

Fusion energy economics

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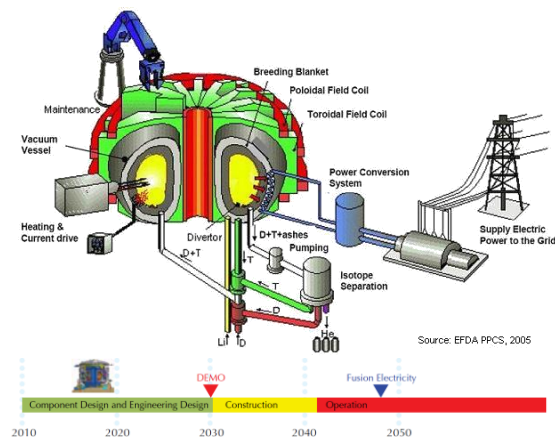
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A fusion power plant.



- A fusion power plant is a **complex system** whose backbone is a structure of superconducting magnets devoted to confine, shape and make current flow in a D-T plasma.
- If the proper density, temperature and confinement time exist at the same time, fusion reactions occur and thermal energy is produced.
- Then the heat is transferred to turbines through the steam generators to generate electricity.
- Fusion power plants are envisaged to enter in the energy market **after 2050** (see the **Fusion Roadmap**)

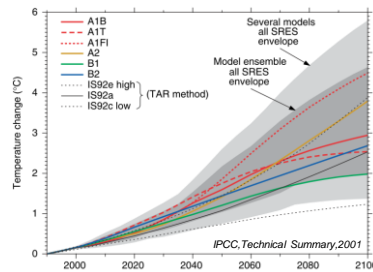


Is fusion likely to play a relevant role in the future?

- The global model EFDA TIMES has been **specifically** developed to **explore the role of fusion** in the future global energy system.
- In an era with an increasing energy demand, a progressive exploitation of conventional energy sources and visible climate changes, the **fusion technology looks to be a good option to:**

1) provide large amount of electricity 2) despite consuming small amount of fuel ($\sim 3.4 \cdot 10^{11}$ J/g, 10^7 times more than coal) 3) while producing small amount of radioactive waste 4) and avoiding CO₂ emission.

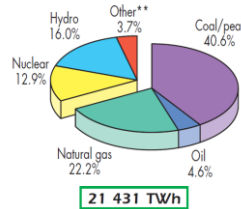
- Thus it well fits with the largely shared goal of current energy policies i.e. to achieve a **fully decarbonized energy system** so as to prevent a further global temperature increase.
- Anyway, a global temperature increase of 2 - 6°C as compared to 1990 levels is expected.



The potential actors of a fully decarbonized energy system after 2050.

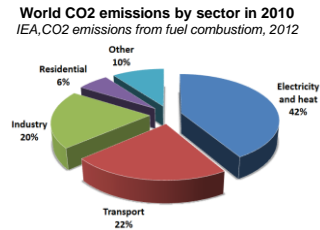
- **Renewable energy.**
 - Intermittent energy source.
 - Thus RES need to be coupled with Storage Systems if they are supposed to provide the great part of the energy demand.
 - Large land use.
 - Upper bounds (technical and/or economical) on capacity to be installed.
- **Fission power plants.**
 - Reduced social acceptability after Fukushima disaster,
 - even if the Gen III+ reactors ensure higher safety and security level.
 - The deployment of Gen IV reactors (~2030) would reduce the uranium consumption and long term waste thus helping fission sustainability.
 - The cost of electricity is low (~6 c€/kWh – median case @5% discount rate, €₂₀₀₈, from Projected Cost of Generating Electricity 2010)

World electricity generation by fuel in 2010
IEA, Key World Energy Statistic, 2012



The potential actors of a fully decarbonized energy system after 2050.

- **Carbon Capture and Storage Systems.**
 - Would help reducing the emission of industry sector as well.
 - But most of the capture and storage technologies are still at demonstration phase
 - For ever coal+CCS PP will be more expensive than coal PP w/o CCS.
- **Fusion power plants.**
 - A number of technological and physical issues have still to be fixed.
 - The economics of fusion is under study as well.



Studies about fusion economics.

- Studies about the economics of fusion started in the late '70s.
- Currently they are carried out by U.S. (ARIES team), Europe (EFDA) and Japan (JAEA and some Universities).
- They all aim at estimating investment and running costs of a fusion power plant cost as well as its availability factor in order to estimate the **levelized cost of electricity**:

$$LCOE = p_{elc} = \frac{\sum_t (I_t + O\&M_t + F_t + C_t + D_t)(1-r)^{-t}}{\sum_t (E_t)(1-r)^{-t}}$$

Investment cost (red arrow pointing to I_t)
 Operation and maintenance (yellow arrow pointing to $O\&M_t$)
 Fuel (green arrow pointing to F_t)
 Carbon Emission allowance (blue arrow pointing to C_t)
 Decommissioning (dark blue arrow pointing to D_t)
 Discount rate (red arrow pointing to $(1-r)^{-t}$)
 Electricity produced (purple arrow pointing to E_t)

THE CHEAPER WILL BE THE ELECTRICITY FROM FUSION, THE GREATER DEPLOYMENT OF FUSION POWER PLANTS IS LIKELY TO OCCUR.

The fusion technology in EFDA TIMES.

- Technical and economical data are taken from the **European Power Plant Conceptual Study (PPCS)**, developed in 2005 in order to outline the features of commercial power plants.

| | Year | Overnight | Efficiency | Fix O&M | Var O&M | AF | Life |
|-----------------------|------|-----------|------------|---------|---------|----|------|
| | | cost | % | cost | cost | % | |
| | | \$/KW | | M\$/GWa | M\$/PJ | | |
| Basic plant | 2050 | 3940 | 42 | 65.8 | 2.16 | 85 | 40 |
| | 2060 | 2950 | 42 | 65.8 | 1.64 | 85 | 40 |
| Advanced plant | 2070 | 2820 | 60 | 65.3 | 2.14 | 85 | 40 |
| | 2080 | 2170 | 60 | 65.3 | 1.64 | 85 | 40 |

*costs are in year 2000 US \$

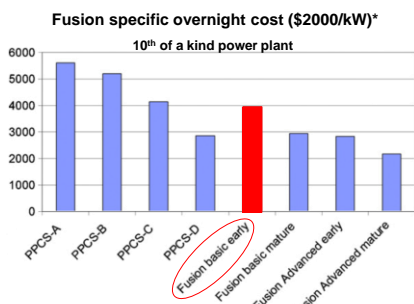
- Given the high number of uncertainties affecting this technology, **these values** can't be managed as forecasts but **just as estimations**.
- Moreover, special attention should be paid to overnight an investment costs, technological life and availability factor which have a great impact on the LCOE.

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Fusion is a «capital intensive» technology.

- The **overnight cost** (\$/kW) is the cost of a construction project if no interest was incurred during construction, as if the project was complete overnight”.
- The **assumed** overnight cost of an early fusion technology in **2050**, looks to be in line with that of new fission power plants (Gen III+ and Gen IV).
- In the new version of ETM a **5 year lead time** is optimistically assumed for all nuclear technologies.



*W.E. Han, D.J. Ward / Fusion Engineering and Design 84 (2009) 895–898

Overnight cost of technologies available in 2050 in ETM

| | Overnight cost | Lead time |
|------------------------|----------------|-----------|
| | \$2000/kW | years |
| Nuclear Fission | 2400-3400 | 5 |
| USC coal | 1400 | 4 |
| IGCC + CCS | 2200 | 4 |
| NGCC | 700 | 2 |
| Onshore wind | 980 | 1 |
| Offshore wind | 1800 | 1 |
| Solar PV | 1800 | 1 |

NOTE: Costs are derived from a number of literature sources (for more details see EFDA reports, WP11)

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Expenditures included in the Investment Cost.

- **Direct Costs:**
 - Structure and site facilities
 - reactor components (first wall, blanket, shield, divertor etc)
 - Power plant components (turbine plant equipment, electric plant equipment, energy storage system etc...)
- **Indirect costs**

“expenses resulting from the support activities required to accomplish direct cost activities. They include Engineering Procurement Construction (EPC) costs, owner’s costs (land, cooling infrastructure, administration and associated buildings, site works, switchyards, project management, licences, etc) and contingency cost, which is generally intended to compensate for uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology.”
- **Interest During Construction**

function of the lead time, of the cumulative expenditure pattern (usually S-shaped), of debt to equity ratio, of debt and equity rates, of taxes and inflation rate.

The uncertainties on fusion Investment Cost.

- **Financial issues.**

Being fusion a capital intensive technology, it needs founding. The financial rules of the country where the power plant is built affects the Interest During Construction (IDC) amount and thus the Investment Cost which leads the LCOE.
- **Lead time.**

The lead time is quite difficult to forecast especially in case of first-of-a-kind power plant (see as example the EPR construction in Europe). It also largely affects the IDC and thus the final Investment cost.
- **Cost of materials.**

The cost escalation of raw materials already experienced with ITER could affect the Investment Cost estimation of a FPP.

The uncertainties on fusion investment cost.

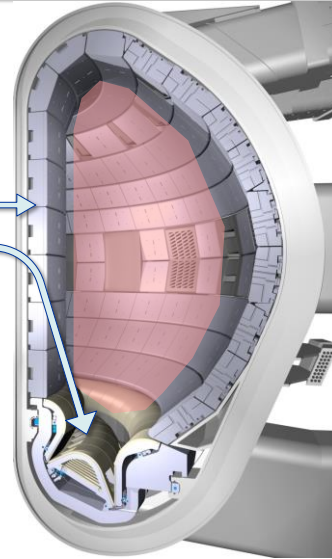
- **Learning factor.**

As much higher experience is acquired in producing specific components, as much lower is the production cost. For this reason the 10th of a kind is likely to be cheaper than the first. But how much cheaper?

- **Replaceable components.**

- How long will be the life of blanket and divertor?
 - How much time will be needed to replace them?
- These aspects largely affects the power plant availability factor.

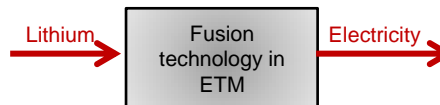
THE LOWER IS THE POWER PLANT AVAILABILITY FACTOR (HOURS OF OPERATION/ HOURS IN A YEAR) , THE LOWER IS THE ANNUAL ELECTRICITY PRODUCTION AND THUS THE HIGHER IS THE COST OF ELECTRICITY.



How much the cost of fuel affects the cost of electricity?

- Similarly to fission, the cost of fuel has not a large impact on the cost of electricity:

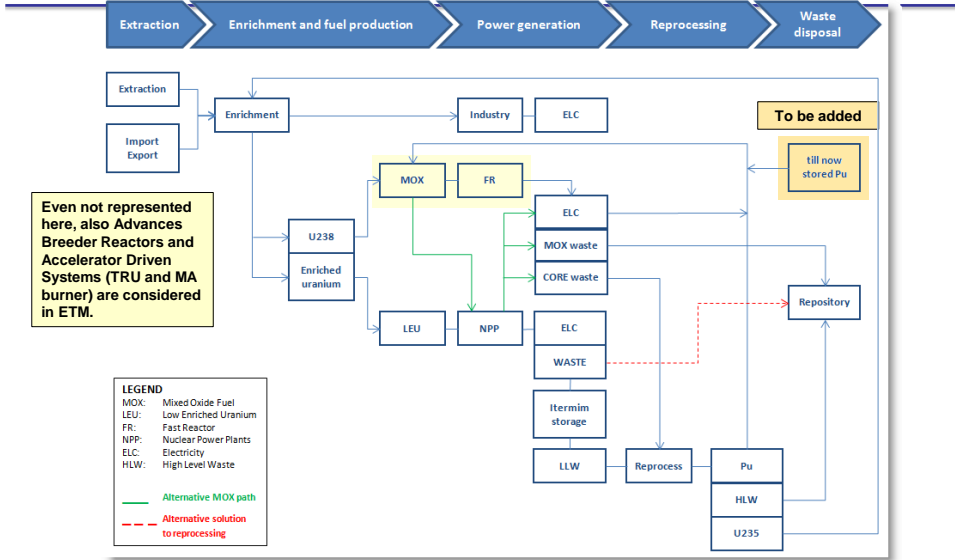
- ~ 70% Cost of capital
- ~ 3% O&M
- ~ 25% BLK and DV replacement
- ~ 1% Fuel
- < 1% Decommissioning



- A *simplified* nuclear fusion fuel cycle is modelled in ETM. Lithium is assumed to be the only fuel and its cost includes both the extraction and enrichment costs. The power plant is also assumed to be tritium self-sufficient (the initial supply coming from another running fusion power plant).

NOTE: On the contrary, the *complete* nuclear fuel cycle of fission power plants (production, reprocessing and spent fuel disposal) has been modelled in ETM being it the peculiarity of Gen IV reactors.

For comparison: the processes implemented in the ETM fission fuel cycle.

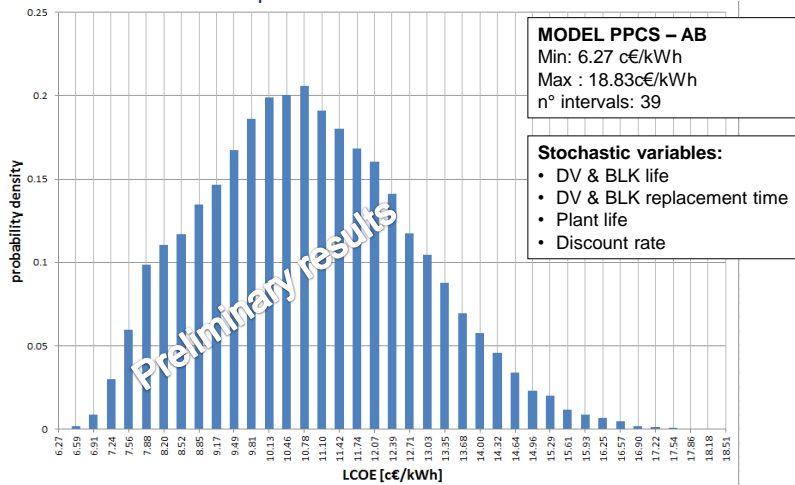


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How to face uncertainties in fusion parameters?

- Preliminary results of a Monte Carlo analysis performed with **FRESCO** code in order to evaluate the impact of uncertainties on the **LCOE**:



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From MC analyses to ETM scenarios and vice-versa.

- The **Monte Carlo analyses** allows to estimate which is the most probable range of values of specific power plant economic parameters (investment costs, cost of electricity...)
- Through the **scenarios analysis**, generated by ETM, the conditions under which fusion is competitive in a future energy market can be deduced. These are specific combinations of environmental constraints and availability of new cheap and carbon-free electricity generating technologies.

Conclusions.

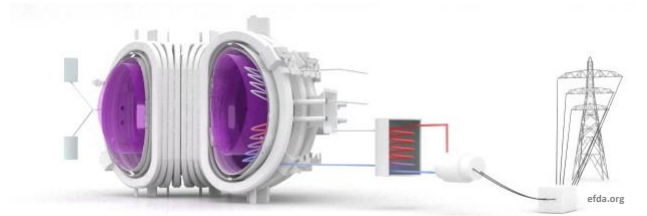
Merging these information we can assess:

If the power plant model under study might have chances to have a weight in a future energy market.

Or, from another point of view:

Which are the features of the power plant to be modified or the economic conditions to be ensured in order to make the fusion technology competitive.

Thank you!
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