Impact of Physics on Power Plant Design and Economics

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Outline

- Setting the scene
- Cost of electricity from fusion
- Materials requirements
- Final remarks

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Why Do We Study Economics of Fusion?

- Fusion has major resource, environment and safety benefits as a new energy source. We must also check it can have a market share by looking at costs and comparing with energy markets.

Commonly Expressed False Views

- “We don’t know the details of a fusion power plant so we cannot say anything about the cost”
- “We can evaluate a detailed conceptual design and derive a precise cost of electricity”

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Setting the Scene

- World electricity market
- Future markets
- Discounting
- Technological learning

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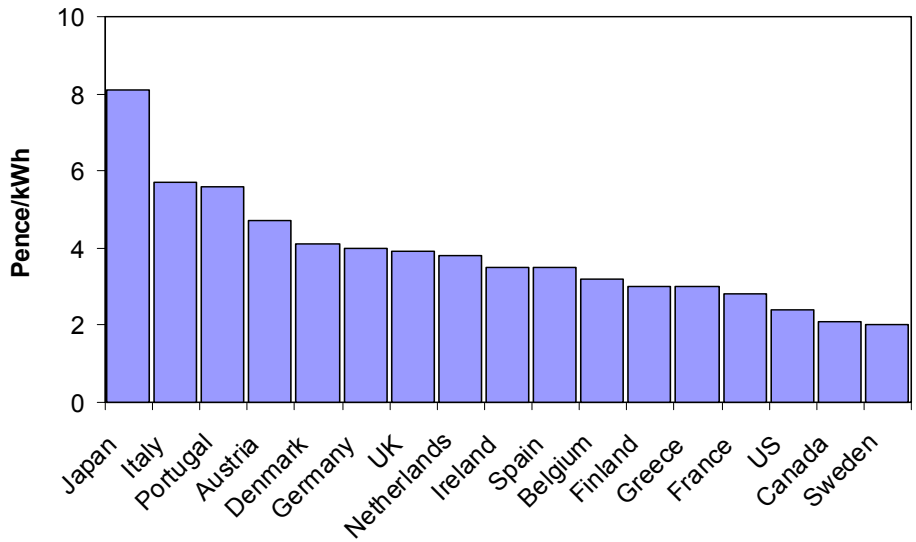
Large Variation in World-Wide Electricity Prices



UK Energy Sector Indicators 1999, DTI

Variations due to different technologies, different prices of raw materials and labour, different market conditions...

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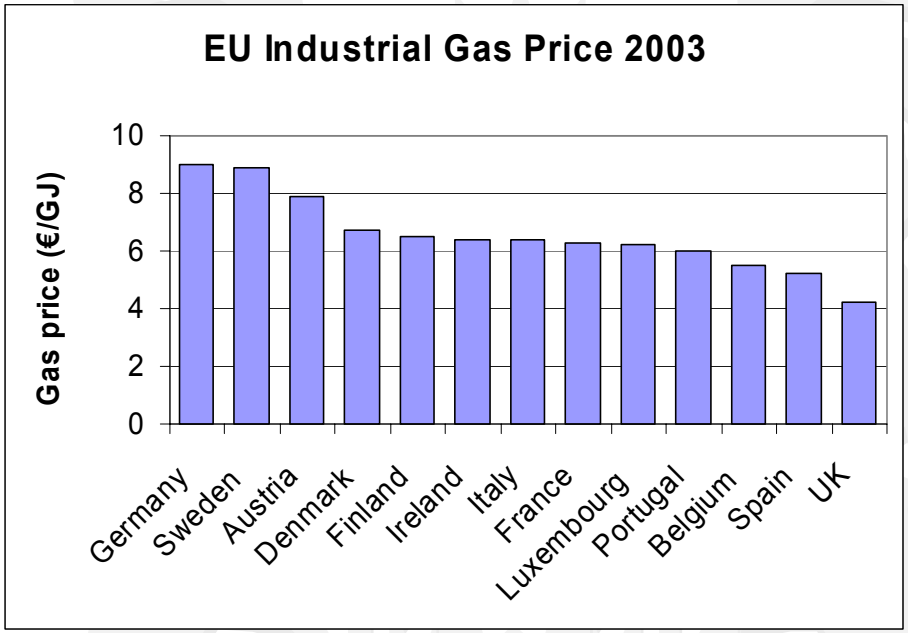
Fuel Prices Can Vary Substantially



These should be seen as cautions against over-simplified economic arguments.

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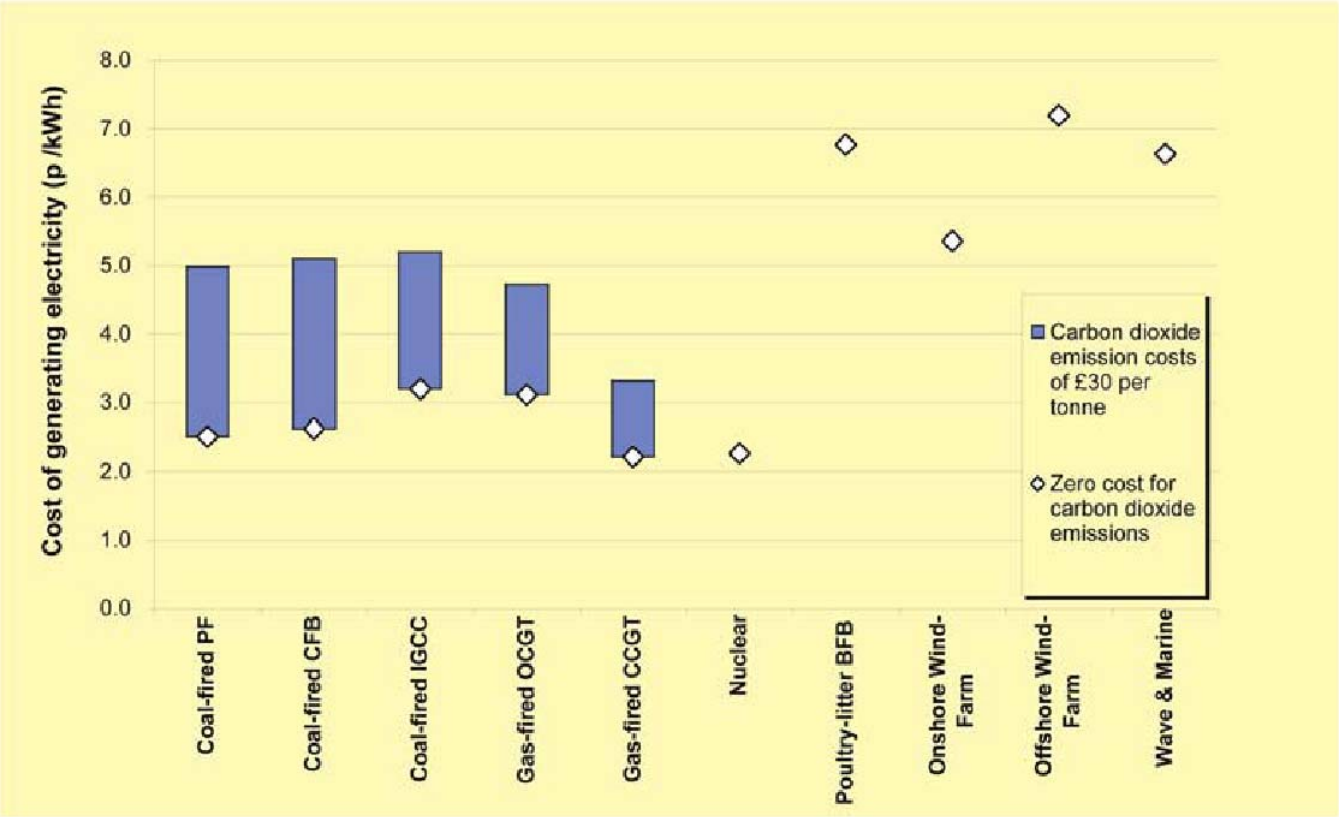
UK Electricity Costs (Royal Academy of Engineering)



Bars show increase if CO_2 cost £30/tonne
Range is 2-7 p/kWh or 3-11€cents/kWh

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How Might the Energy Market Evolve in the Future?

- Modelling carried out for the UK Energy White Paper shows marginal cost of avoiding carbon emissions to be enormous by 2050. The implication is for substantial price increases to the end user.

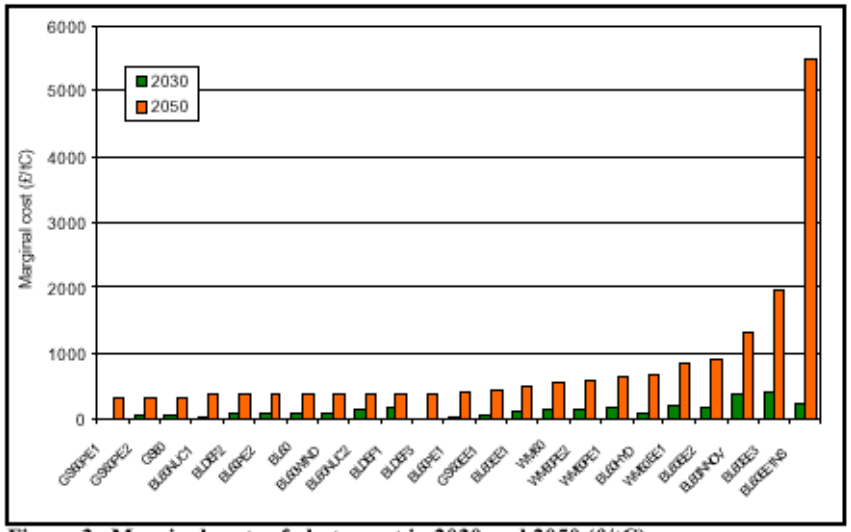

Figure 3 Marginal costs of abatement in 2030 and 2050 (£/tC)

AEAT

Example of information from scenario modelling of future energy markets under CO_2 constrained future (UK Energy White Paper)

Implies large additional costs in electricity market.

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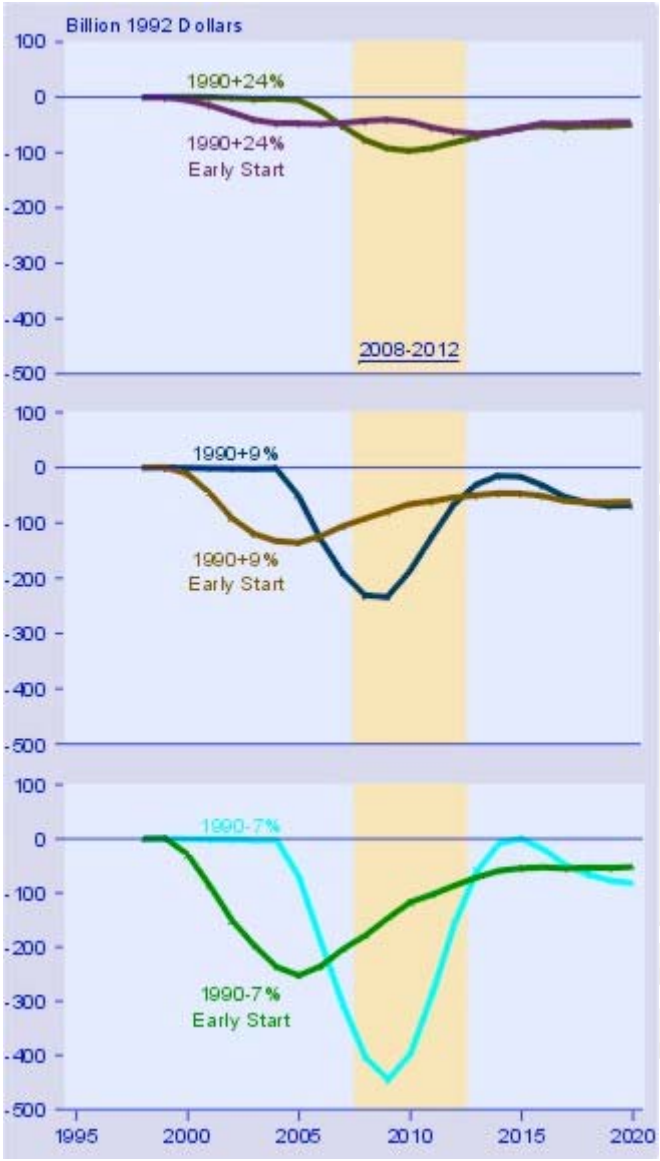
US Kyoto Costs - Is 1B$ a lot of money?



Source:US DOE

Conforming to Kyoto targets projected to cost the US 200-400B$ per year.

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Discounting

- Discounting is a crucial part of an economic analysis
- It captures the fact that individuals or society prefer benefits now rather than in the future; the discount rate tells us how much they prefer them. “How much would you pay today to earn 1€ next year?” Nothing to do with inflation.
- The discount rate captures catastrophic risk, pure impatience, the reducing value of benefits as the average standard of living increases etc.
- For public funding, discount rates of around 5% real are typical (UK 3.5%). For private funding, discount rates of 10% or above are typical.
- Long term discount rates are lower than short term.

Levelised Cost of Electricity Approach (IEA)

- IEA approach recommended for international comparisons.
- All future expenditures and incomes determined, capital, O&M, replacements, fuel and decommissioning charge, electricity sales.
- All discounted to present day (date of first operation)
- Equate discounted costs to discounted incomes.
- All calculations in real terms.

$$coe = \frac{\sum_t (C_t + OM_t + F_t + R_t + D_t)(1+r)^{-t}}{\sum_t E_t (1+r)^{-t}}$$

  - C capital, OM operation and maintenance, F fuel, R replaceable component costs, D decommissioning and waste costs, E annual generation of electricity, r discount rate

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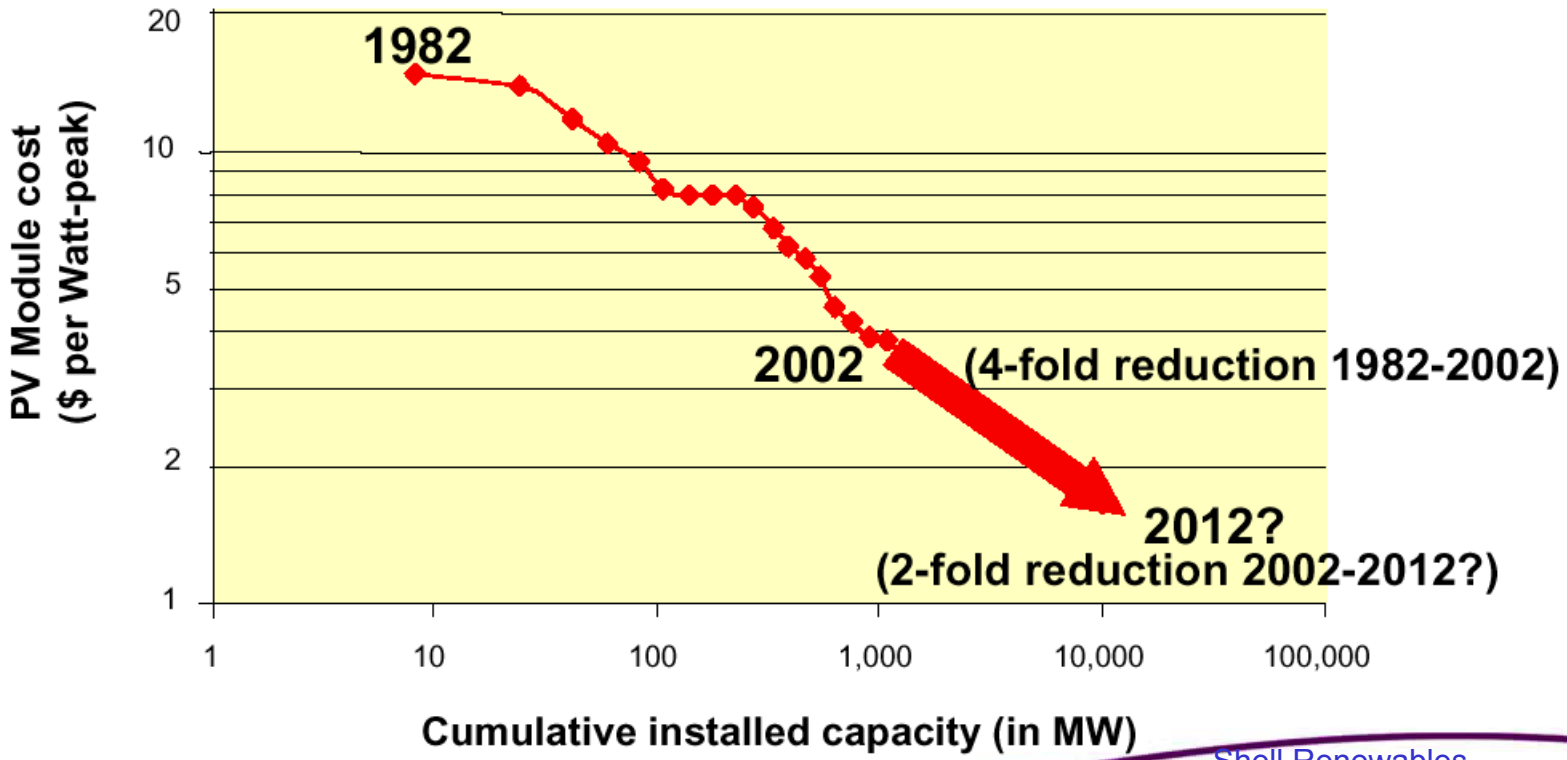
Technological Learning Reduces Costs Through Experience

20% reduction in cost for every doubling of installed capacity (~ 3 years at 25% annual growth)



Shell Renewables

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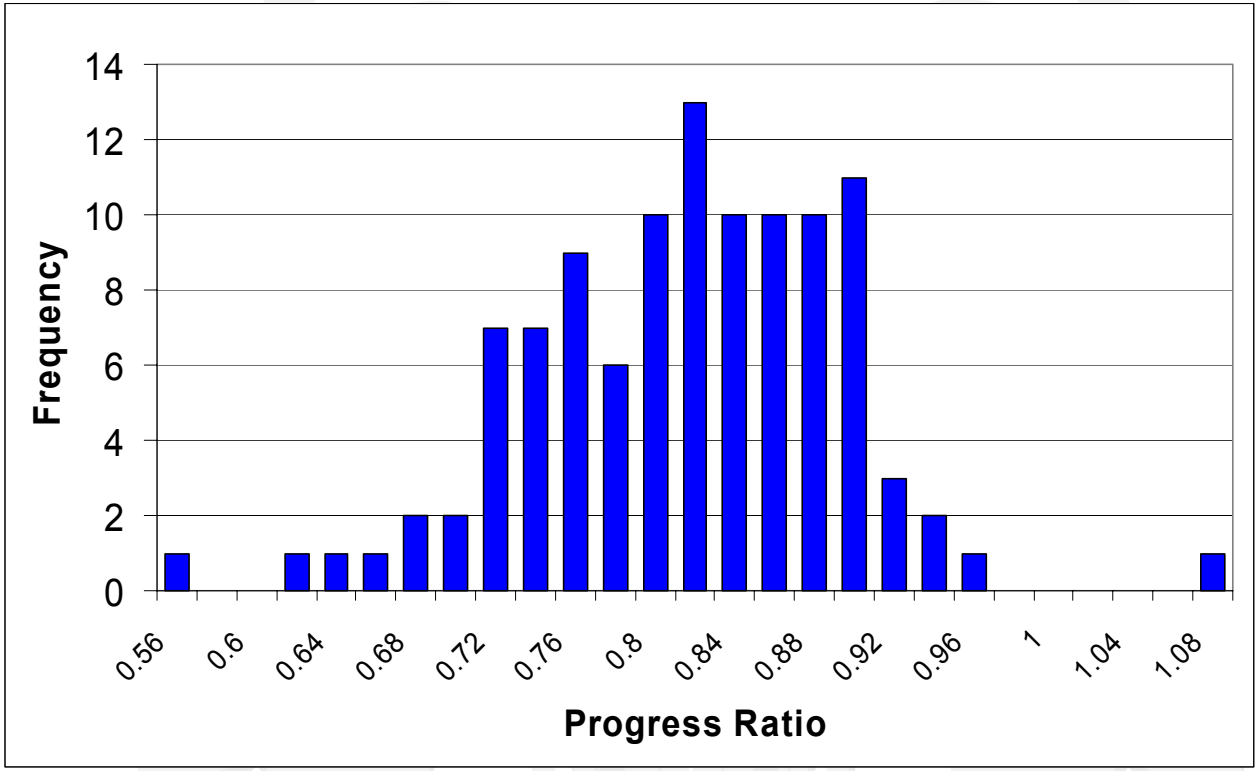
Progress Ratios Across Technologies



Dutton and Thomas 1984

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Cost of Electricity from Fusion

- System studies
- Cost breakdown
- ITER-based example
- General study
- Specific design points (EU Power Plant Conceptual Study)

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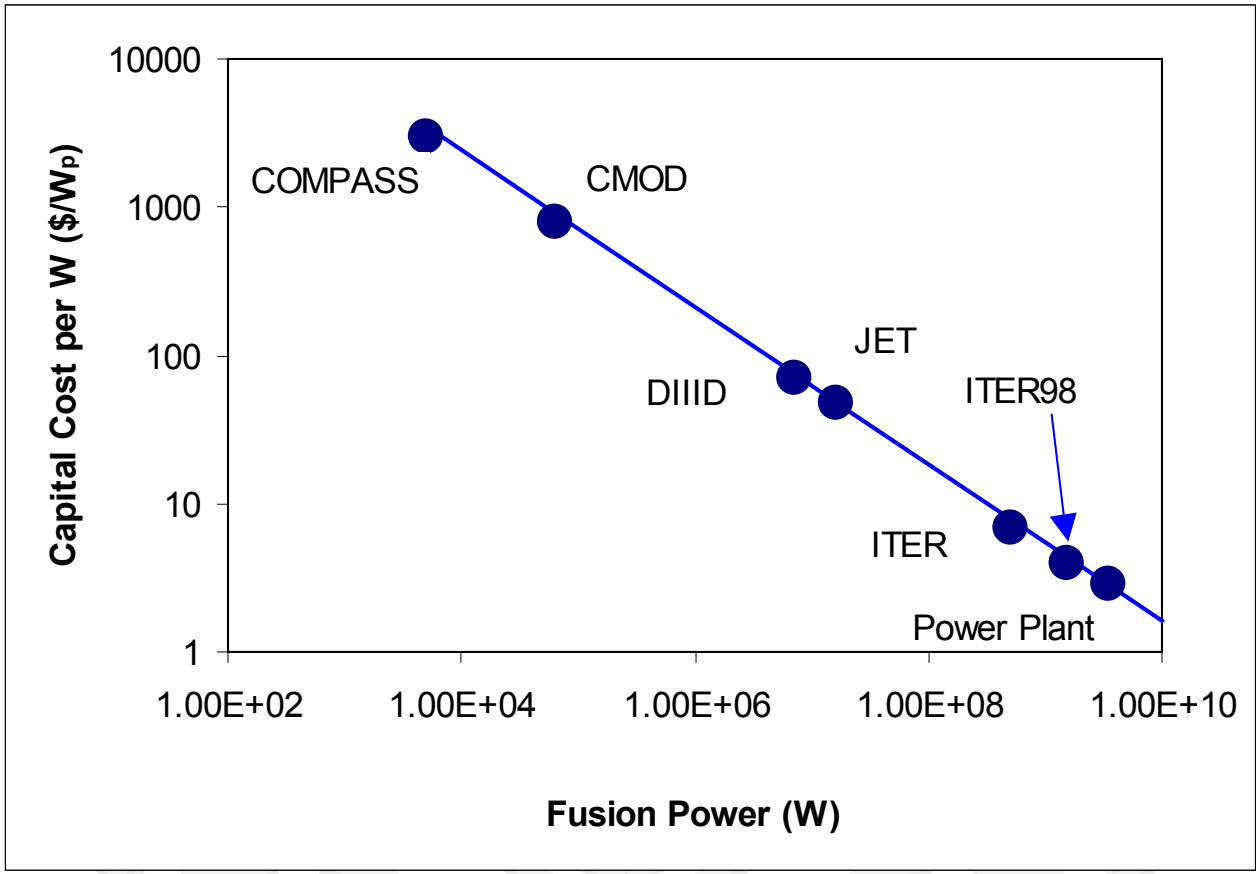
Systems Studies Underlie all That Follows

- A systems code, PROCESS, uses models of all the major systems to put together a conceptual power plant design. Costing algorithms are then used to determine the cost of each system.
- Economic assumptions then crucial in turning this into cost of electricity.

Specific Cost of One-Off Devices



Power which would be produced if non-DT devices were to use DT

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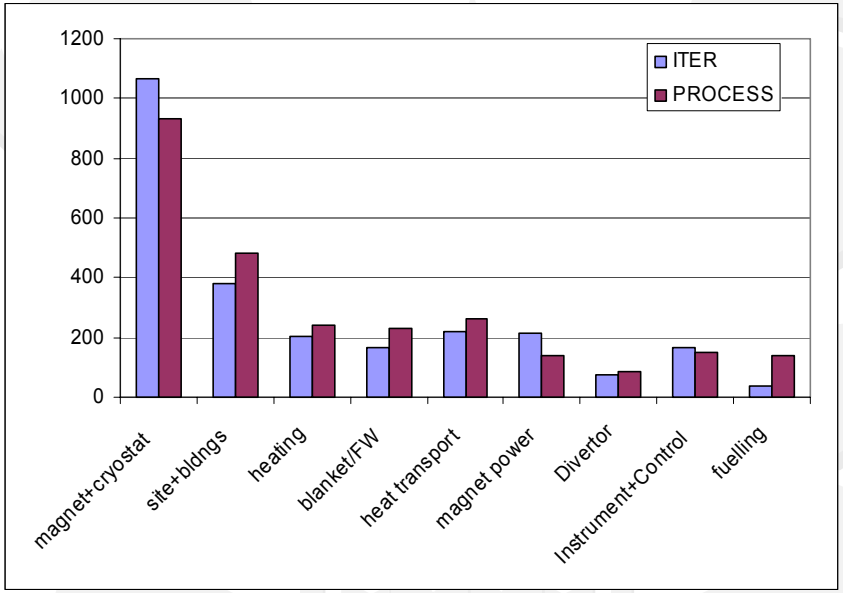
Comparison of ITER costs with Predictions from PROCESS



Broad brush comparison.
Dimensions could be refined further to more closely reproduce the ITER design

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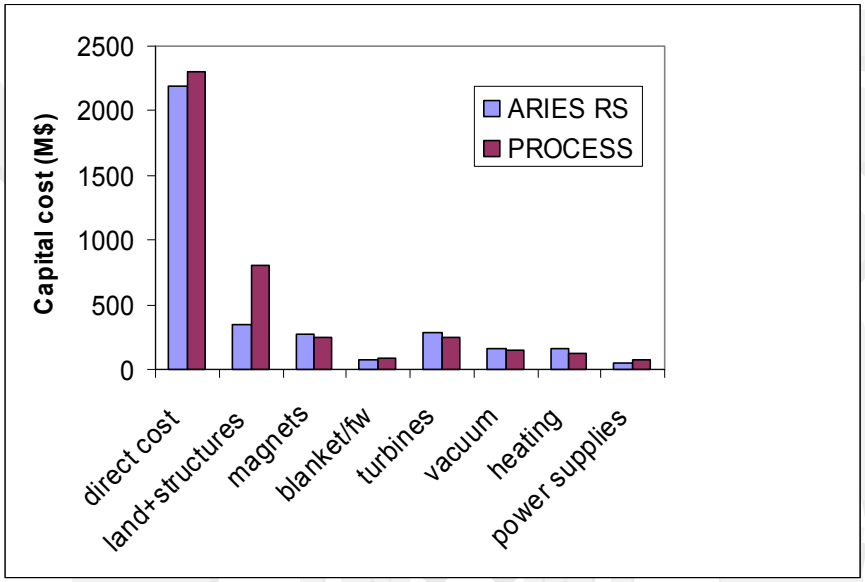
Comparison Between EU and US Studies



Given the same assumptions, cost assessments are broadly similar across the Atlantic

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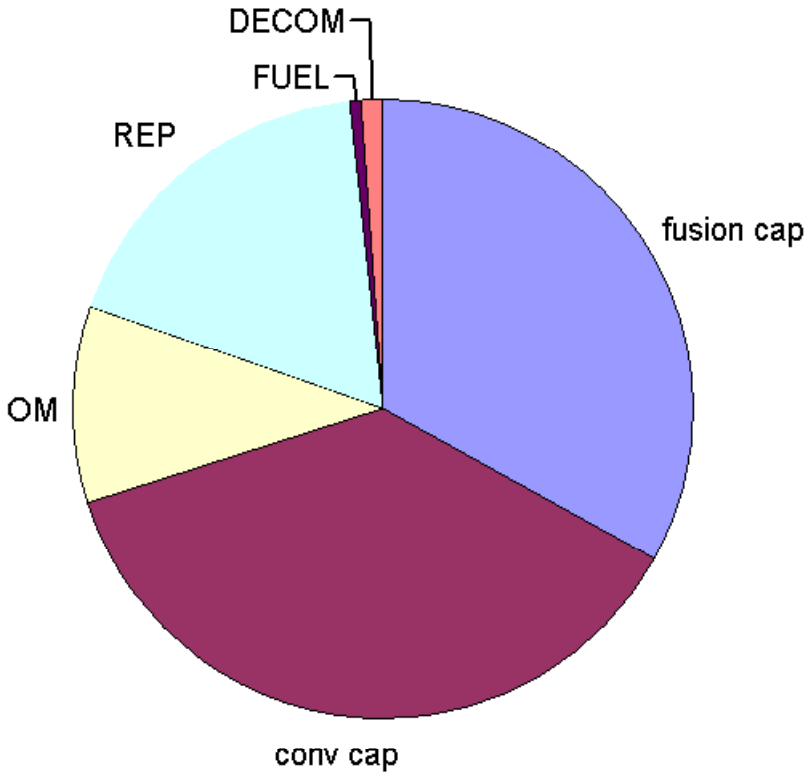
Contributions to Cost of Electricity



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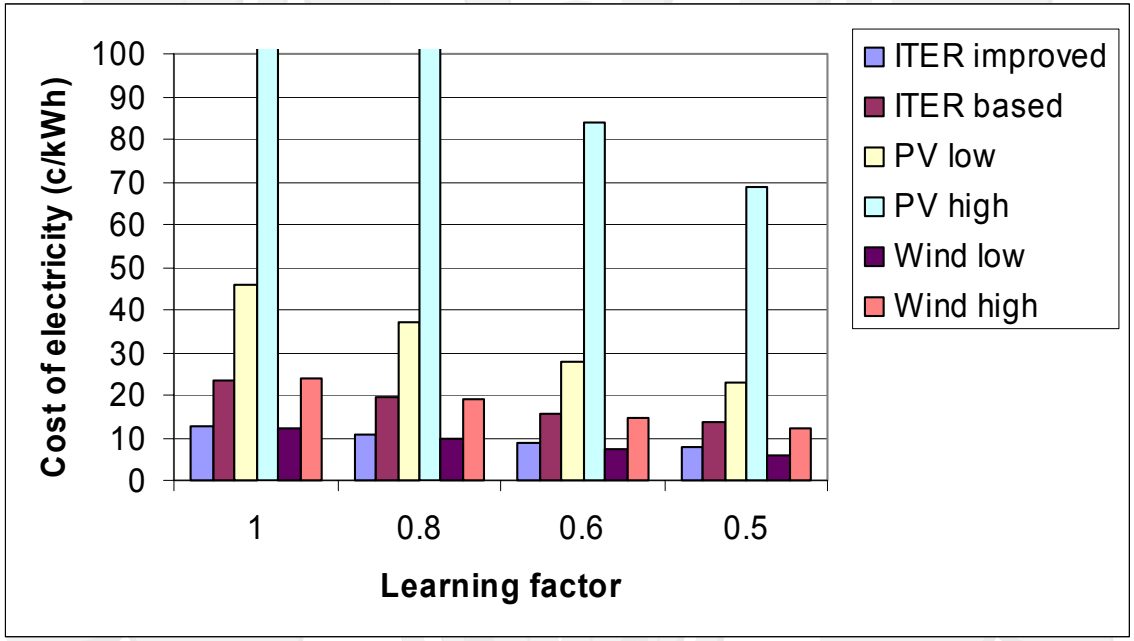
An ITER-based Fusion Power Plant Would Produce Electricity at less than PV and around Wind Power Costs



For wind and PV, the upper value allows for storage.
For fusion the range is from the ITER operating point up to β_N=3.4

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General Study of Costs:How Can We Study the Effect of Different Parameters on COE?

Variable	Minimum	Mean	Maximum
Discount Rate (%)	5	7.5	10
10th of a kind factor	.5	.6	.7
Unit Size (GW)	1	1.7	2.5
β_N	2.5	4	5.5
Limiting density N_G	0.7	1	1.4
η_{th}	0.35	0.48	0.6
Availability	0.6	0.7	0.8

Assume a range of key parameters, design power plants that encompass the range, then look at how costs vary.

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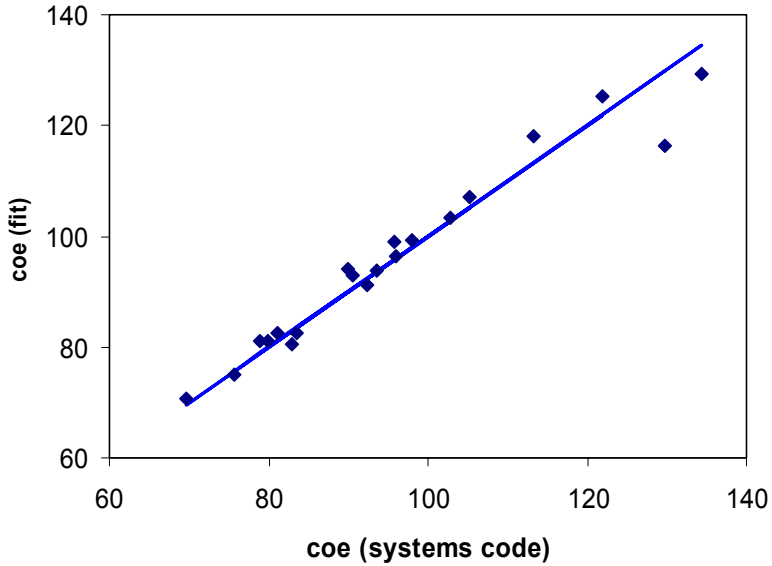
Derive a Scaling Law for Cost of Electricity



Order of Merit:

- Learning
- discount rate
- availability
- efficiency
- unit size
- β_N
- density limit

$$coe \propto \left(\frac{DF}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}}$$

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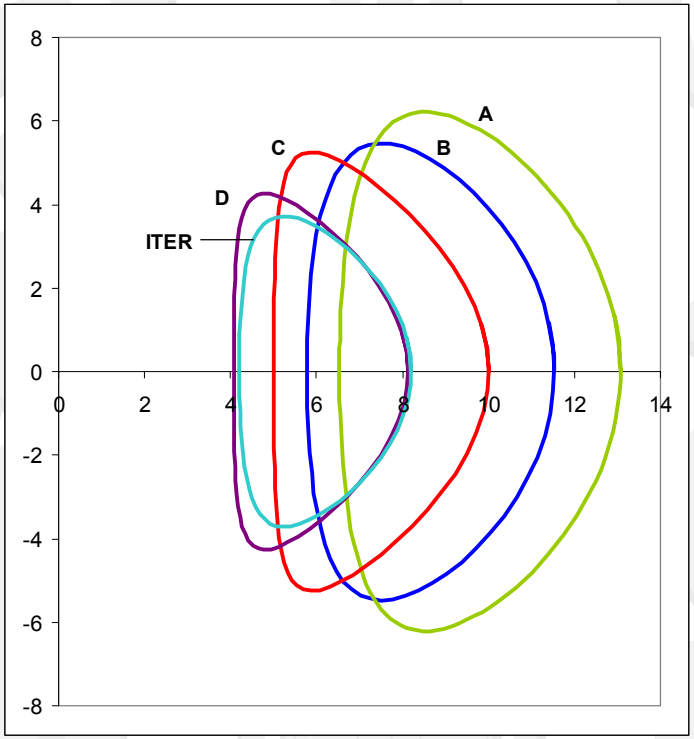
Power Plant Conceptual Study: Specific Studies of Costs:



Power Plant Conceptual Study will be discussed in more detail in later talks

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Plant Model Technologies

- A: Water cooled, steel plant (efficiency 35%)
- B: helium cooled pebble bed (efficiency >40%)
- C: Dual cooled (He and LiPb) steel with SiC/SiC inserts
- D: SiC/SiC LiPb cooled. (efficiency >50%)
- These will be described in much more detail in talks throughout the Course.

Plant Parameters for PPCS

Parameter	Model A	Model B	Model C	Model D
Unit Size (GW_e)	**1.5**	**1.5**	**1.5**	**1.5**
Blanket Gain	1.18	1.39	1.17	1.17
Net Conversion efficiency	0.35	0.405	0.44	0.59
Fusion Power (GW)	5.0	3.6	3.4	2.5
Aspect Ratio	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.25	0.47	0.47
Major Radius (m)	**9.55**	**8.6**	**7.5**	**6.1**
TF on axis (T)	7.0	6.9	6.0	5.6
TF on the TF coil conductor (T)	13.1	13.2	13.6	13.4
Plasma Current (MA)	**30.5**	**28.0**	**20.1**	**14.1**
β_N(thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Average Temperature (keV)	22	20	16	12
Temperature peaking factor	1.5	1.5	1.5	1.5
Average Density ($10^{20}m^{-3}$)	1.1	1.2	1.2	1.4
Density peaking factor	0.3	0.3	0.5	0.5
H_H (IPB98y2)	1.2	1.2	1.3	1.2
Bootstrap Fraction	0.45	0.43	0.63	0.76
P_{add} (MW)	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Q	20	13.5	30	35
Recirculating power fraction	0.28	0.27	0.13	0.11
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor Peak load (MW/m^{-2})	15	10	10	5
Zeff	2.5	2.7	2.2	1.6

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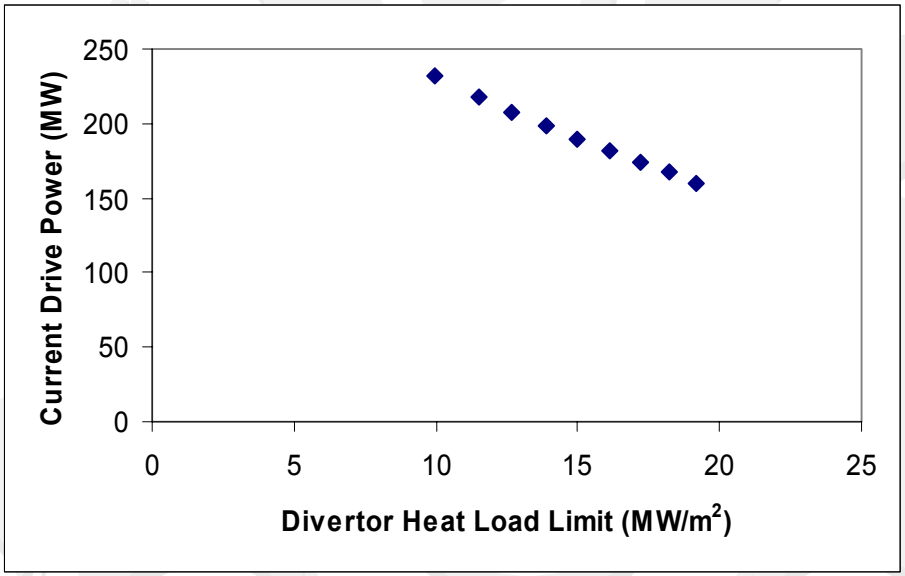
Example of Interesting Physics

To protect the divertor, must radiate power away

More radiation implies a need for higher confinement

The associated higher plasma current needs higher current drive power



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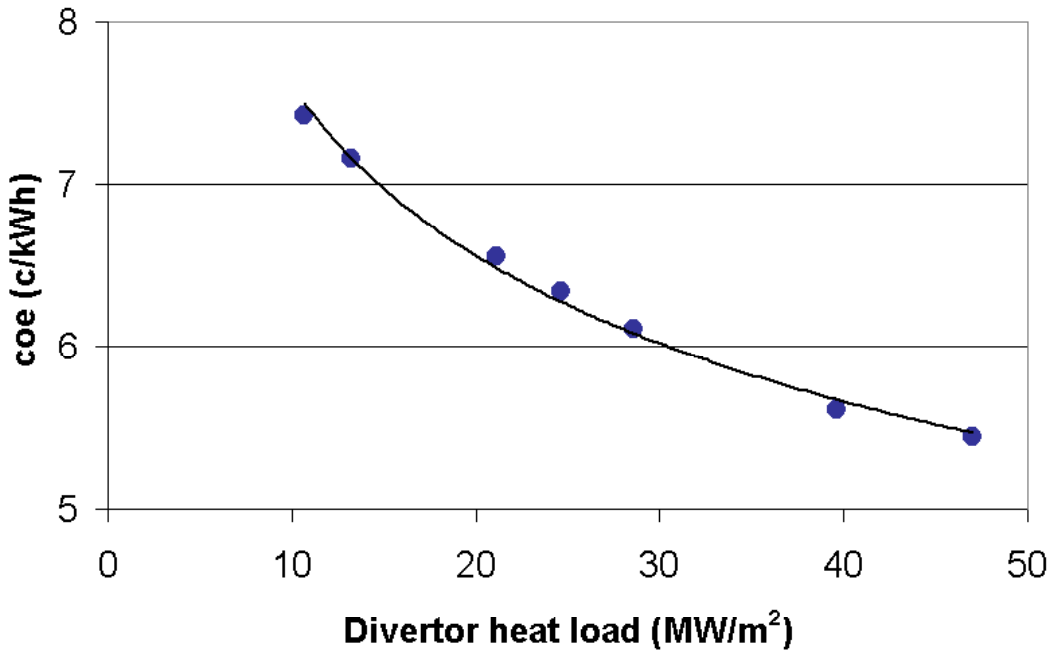
Divertor Heat Load Can be Crucial



Assumes an otherwise fixed power plant concept

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Where Do the Main Costs Lie?

- Model B:
  - Specific capital costs 5.3$/W (65% learning) 4.6$/W (50% learning)

Magnets	33%
Site and buildings	22%
Heating	11%
First wall/Blanket	5.5%
Divertor	2.5%

  - Target set at start of PPCS was 2.5-6$/W so Model B lies in the middle/upper area of this range.

Cost of Electricity (€ 2000)

- Model B:10th of a kind
  - 8.1 €cents/kWh (50% learning)
  - 9.6 €cents/kWh (65% learning)

Capital	70%
Divertor replacement	11%
O+M	10%
Blanket/FW replacement	6%
Decommissioning	0.6%

  - Divertor replacement costs are substantial.

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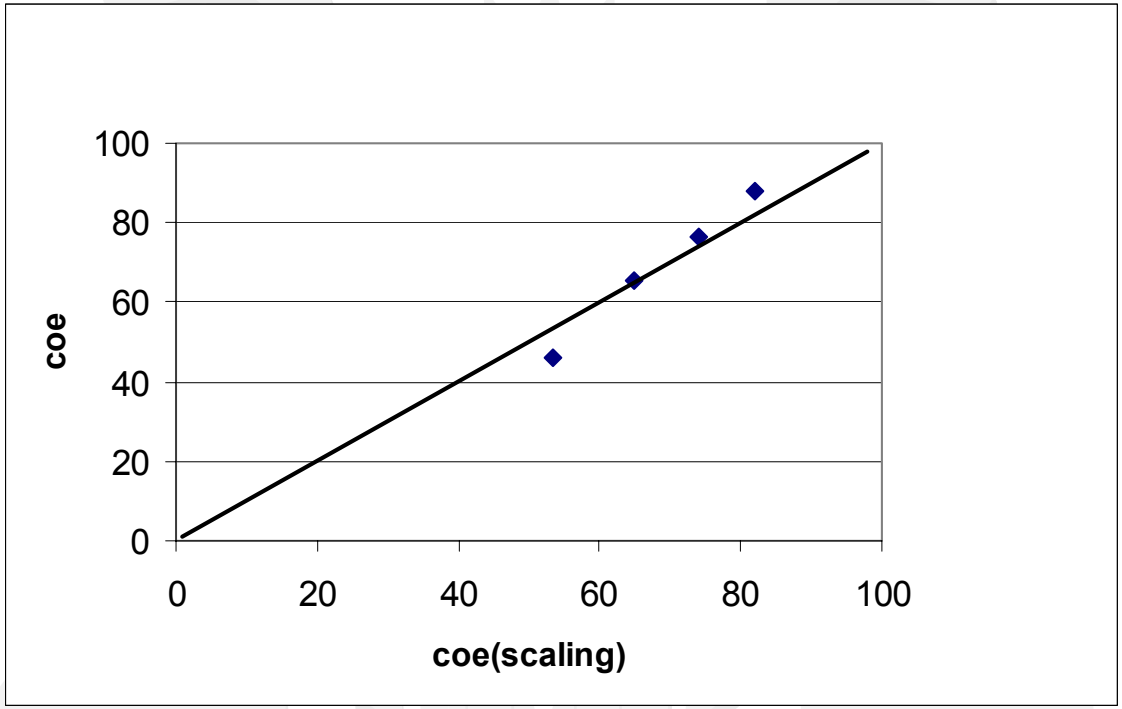
Specific Compared to General Cost Study



IAEA Conference Sorrento 2000

$$coe \propto \left(\frac{DF}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}}$$

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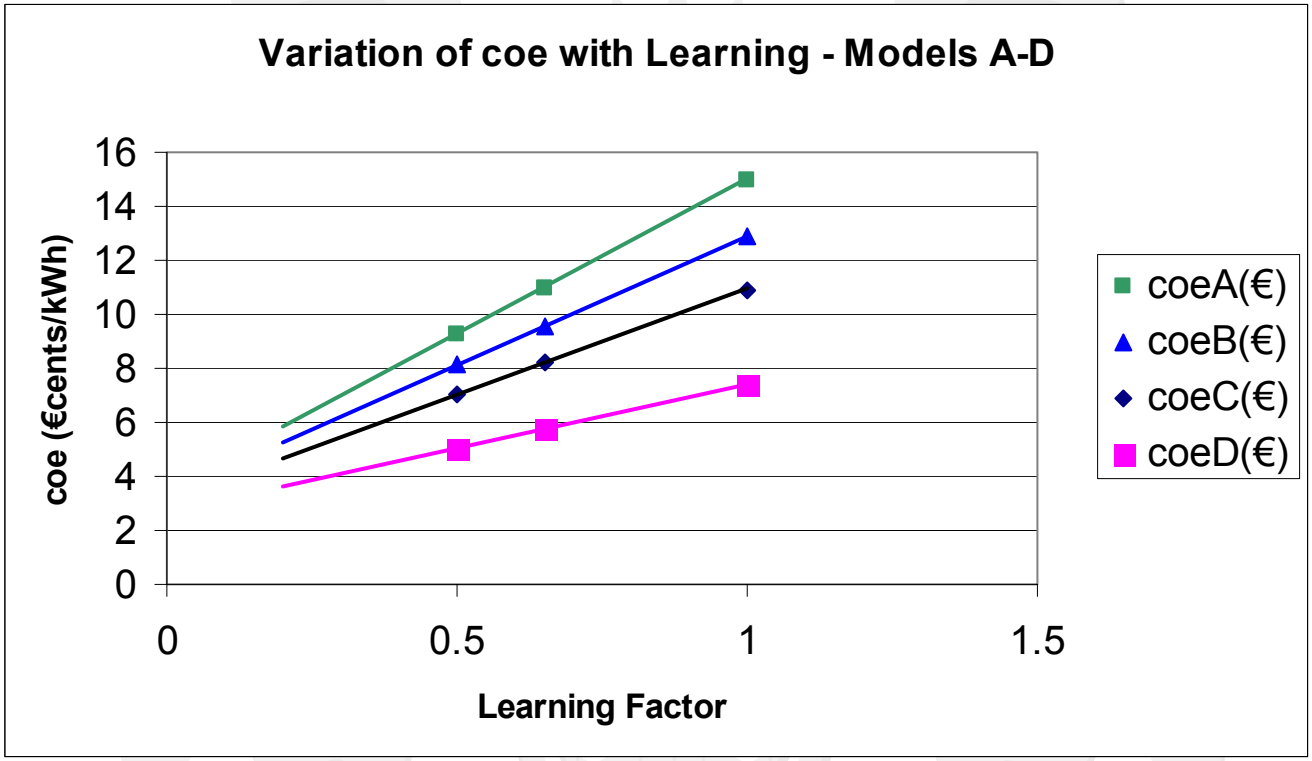
Learning Factor Important Part of Cost of Electricity



This assumes learning effects only applied to fusion-specific components. Early generations 5-10c/kWh
Mature technology 3-6c/kWh

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Materials Requirements

- Blanket
- Divertor

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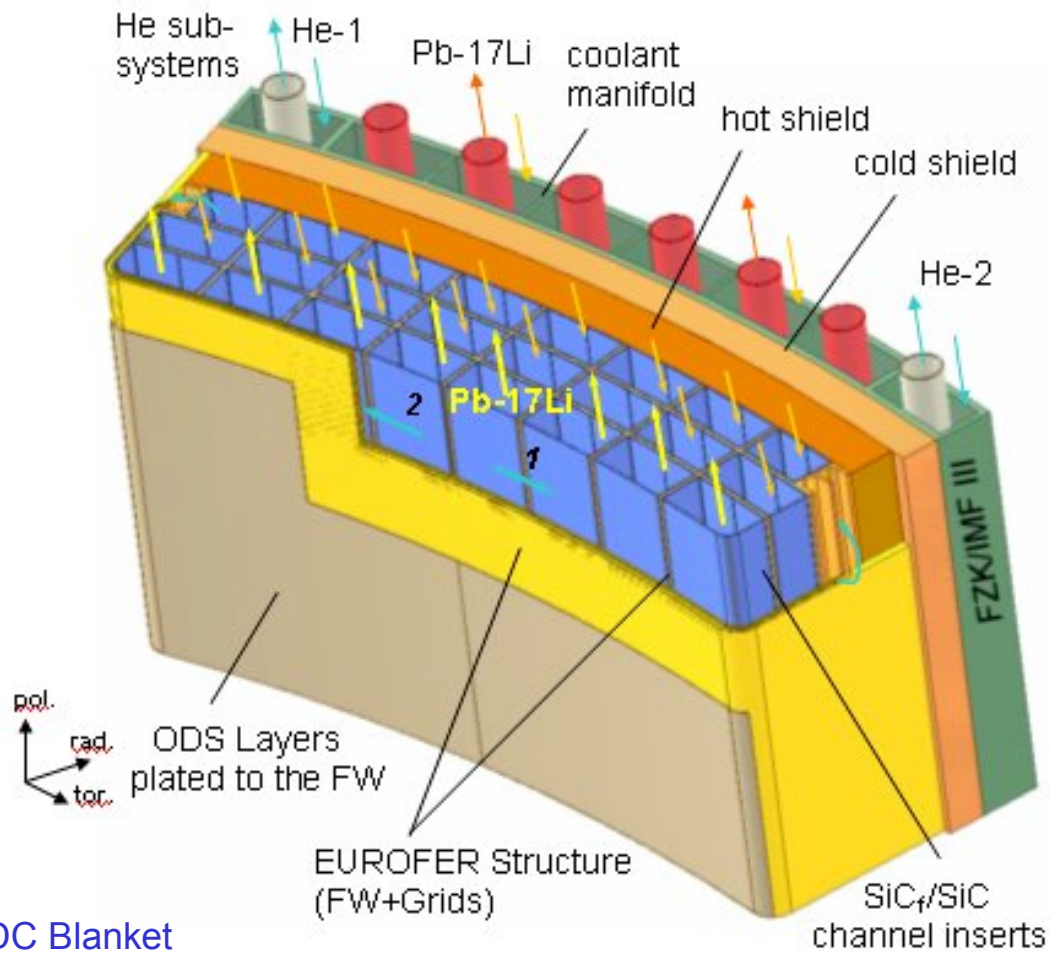
Blanket



FZK DC Blanket
(PPCS Model C)

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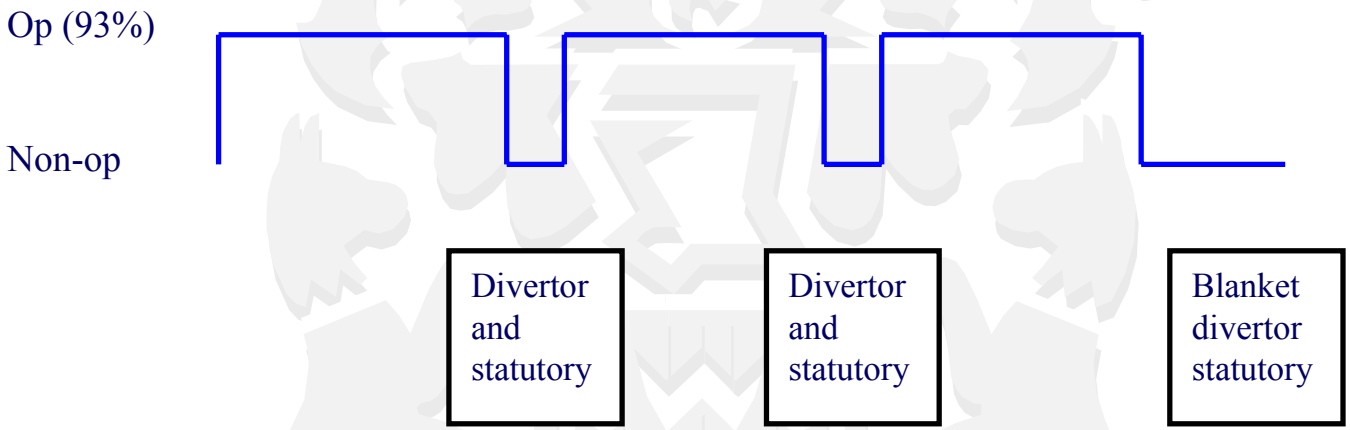
Maintenance Schedule



Sherwood et al, NNC

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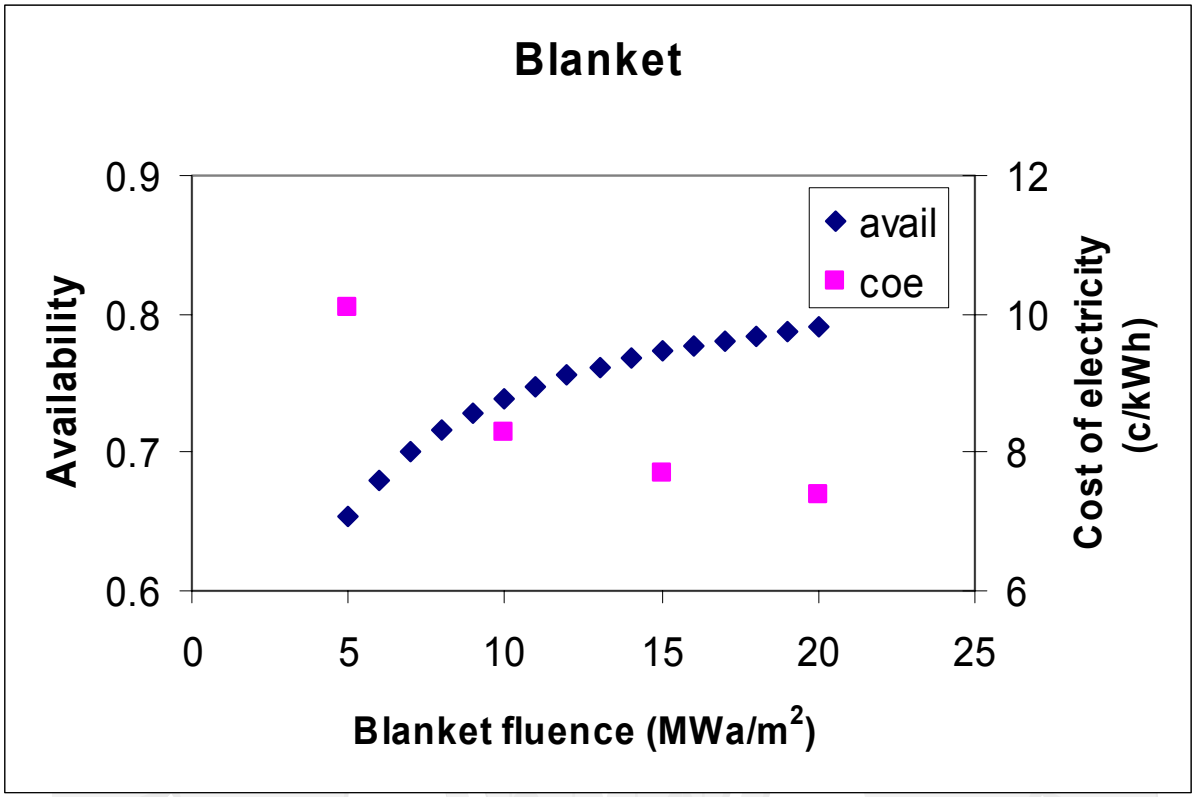
What are the Demands of the Blanket?



<5MWa/m^2 is not enough, 10-20 desirable
(1MWa/m^2 equivalent to 10 dpa)
If materials could only tolerate 5MWa/m^2, what could be done? Reduce replacement time.

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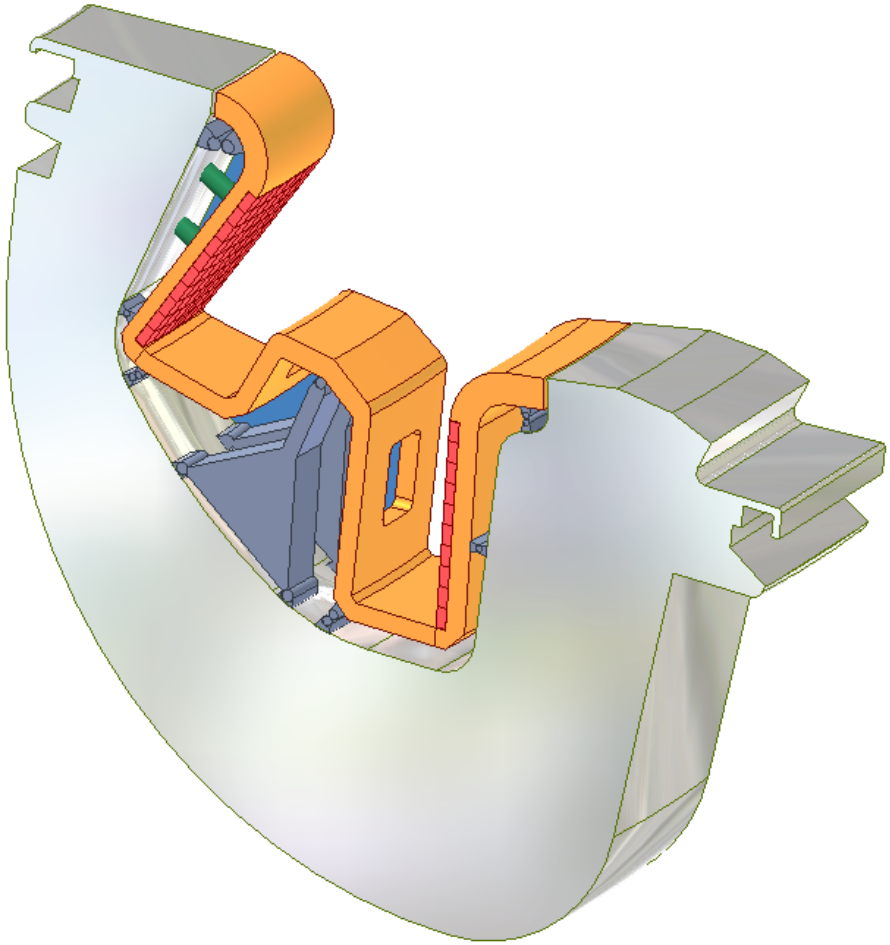
Divertor



FZK Model C
Tungsten and
Eurofer

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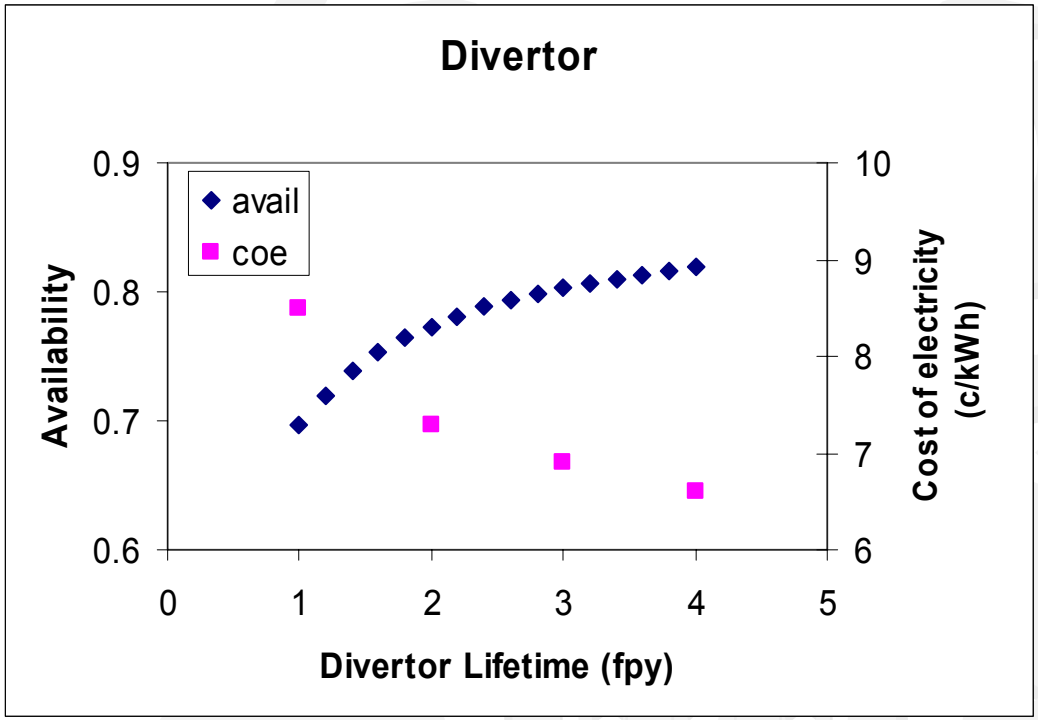
Divertor Lifetime is Very Important



(May be discontinuous if statutory inspections included)

Materials issues are at least as important as for the blanket. Erosion, from power handling, is expected to be the biggest problem.

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Final Remarks

- External costs
- Comparison with cost projections

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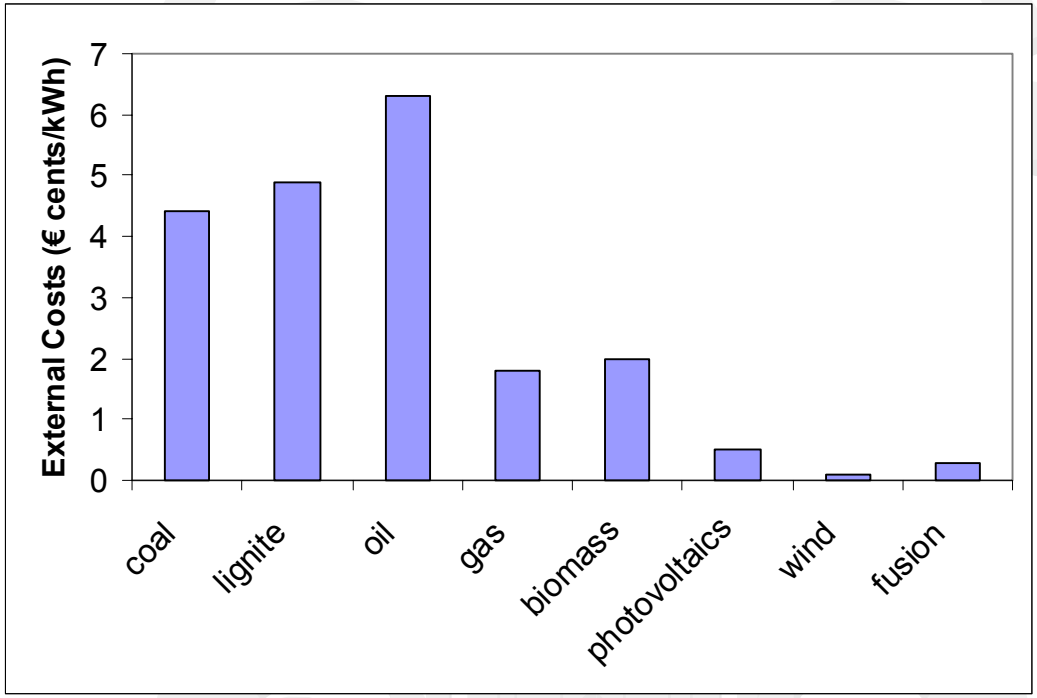
External Costs

- External costs are those not paid directly by the consumer.
- Particular examples are health effects due to atmospheric pollution, accidents during construction or operation etc.
- Fusion expected to perform well because of low atmospheric emissions.

External Costs of Electricity Generation



Although implied precision is misleading, fusion belongs to the group of technologies with low external costs.

Cabal et al EPS (1999)

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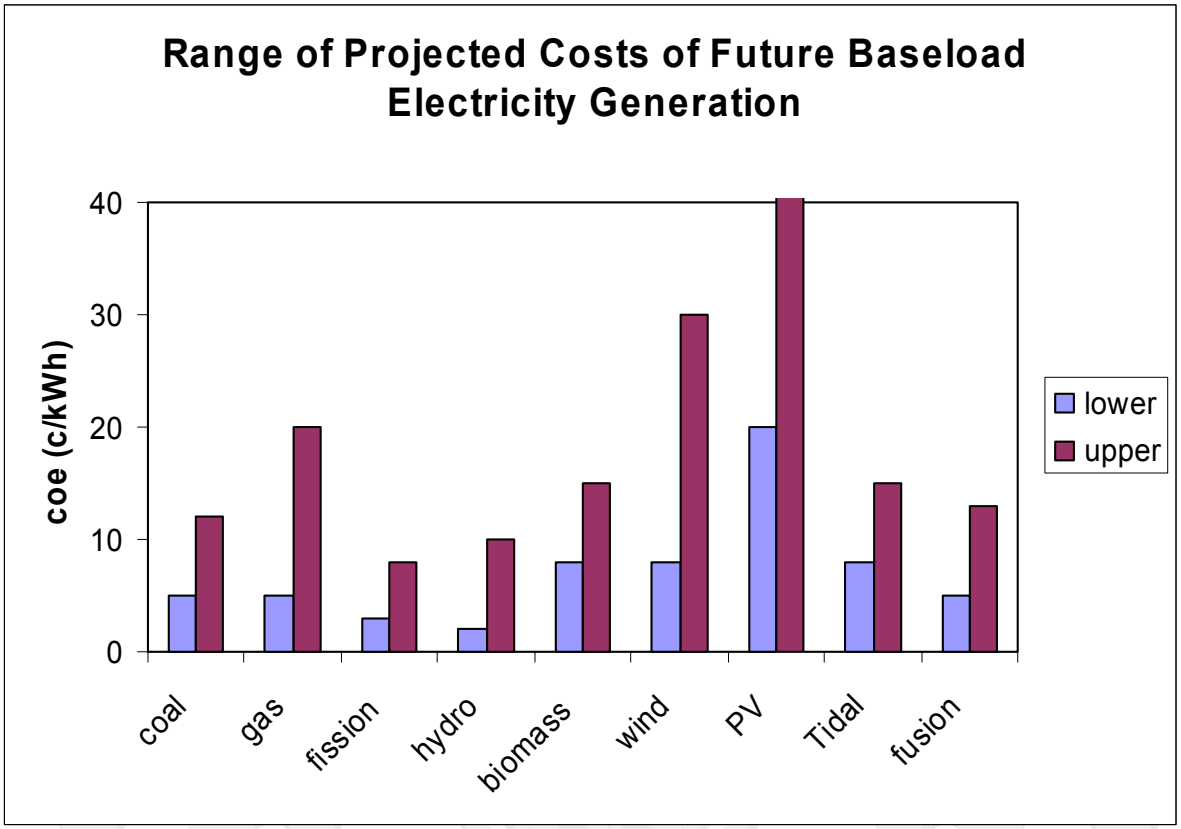
Direct Cost Comparison with Other Future Projections



Includes fuel price increases, pollution abatement, energy storage as well as capital cost reductions.

Based on data from "Projected Costs of Generating Electricity" IEA, 1998 Update.

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Conclusions

- IF THEY WORK RELIABLY even early generation fusion power plants are likely to be cost competitive in some nations, even without pollution constraints imposed on other systems.
- With learning effects, more developed fusion plants could be cost competitive world-wide, even without pollution constraints.
- With pollution constraints already being introduced, the economics look even better.
- This still requires a lot of work, especially in making reliable plants with high availability (materials in divertor and blanket/first wall).
- Let's get on with it!

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Economist February 5 2004

- “the discount rate over three decades... would probably make it uneconomic”
- **THERE IS NO TRUTH IN THIS AT ALL.**
- Total lifetime cost of ITER represents one day of spend in the energy market.
- Energy market is presently €2-3 trillion per year, growing at around 2%. If fusion could capture 10% of that future market, the discounted benefit would be 100 times larger than the development cost.
- If fusion is successfully introduced into the market at almost any level, the discounted benefits will far exceed the costs.

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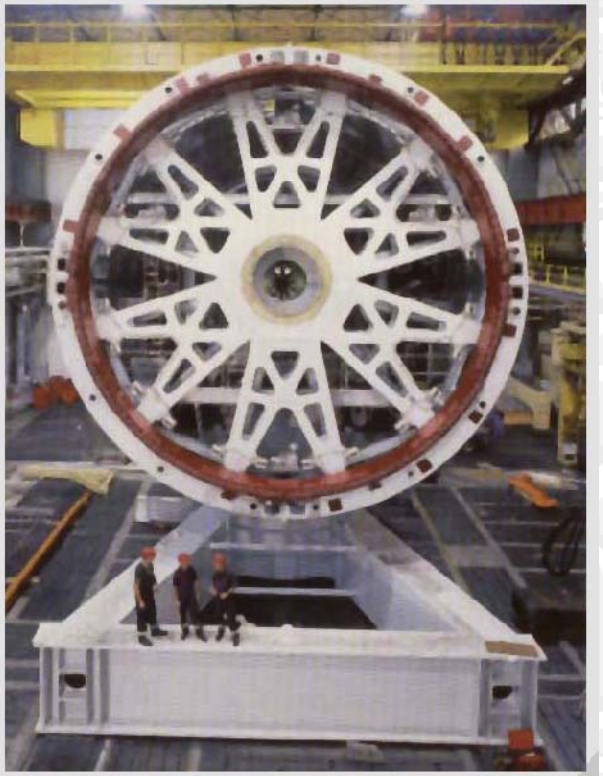
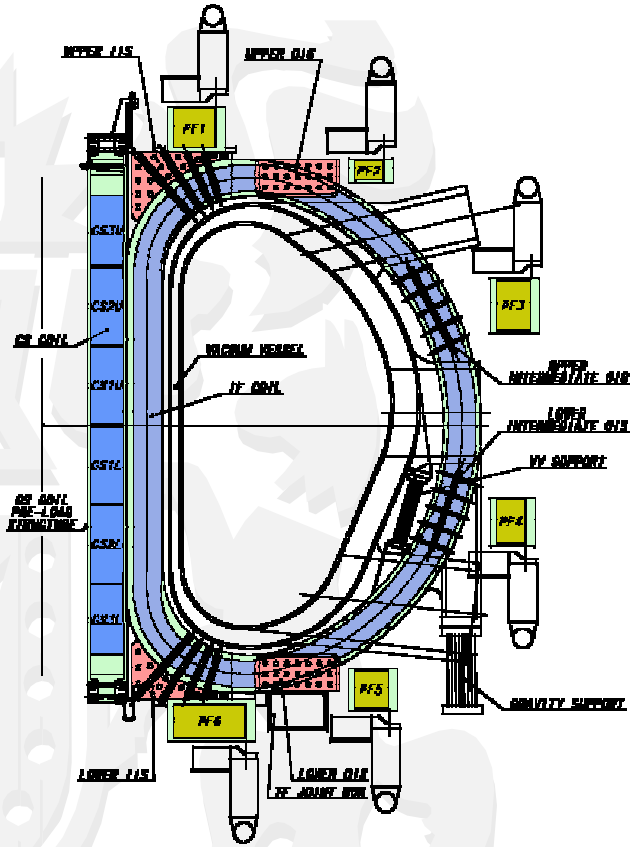
ITER Magnets Compared to Wind Turbine Hub



Enercon E 112
4.5 MW



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