.com/science/article/abs/pii/S0301421511004836 (1 TW)

2013-02-25 Are global wind power resource estimates overstated, Adams & Keith, https://www.researchgate.net/profile/David_Keith/publication/258310130_Are_global_wind_power_resource_estimates_overstated/links/549233ae0cf2ac83c53dbfea/Are-global-wind-power-resource-estimates-overstated.pdf (maybe only 56/4 = 14 TW)

Solar and Wind
2013-08-11 Global solar electric potential: A review of their technical and sustainable limits, de Castro et al, https://content.csbs.utah.edu/~mli/Economics%207004/Castro%20et%20al-Global%20Solar%20Electric%20Potential.pdf
(Around 60–120EJ/yr) (2-4 TW).

2019-03 100% Renewable Energy, All Sectors, Global Report, Breyer et al, http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf
P 32. Solar PV in 2050 harnessed is 63.4 TW and Wind in 2050 harnessed is 8.13 TW (So the potential resources are greater).

Biomass and Waste
2003-08 Exploration of the ranges of the global potential of biomass for energy, Hoogwijk et al, https://www.sciencedirect.com/science/article/pii/S0961953402001915
The Abstract includes: 'The main conclusion of the study is that the range of the global potential of primary biomass (in about 50 years) is very broad quantified at 33-1135 Ejy^{-1}. (1 to 36 TW)

Geothermal
2010-05 Contribution of Geothermal Energy to Climate Change Mitigation: the IPCC Renewable Energy Report. Bromley et al,
https://www.researchgate.net/profile/Ernst_Huenges/publication/228606059_Contribution_of_Geothermal_Energy_to_Climate_Change_Mitigation_the_IPCC_Renewable_Energy_Report/links/0deec52175af1c4e1c000000/Contribution-of-Geothermal-Energy-to-Climate-Change-Mitigation-the-IPCC-Renewable-Energy-Report.pdf
Page 2 includes: 'By 2050, the estimated global electricity generation from known hydrothermal resources is predicted to grow from 10 GWe to 140 GWe, of which 70 GWe is confidently anticipated to be achievable using current technology and the balance will be achieved if new technology develops as expected (Figure 1)'. (Assume 70 GWe).

Hydro
2015 A comprehensive view of global potential for hydro-generated electricity, Y. Zhou et al, https://pubs.rsc.org/en/content/articlelanding/2015/ee/c5ee00888c#!divAbstract
The Abstract includes: 'Total global potential of gross, technical, economic, and exploitable hydropower are estimated to be approximately 128, 26, 21, and 16 petawatt hours per year, respectively. The economic and exploitable potential of hydropower are calculated at less than 9 cents per kW h'. (The exploitable potential of 16 PWh/y is 1.8 TW annual average).

Chris Llewellyn Smith asked 'What can replace the 13 TW (and growing) from fossil fuels?'
He estimated the sizes of renewable sources as:
'Wind 3 TW (claim of 72 Twe), Geothermal 100 GW, Hydro 2 TW, Bio 1 TW, Marine 100 GW, Solar e.g. 19 TW'.
2010-03-04 The Energy Challenge and The Case for Fusion, Slide 13 and 14.
https://energy.stanford.edu/sites/default/files/energy_challenge_and_the_case_for_fusion.pdf

'Solar photovoltaics (PVs) and wind constitute more than 60% of global annual net new capacity additions. Balancing an electricity system with 30–100% variable PV and wind is straightforward using off-the-shelf techniques comprising stronger interconnection over large areas to smooth out local weather, storage, demand management, and occasional spillage of renewable electricity. The overwhelming dominance of PV, wind, and hydro-electricity in new renewable energy deployment means that renewable electricity is tracking toward near equivalence with renewable energy. A global survey of off-river (closed-loop) pumped hydro energy storage sites identified 616 000 promising sites around the world with a combined storage capacity of 23 million GWh, which is two orders of magnitude more than required to support 100% global renewable electricity. This is significant because pumped hydro storage is the lowest cost storage method and is available off-the-shelf in large scale. Australia is deploying PV and wind at a rate of 250 W per year per capita, which is four to five times faster than in the European Union, the USA, Japan, and China. This is significant because it demonstrates that rapid deployment of PV and wind is feasible, with consequent rapid reductions in greenhouse gas emissions'.
(See: 2019-11 Pathway to 100% Renewable Electricity, Andrew Blakers et al, Abstract, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8836526).

The above annual average renewable power supplies of Wind 1-14, Solar 2-19, Hydro 2, Biomass 1-36 and Geothermal about 0.1 TW, total to 6-71 TW.

23) **World Energy Demand**
• *Lopes Cardozo 2019 projected world energy demand in 2050 as an annual average of ~ 30 TW*
• *Major energy demand reductions are advocated by Moriarty and Honnery 2012 and Anderson 2015*
• *The findings of Cullen, Allwood and Borgstein 2010, 2011 imply that the global energy savings could be 85%*
• *Thus world energy demand would be well within the potentials of renewables*
The world energy demand in 2050 has been projected as about 30 TW.
Wind and solar power are already proven and approaching 1% of the world energy demand, with a doubling time of 2.5 years. (See Fig.2: Total installed effective power (i.e. adjusted for capacity factor) versus Year in: 2019-02-04 Economic aspects of the deployment of fusion energy, Lopes Cardozo, https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2017.0444 and https://pure.tue.nl/ws/files/123942756/RS.LopesCardozo.FutureofFusion.lastauthorversion_2_.pdf).

'So, in meeting the challenges of the 21st century, the world now faces a triple uncertainty: in the timing and severity of climate change, in the future supply of fossil fuels, and—as argued here—in future RE availability. Fossil fuel use may have to be reduced to near zero in the coming decades, and future RE output could be far below present energy use. Thus a prudent course would involve major energy reductions (Anderson, 2015; Moriarty and Honnery, 2012b). Not only will we need to maximise the energy services obtained from each unit of energy (for instance, through gains in technical energy efficiency), but we will likely also need to re-evaluate all energy-consuming tasks, discarding those that are less important'.
(See: 2016-03 Can renewable energy power the future?, Moriarty and Honnery, https://www.researchgate.net/profile/Patrick_Moriarty/publication/296486936_Can_renewable_energy_power_the_future/links/56d614cc08aee73df6c05887/Can-renewable-energy-power-the-future).
(See: 2012-12 Preparing for a low-energy future, Moriarty and Honnery, https://www.sciencedirect.com/science/article/abs/pii/S0016328712001802 and https://www.researchgate.net/profile/Patrick-Moriarty-5/publication/233911731_Preparing_for_a_low-energy_future/links/0c96052c0c3a3d9207000000/Preparing-for-a-low-energy-future and 2015 Duality in climate science. Anderson, K., https://www.nature.com/articles/ngeo2559 and https://unece.org/fileadmin/DAM/energy/se/pdfs/comm25/rd/CSE.25.2016.INF.13_Duality.Climate.Science.pdf).

Least cost solutions could comprise energy savings of up to 85% identified by Cullen, Allwood and Borgstein, and energy demand reduction as suggested by Moriarty and Honnery 2012 and Anderson 2015, with renewable energy supplies.
While food and shelter (heating and cooling) are essential to life, much of transport is not, yet it accounts for around one-third of all carbon dioxide emissions. (See: 2020-03-26 2019 UK greenhouse gas emissions, provisional figures, National Statistics, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875485/2019_UK_greenhouse_gas_emissions_provisional_figures_statistical_release.pdf Page 10).

24) **Fusion Conclusions - 1**
• *Safety – like fission, fusion generates radioactivity, where PV, wind and storage do not.*
• *Fusion power plants with TBR say 1.25, Q say 10, and competitive COE have yet to be demonstrated.*
• *For a Doubling Time of 5 y, the exponential growth period from 1 GWe to 1 TWe would be about 50 years*
• *If the Doubling Time is less than (Construction Time + EPT), then during the exponential growth period, the Net Energy Production is negative and the Return on Investment is zero*

25) **Fusion Conclusions – 2**
• *Learning - fission is negative but PV and wind positive*
• *Fusion power has several very well-informed critics. Most have worked for decades in fusion research*
• *Energy saving and efficiency could reduce energy demand – and thus GHG emissions - by up to 85%*
• *Spending money, time, energy, GHG and talent on fusion means less for energy use, PV, wind and storage*
• *So fusion power is not just futile in itself, but actually counterproductive in addressing the climate crisis*

26) **Fusion Conclusions – 3**
• *Energy savings and renewables avoid the risk of human harm from tritium leaks and other radioactive components*
• *They also leave no radioactive waste for future generations*
• *Rather they offer huge opportunities to investors and employees, and can certainly meet the climate challenge*
• *They work in every country and improve resilience*
• *This brings satisfaction and rewards to both investors and employees*

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