The Futility of Fusion
A Dream Too Far

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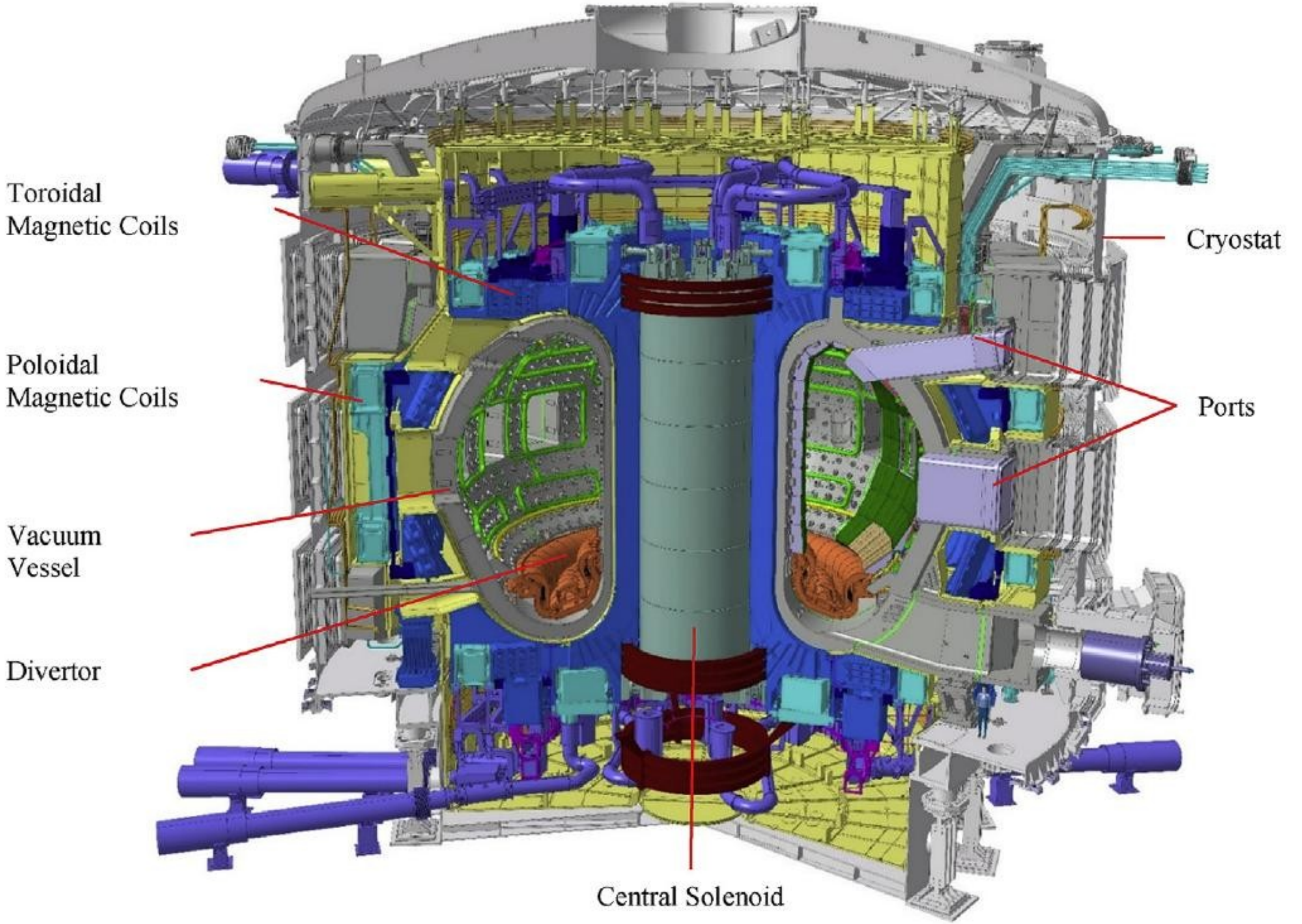


Fig. 1. Fusion reactor ITER [1].

Entler, 2018

The Physics of Fusion

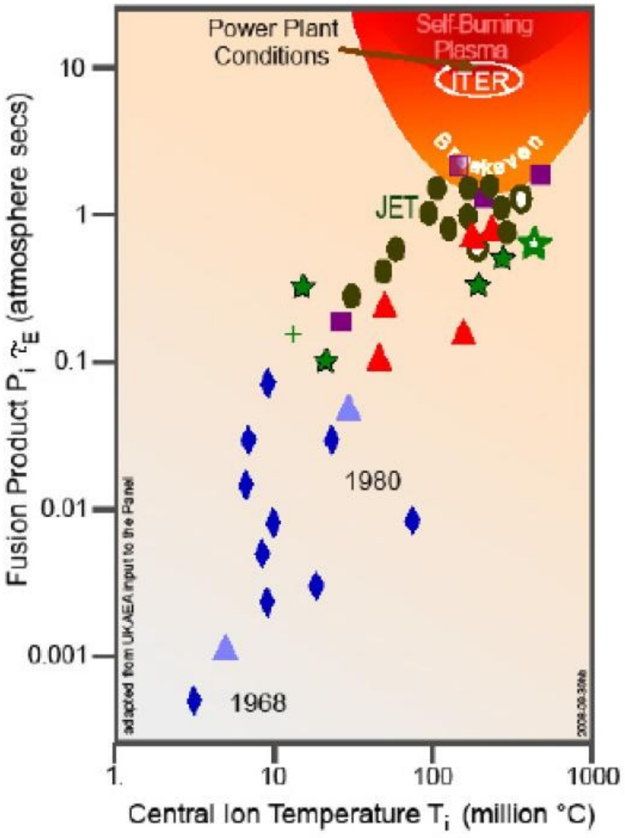
- Fusion obeys Einstein's equation $E = mc^2$ whereby Mass (m) is transmuted into Energy (E)
- The Sun uses the Proton-Proton reaction, with P of 10 billion bar and T of 15 million degrees C
- Lawson 1955 discussed fusion on earth with the Deuterium-Deuterium & Deuterium-Tritium reactions
- D-D requires around 700 million C, and D-T requires about 100 million C - both far hotter than the Sun

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

Progress

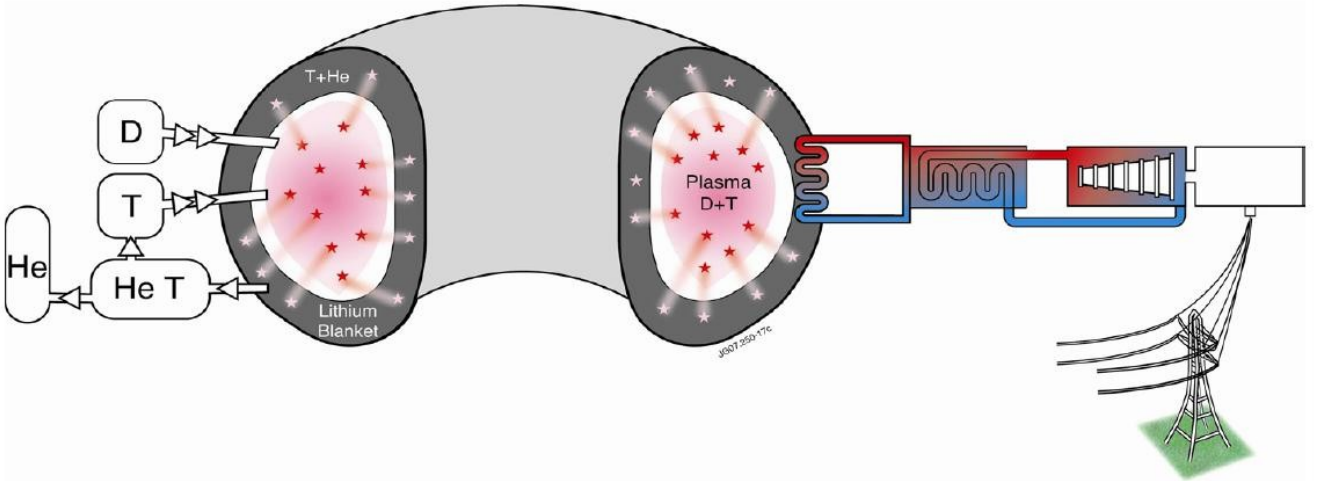
- Huge strides in physics, engineering, technology
- **JET**: 16 MW of fusion power ~ equal to heating power
- Ready to build a Giga Watt-scale tokamak: **ITER** – expected to produce 10 x power needed to heat the plasma



P_i =pressure in plasma;
τ_E = (energy in plasma)/(power supplied to keep it hot)

Llewellyn Smith, 2010

A Fusion Power plant would be like a conventional one, but with a different fuel and furnace



The blanket captures **energetic neutrons** produced in the fusion process, which:

- react with lithium in the blanket to **produce Tritium** (⇨ fuel the reactor)

- deposit **their energy ⇨ heat** which is extracted through a cooling circuit and used to boil water and produce steam to drive a generator

Llewellyn Smith, 2010

Nuclear Dangers - 1

- Fusion would most likely use radioactive Tritium as a fuel, which as a hydrogen isotope, may well leak
- 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

Nuclear Dangers - 2

- The tokamak inner walls & blankets suffer intense neutron bombardment, making them radioactive
- The resulting damage requires them to be renewed about every two years, so they are segmented
- After a lifetime of maybe 25 y, the entire fusion plant would require expensive decommissioning
- The plant and e.g. 12 sets of walls would require storage as radioactive nuclear waste
- Decommissioning and waste storage add to the COE

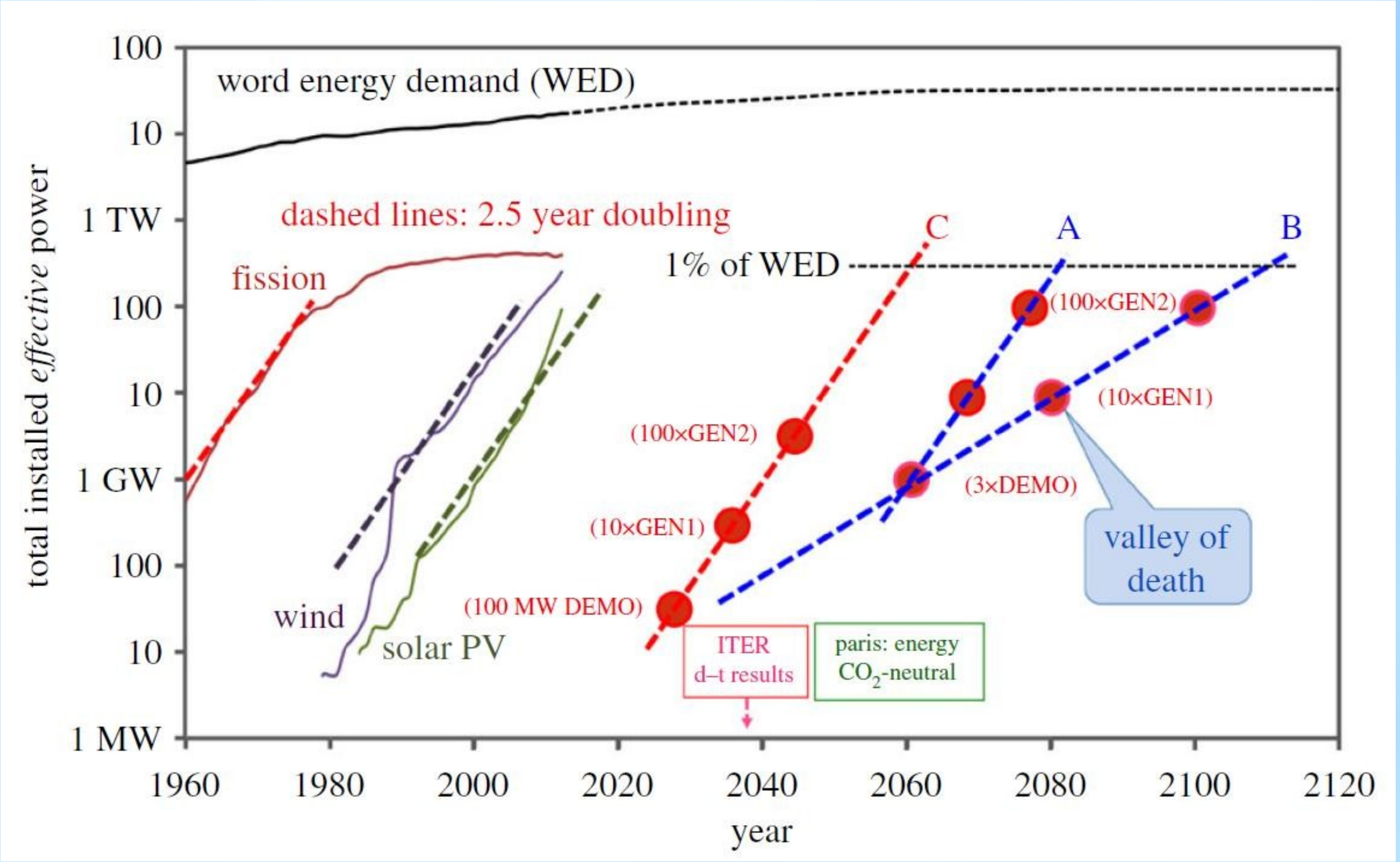
Tritium Balance and Supply - 1

- 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
- But the world inventory is small - e.g. 30 kg – and the price is 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

Tritium Balance and Supply - 2

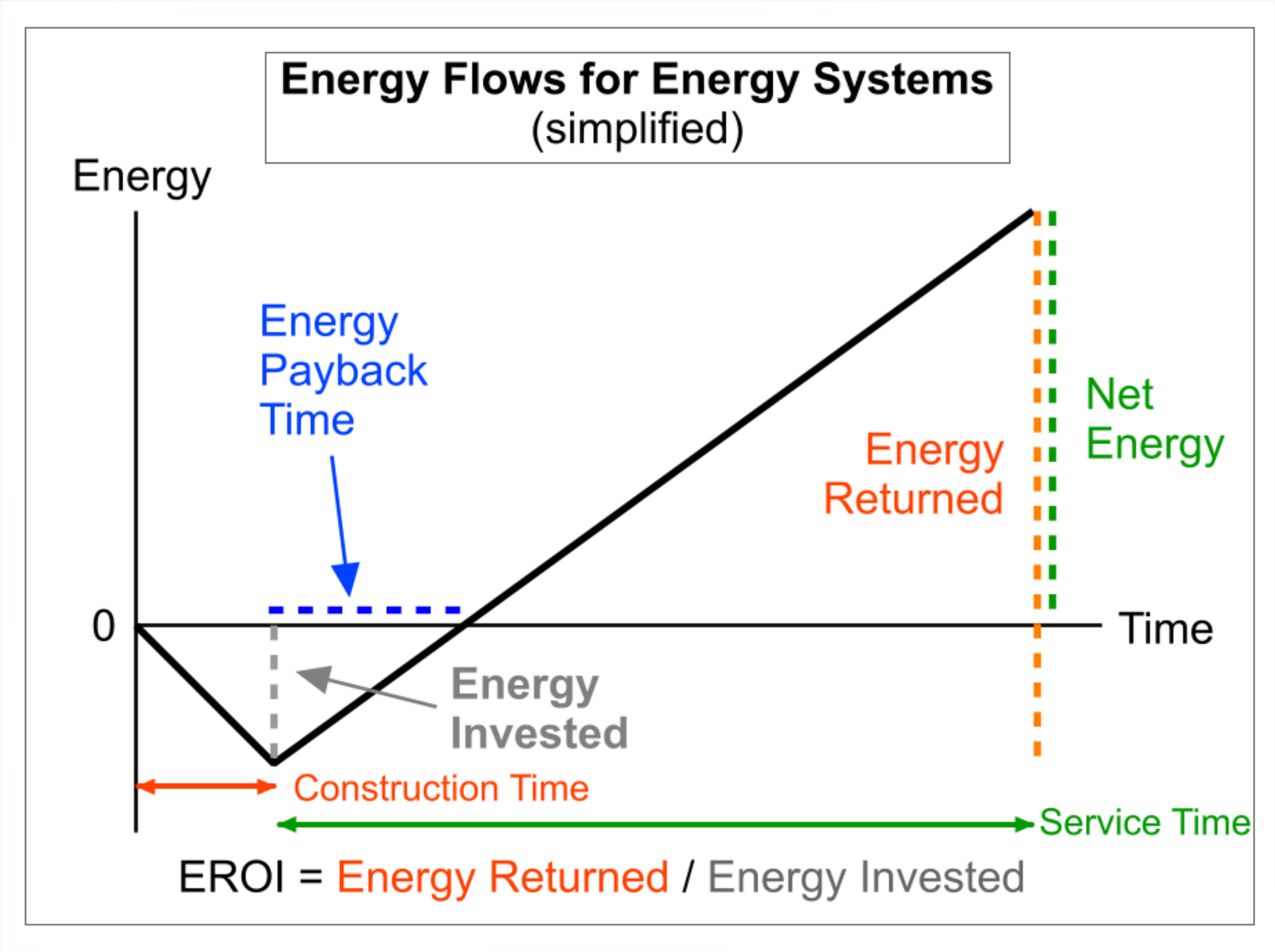
- A D-T plasma emits neutrons that heat the walls cooled by e.g. molten salt for a steam power cycle
- The walls also include a ‘blanket’ of lithium wherein some of the neutrons produce Tritium
- A neutron hits Li7, creating a Tritium ion and a 2nd neutron, which hits Li6 and creates a 2nd Tritium ion
- 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

Installed Effective Power - 1



Lopes Cardoso et al, 2019

Installed Effective Power - 2



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

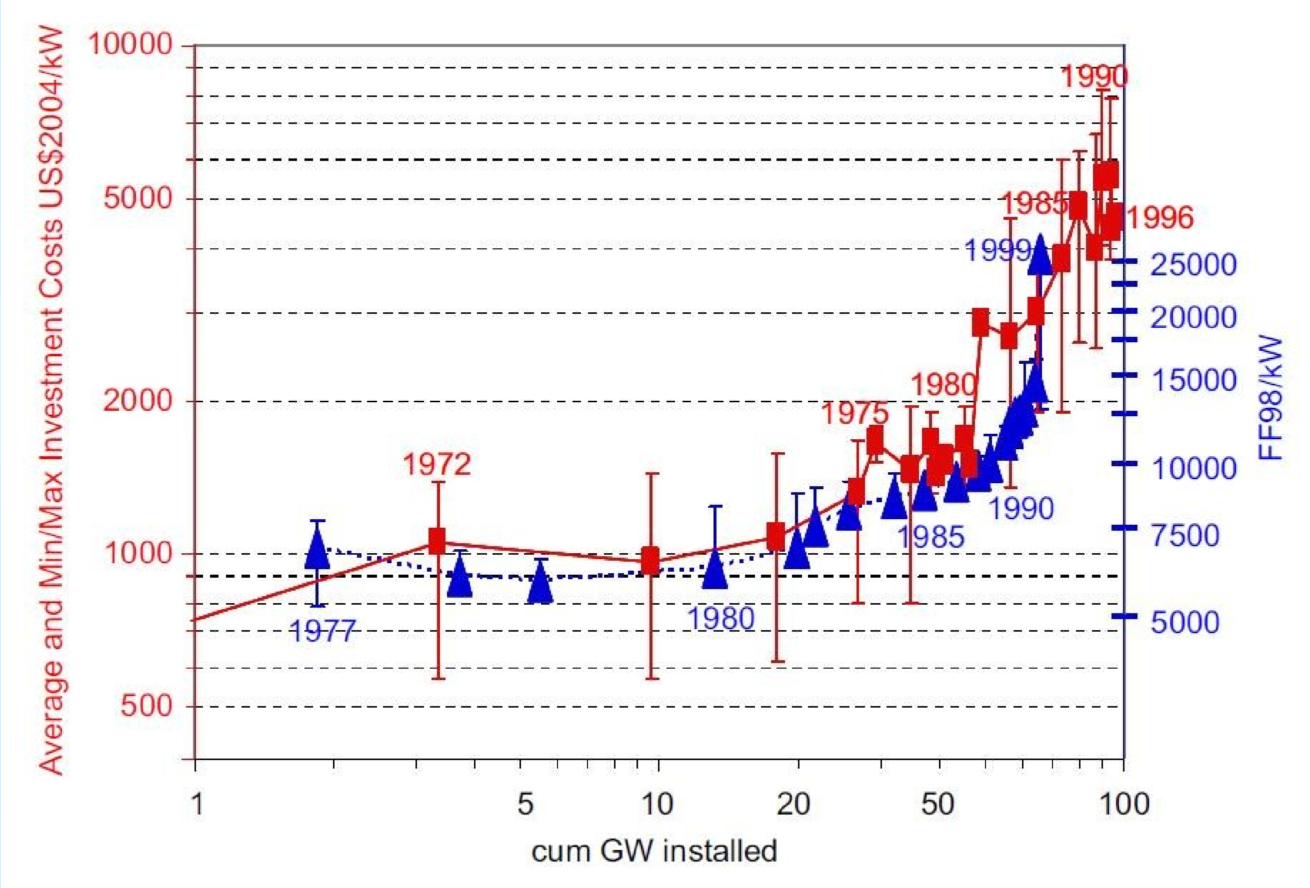
Timeline for Fusion Power - 2

- Tokamak Energy claims that a smaller unit – e.g. 100 MWe – would be quicker to develop
- This would use a spherical tokamak and high-temperature superconducting magnets
- But the ‘Power Plant Study’ shows that the cost of electricity (COE) from fusion varies as $(\text{Power})^{-0.4}$
- So compared with a unit of 1.5 GWe, the COE for a unit of 100 MWe would be three times as high

Cost of Electricity - 1

- The ‘Power Plant Study’ gave a COE, for a 10^{th} 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

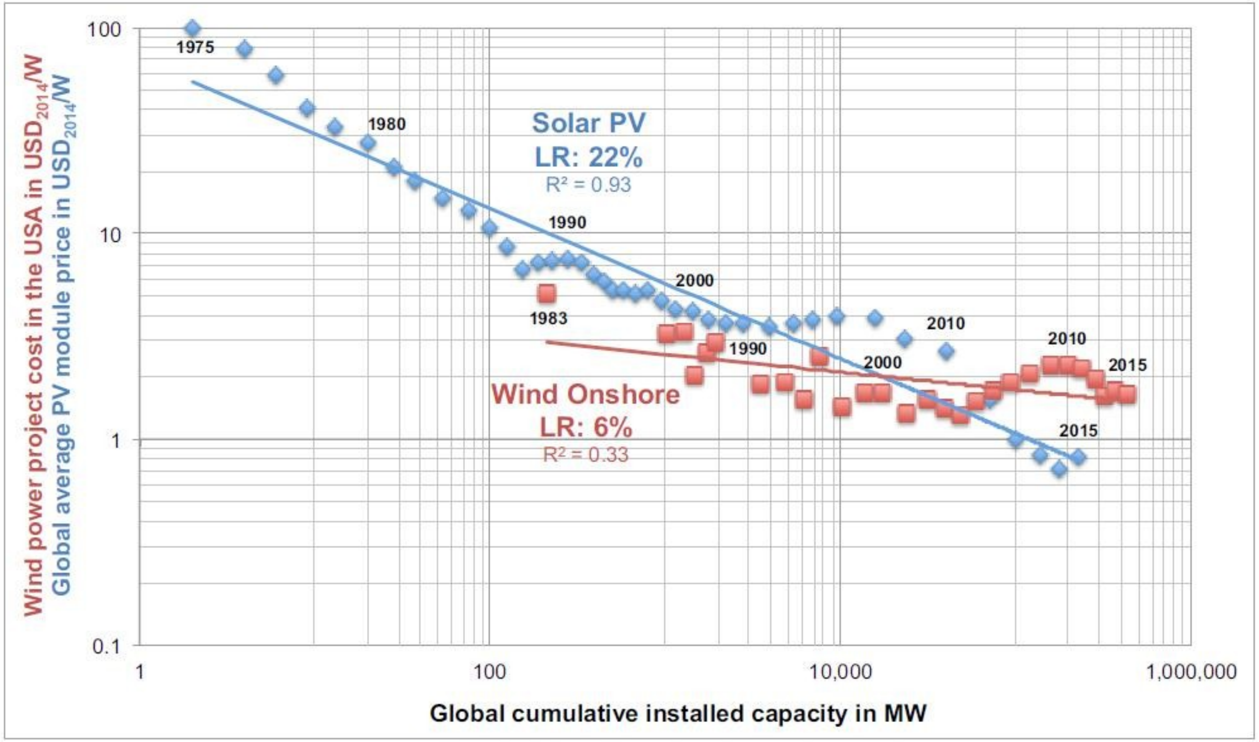
Nuclear - Negative Learning



Grubler, 2010

Solar PV, Wind - Positive Learning

Figure 1: Experience curves for global solar PV module manufacturing (1975-2015) and for wind power projects in the USA (1983-2015)



Data sources: [33–39]

Samadi, 2018

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)

Critics of Fusion Power

- William Parkins of Rockwell International:
  2006 ‘Fusion Power: Will it Ever Come ?’
- Daniel Jassby of Princeton:
  2018 ‘ITER is a showcase..for the drawbacks..’
- Michael Dittmar of ETH:
  2019 ‘...Is it time to terminate the project ?’
- Mohamed Abdou of UCLA:
  2020 ‘The...state-of-the-art will not enable DEMO and future power plants to satisfy..T self-sufficiency’

Energy Efficiency and Savings - 1

- Cullen and Allwood found that – if all energy converters operated at their theoretical efficiency – global demand could be reduced by almost 90%
- So at half this, demand could be reduced by 45%
- They and Borgstein found that achievable changes to passive systems could save 73% of demand
- Combining energy converters and passive systems, the global energy savings could be 85%

Energy Efficiency and Savings - 2

- 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 all end use devices are made in many factories

Global Potentials of Renewables - TW

Author	Solar PV	Wind	Wave	Hydro	Biomass	Geothermal
Smith	19	3	0.1	2	1	0.1
Hoogwijk		15.3			1-31	
Jacobson	72					
De Castro	2-4	1				
Breyer	63.4	8.13				
Bromley						0.07
Zhou				1.8		

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

Fusion Conclusions - 1

- Safety: like fission, fusion generates radioactivity, where energy savings, solar PV, wind and storage do not
- Fusion power plants with Q say 10, TBR say 1.25, and competitive COE have yet to be demonstrated
- For a Doubling Time of 5 y, the exponential growth period would be about 50 years
- If the Doubling Time < (Construction Time + EPT), then during the exponential growth period, the Net Energy Production and the ROI are negative

Fusion Conclusions - 2

- Learning: fission is negative but solar 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, solar PV, wind and storage
- So fusion power is not just futile in itself, but actually counterproductive in addressing the climate crisis

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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My nuclear reports with references are at:

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