Too cheap to meter? A stochastic analysis of the future costs of fusion power plants

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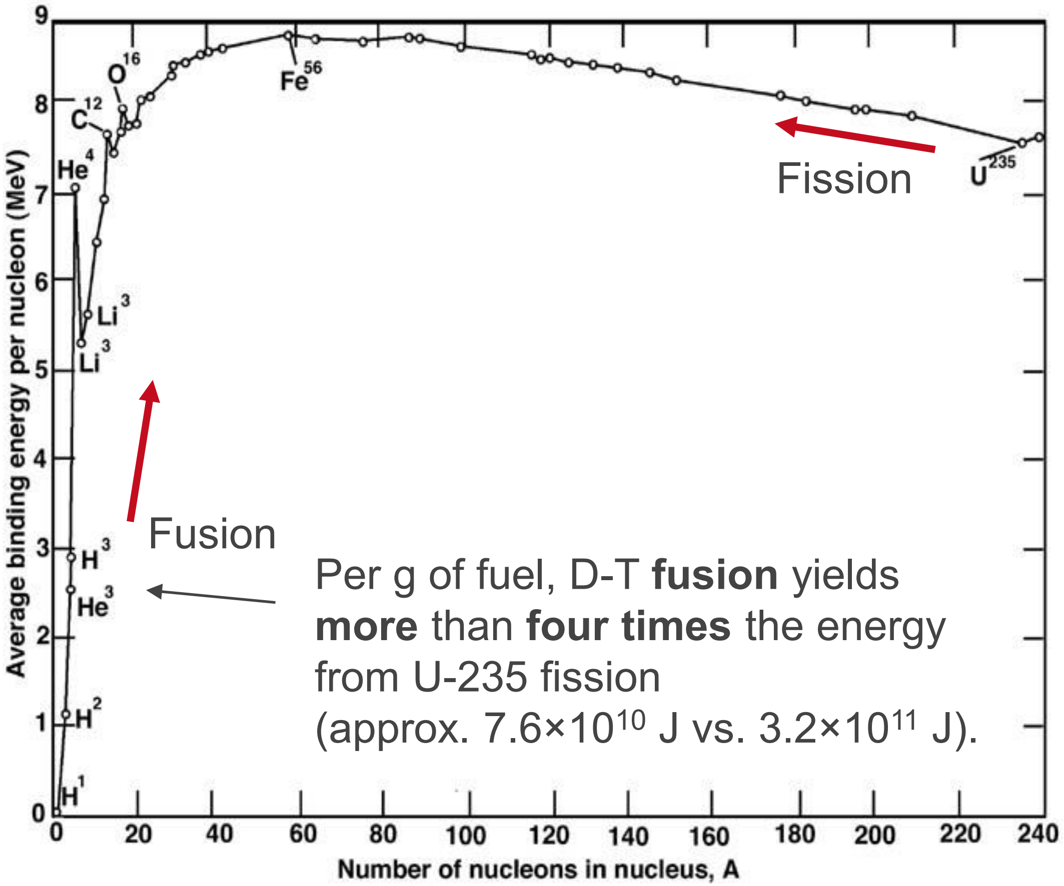
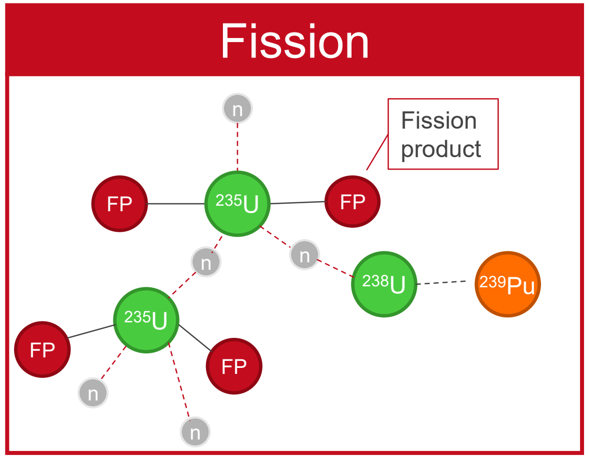
Introduction
Fusion energy promises increased energy yields compared to fission

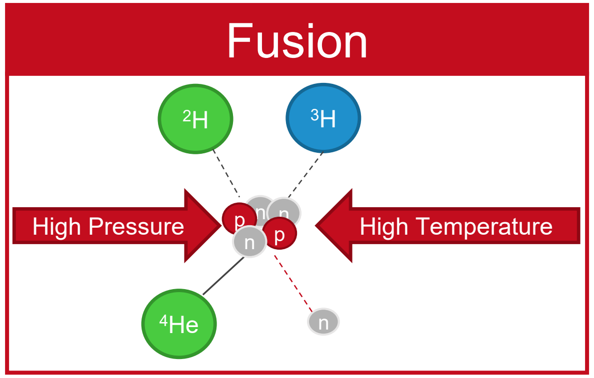
> *“**Fission** obtains energy through the **splitting** of large heavy atoms [into smaller ones], while nuclear **fusion** produces far greater levels of energy through the **joining** together of small light atoms. “*

Nuttall (2022, p. 239)



Per g of fuel, D-T **fusion** yields **more** than **four times** the energy from U-235 fission (approx. 7.6×10^{10} J vs. 3.2×10^{11} J).

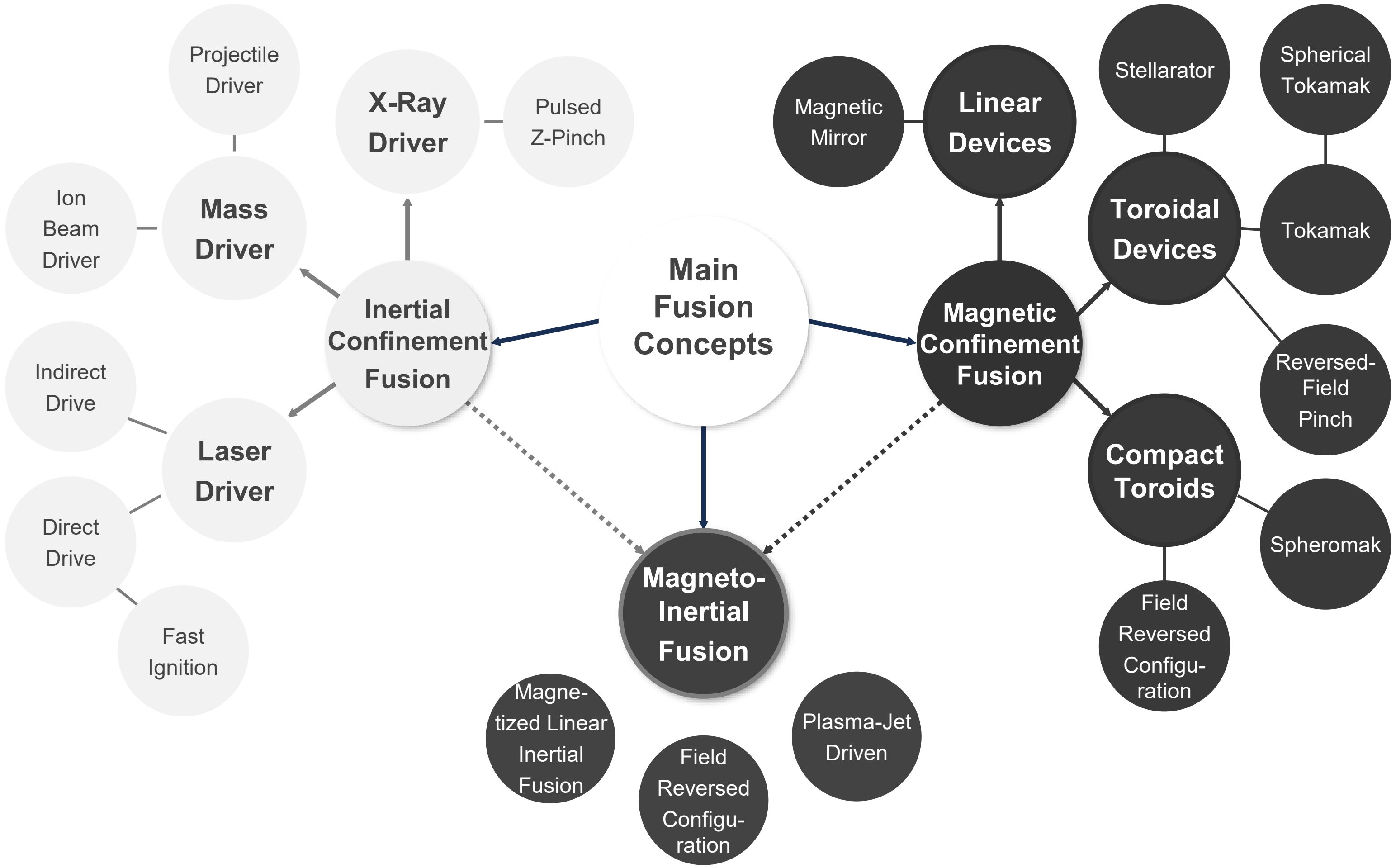

Fission


Fusion

Sources: Nuttall (2022), Yim (2022)

Introduction

There exist many different fusion concepts – all are prototypes at best



Main Fusion Concepts

Inertial Confinement Fusion
- **Mass Driver**
  - Projectile Driver
  - Ion Beam Driver
- **X-Ray Driver**
  - Pulsed Z-Pinch
- **Laser Driver**
  - Indirect Drive
  - Direct Drive
    - Fast Ignition

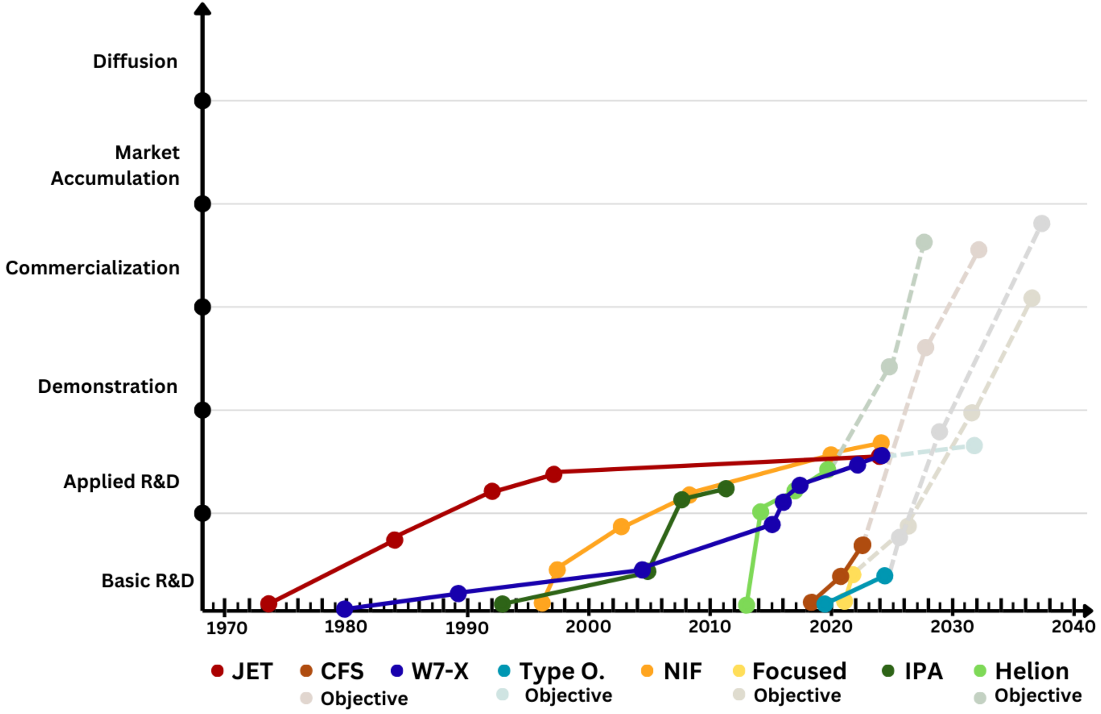
Magnetic Confinement Fusion
- **Linear Devices**
  - Magnetic Mirror
- **Toroidal Devices**
  - Stellarator
  - Tokamak
    - Spherical Tokamak
  - Reversed-Field Pinch
- **Compact Toroids**
  - Spheromak
  - Field Reversed Configuration

Magneto-Inertial Fusion
- Magnetized Linear Inertial Fusion
- Field Reversed Configuration
- Plasma-Jet Driven

Source: Böhnlein et al. (2026)

Motivation

Fusion is often described as clean, cheap, and reliable technology despite high uncertainty of feasibility



Technological Development Stages of Selected Fusion Concepts

Source: Dering et al. (2026), Fig. 2

- Fusion reactor concepts remain in early development stages although “new ventures” promise ambitious development trajectories
- Regardless, uncertainty about technological feasibility remains
- Cost assessments of potential fusion power plants (aka devices for commercial electricity generation) have been published for more than 40 years
- However, all of these cost assessments remain hypothetical as none of the described devices has been built
- We therefore conduct a stochastic analysis of potential future costs for different fusion plant concepts based on an extensive literature analysis and determine necessary learning rates for cost reductions of matured technologies

Methodology

Based on an extensive literature analysis, we conduct a stochastic assessment of future LCOE for fusion as well as implied learning rates for “readiness levels”

Literature Analysis

- Data set based on 67 references
- References cover different reactor types, cost parameters, and comprise various cost-assessment methods and scopes; MCF (tokamak) referred to most
- 71% journal publications (mostly in Fusion-specific outlets), remainder grey literature like “tech-reports”
- 24 references published before 2000; 17 between 2000 and 2010; 16 between 2010 and 2020; 10 since 2020

Stochastic Levelized Cost of Electricity Calculation

- Stochastic calculation of potential LCOE based on data from literature
- Calculation for ICF (10^{th}-OAK), MCF (FOAK, NOAK, 10^{th}-OAK, “Mature” OAK), MIF (10^{th}-OAK) due to limited data availability for other readiness-device combinations
- Monte Carlo simulation with N = 10,000

Implied Learning Rate Assessment

- Assessment of implied learning rates for ICF, MCF, MIF reactors to achieve 10^{th}-OAK LCOE (based on OCC)
- Learning rates x are calculated following the relation

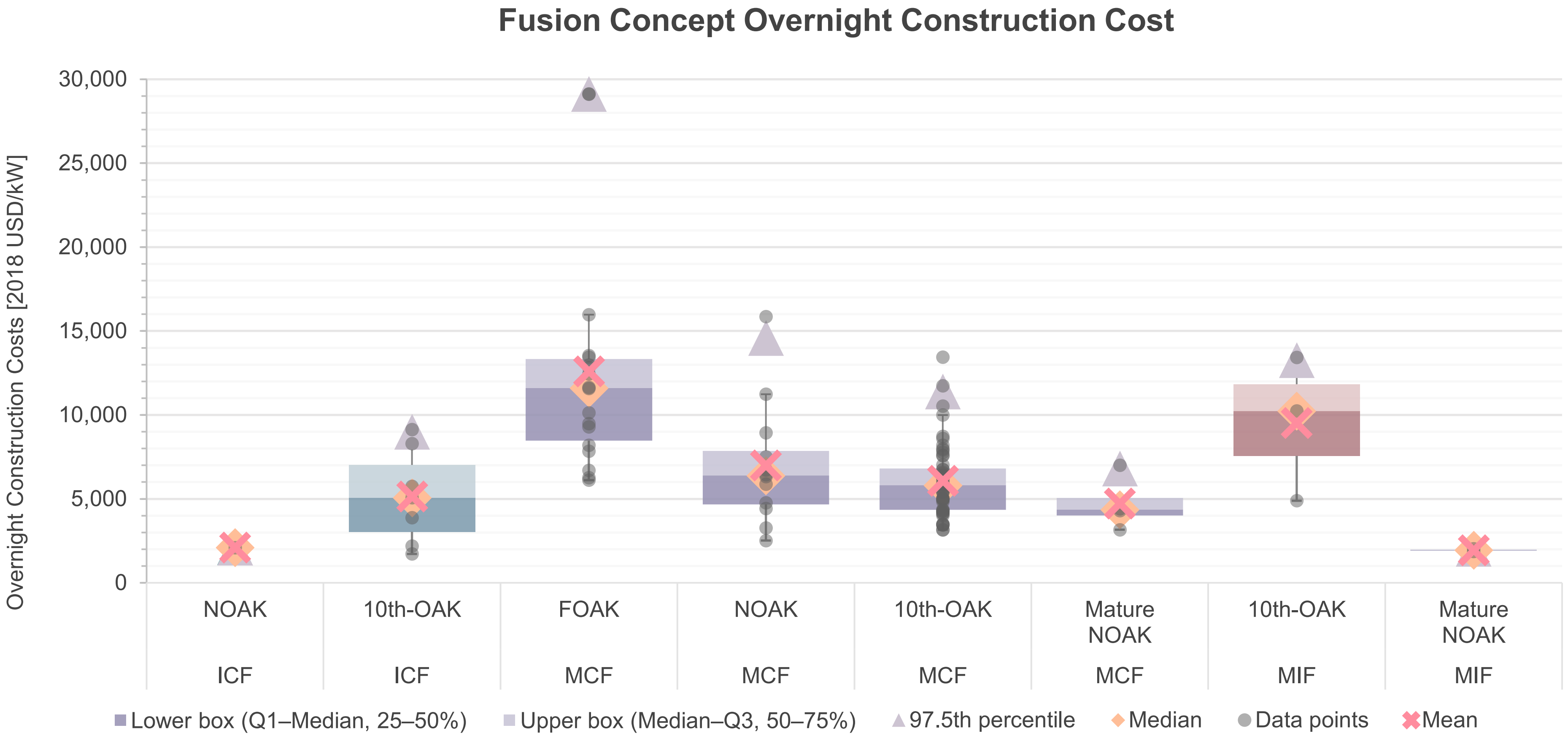
$$NOAK_n = FOAK * (1-x)^d$$
$$d = log_2(n)$$

Techno-Economic Feasibility Assessment

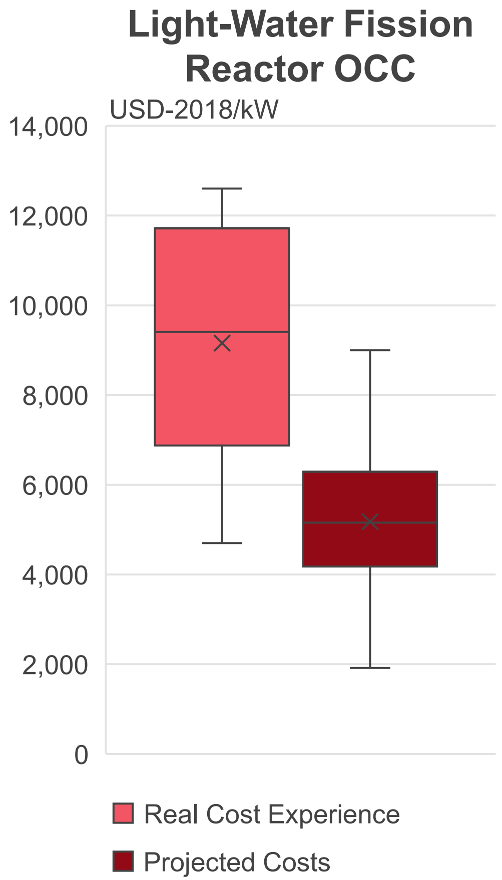
Could fusion be an economically competitive technology in the future?

Results | Descriptive Literature Analysis

Overnight construction cost (OCC) are expected to be the main driver of fusion LCOE



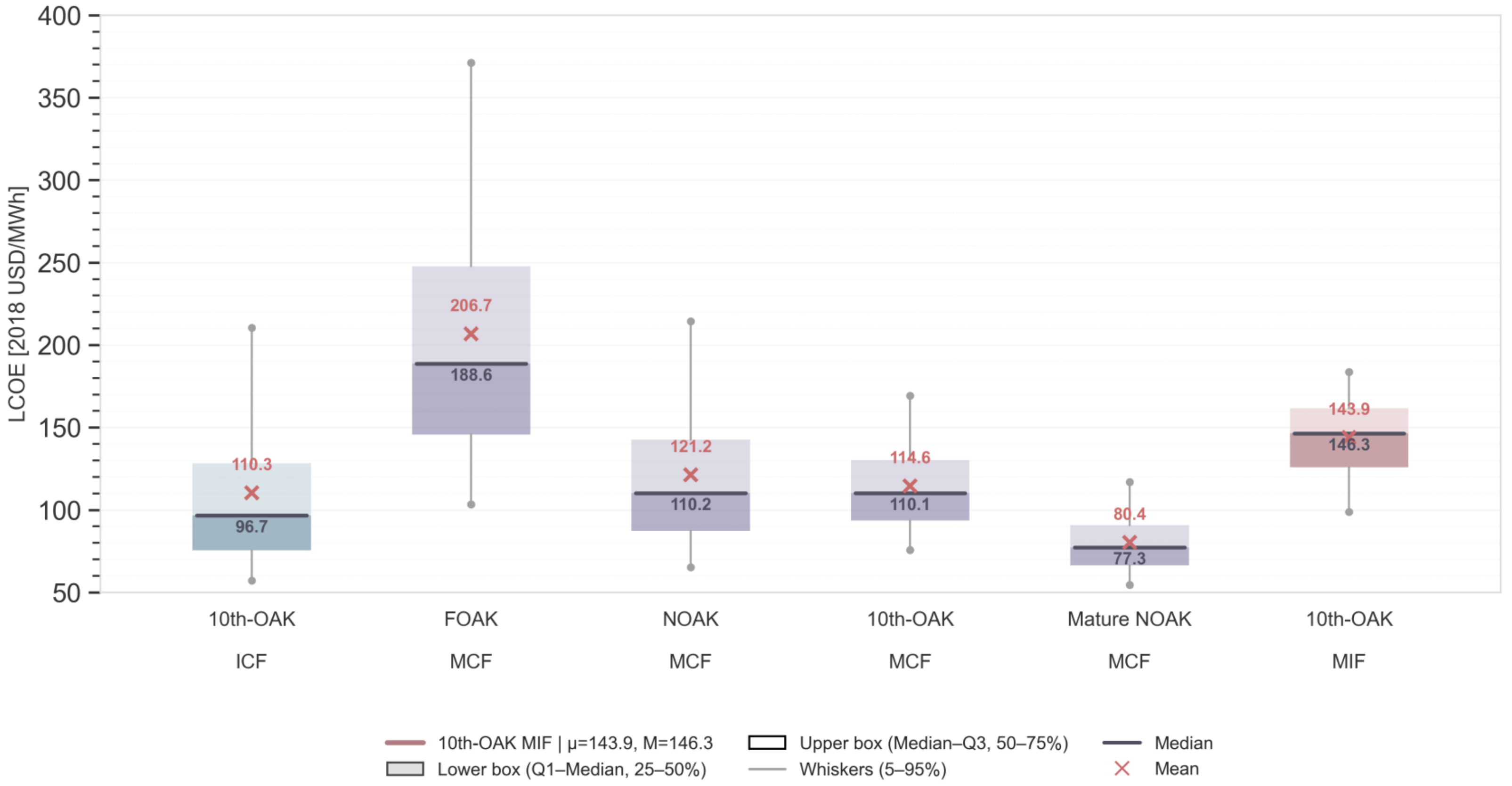
Sources: Various.



Taken from Göke et al. (2025)

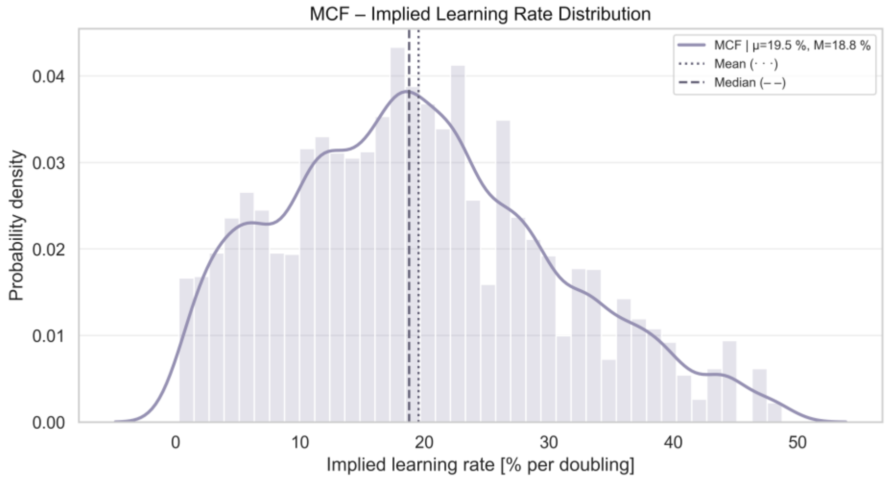
Results | Stochastic LCOE Calculation

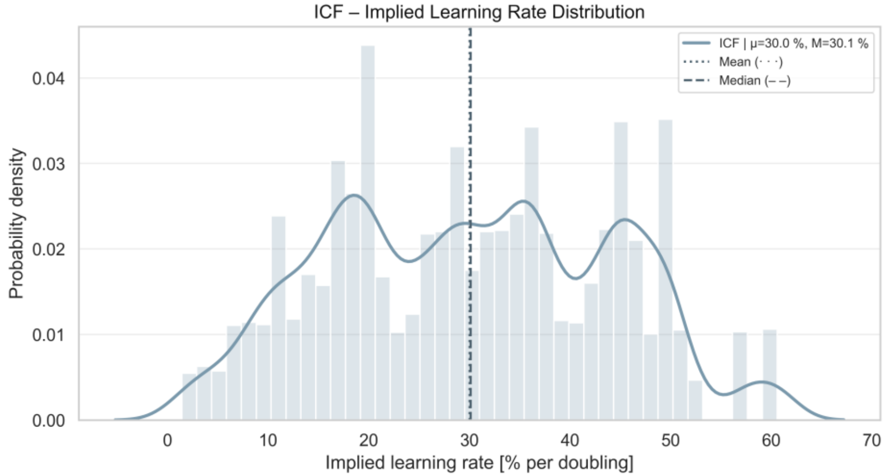
LCOE values are in the range of (expected) cost for fission plants but are higher than renewable LCOE



- LCOE simulation for fusion concepts and readiness levels depending the availability of cost data
- Even for relatively high readiness levels (10th-OAK), LCOE range above 110 USD/MWh
- None of these plants has been built, therefore there is a high degree of uncertainty
- However, LCOE do not include “system” values like flexibility, nor waste considerations; applicability is therefore limited

Results | Implied Learning Rates
Assuming ambitious learning reduces cost but is questionable



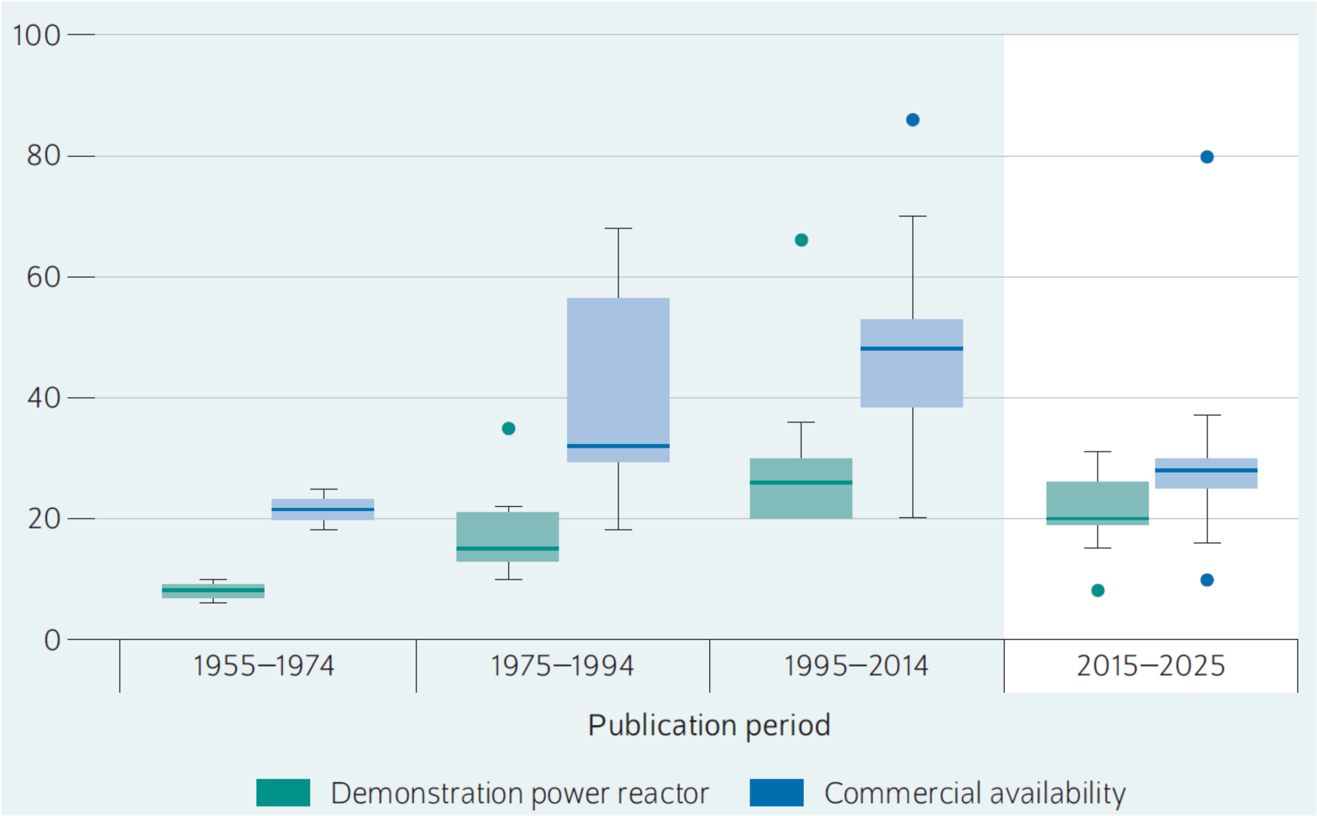


- We calculate implied learning rates for each LCOE result
- FOAK “starting” cost and 10th-OAK “target” cost are based on our literature data
- Due to limited data availability, calculations are shown only for MCF and ICF devices
- We find mean learning rates around 20% for MCF and 30% for ICF devices
- These are very ambitious assumptions, e.g., historical learning rates for fission range from 2 to 15% (depending on analysis scope); but also negative learning possible (e.g., observed for French fleet)
- In line with Tang et al. (2026) who conducted a survey on learning rates and find that 8-20% for fusion are highly overestimated
- Learning implied standardized designs, vendors, licensing procedures, etc.

Conclusion & Outlook

Fusion is likely to be expensive; and technological maturity still uncertain

Expected time until fusion becomes available – aka the "Fusion Constant"



Source: Wimmers et al. (2025), Fig. 1

- The "breakthrough" of fusion remains highly uncertain and many decades away
- Future costs are highly uncertain and mostly subject to assumptions made in literature
- These assumptions vary depending on selected fusion devices, readiness levels, and (potential) learning
- Our analysis shows that fusion power plants – if they are ever built – will be more costly than existing technologies today (i.e., renewables) and therefore will most likely not be economically viable on a mere cost base
- Future work will extend the literature analysis and could implement the cost analysis into an energy system model

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Thank you for your attention!

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Fusion Power | Introducing the “Lawson criterion” which must be fulfilled for fusion to ignite

The so-called “triple product” or “Lawson criterion” states that a certain threshold of the product of temperature, pressure and energy confinement time must be achieved for a fusion reaction to sustain itself. This results from the necessary diffusion of energy from the reaction to the reactor walls to extract excess energy for, e.g., power production.

Eq. (1) gives the condition for a DT-fusion to ignite and be self-sustaining, i.e. the plasma is heated by the alpha-particles emitted by the fusion reaction itself.

$$n * T * \tau_E > 6 \times 10^{21} keV m^{-3} s \qquad \text{Eq. (1)}$$

with n being the density of the plasma (ions per cubic meter), T the temperature of those ions (keV*), and τ_{E} being the energy confinement time (s).

This threshold bring with it extreme technological complexity relating to, e.g., materials capable of withstanding temperatures of millions of K, precise lasers and electronics with high pulses, constant fuel supply, plasma management, particle accelerations, neutron activation, and more.

Source: Lawson (1957), Horvath and Rachlew (2016), Wurzel and Hsu (2022)

*Note: 1 keV corresponds to 11.6 x10^6 K following the Boltzmann constant.

Fusion Power | The triple product, ignition, the energy gain factor Q and actual fusion devices

As the goal of (commercial) fusion reactors is to generate excess energy from fusion to produce power (or heat), the energy released from a fusion reaction must be higher than the energy that was used to ignite the process.

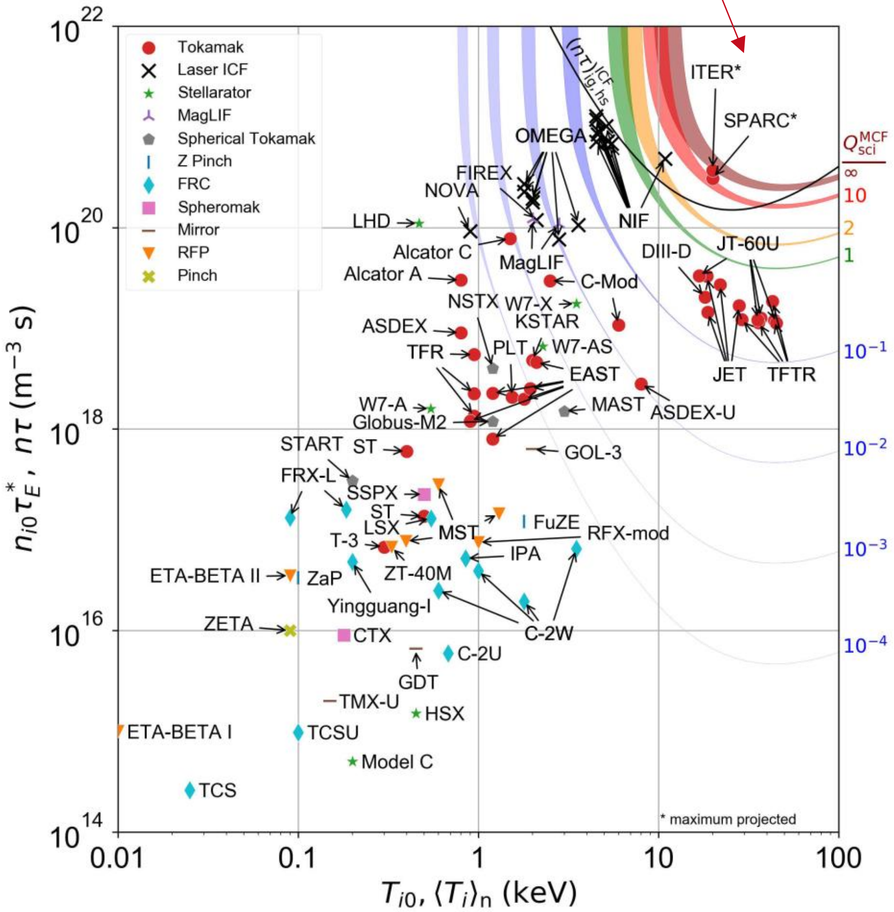
The energy gain factor Q thus measures this as the ratio of power produced by fusion and the power required to keep the plasma heated. This gives Eq. (2):

$$Q_{fus} = \frac{P_{fus}}{P_{heat}} \qquad \text{Eq. (2)}$$

There are several “breakeven” definitions for different values of Q. Q > 1 has been achieved*, but Q > 5 is generally required for a self-sustaining reaction.

Q	Breakeven	Description
1	Scientific	Energy yield larger than input (without external factors), not self-sustaining
5	Engineering	Required for self-sustaining reaction
20	Economic	Fusion plant covers its own operating costs
???	Commercial	Fusion plant able to compete on competitive energy markets

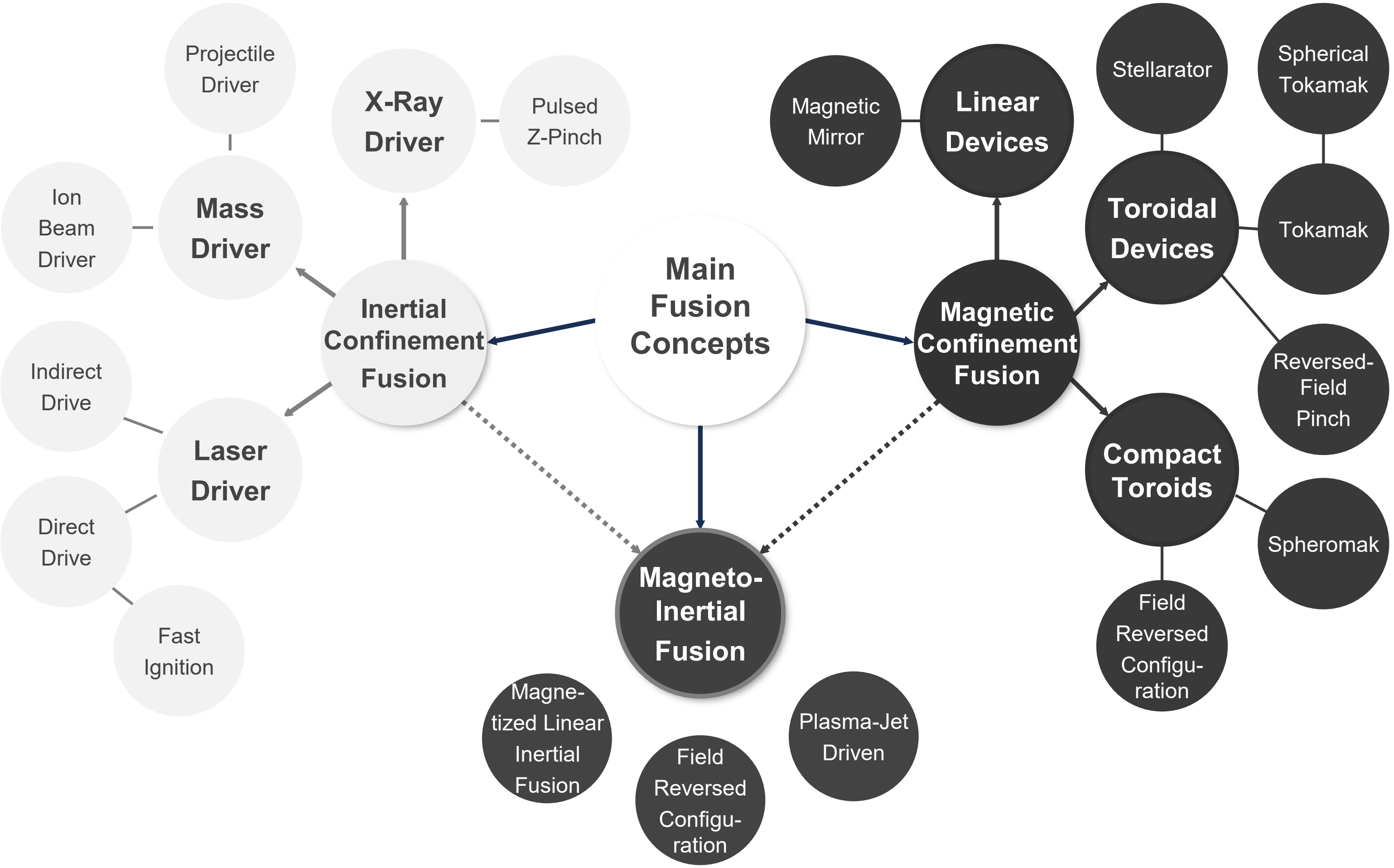
Asterisks indicate **planned** Q!



Taken from Wurzel and Hsu (2022), Fig. 2

*Note: In December 2022, the National Ignition Facility at the Lawrence Livermore Lab was the first fusion reaction to achieve Q > 1 as 3.15 MJ were released from a fusion reaction that had been ignited using 2.05 MJ of laser energy.
Source: Nuttall et al. (2020), Reinders (2021), Wurzel and Hsu (2022), Thomas (2022)

Fusion Technologies

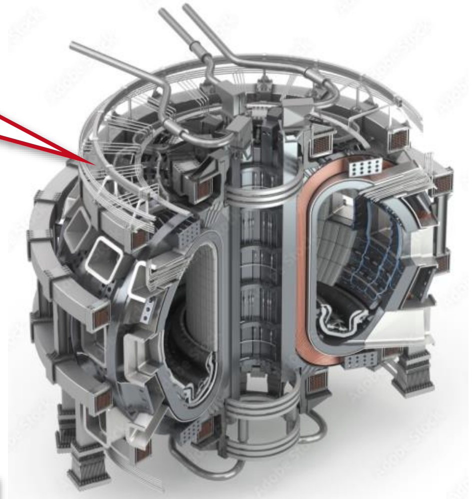


Source: Böhnlein et al. (2026)

Fusion 101 | Two general types of fusion devices exist (I/II)

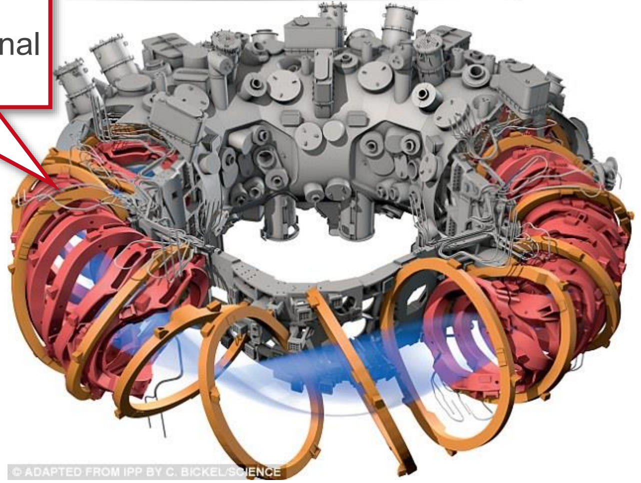
Magnetic confinement

- MCF takes advantage of the fact that plasmas are positively charged and can be manipulated by using magnetic and electrical field
- MCFs thus use magnets to create and confine plasmas with a relatively low density but high confinement times and temperatures
- Two approaches have materialized: Tokamak designs with two magnetic fields (one generated by a set of toroidal magnetic coils and a solenoid in orthogonal orientation), and Stellerators with only one set of magnetic coils in complex geometrical arrangements
- Tokamak research is considered to be the most advanced of all fusion devices, as several research reactors exist, e.g., JET (UK), TFTR (US), and are planned, e.g., ITER (France)
- Major challenges: overcoming disruptive plasma instabilities, constant energy and fuel provision, material sciences



ITER tokamak
(under construction)

https://as2.ftcdn.net/v2/jpg/04/62/63/11/1000_F_462631147_9KC2d2Pvst2widPFngPYJHAQ0MLrPtBu.jpg



Wendelstein 7-X
stellarator (operational
since 2015)

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https://i.dailymail.co.uk/i/pix/2015/10/26/17/2DCE762200000578-0-image-a-1_1445880883149.jpg

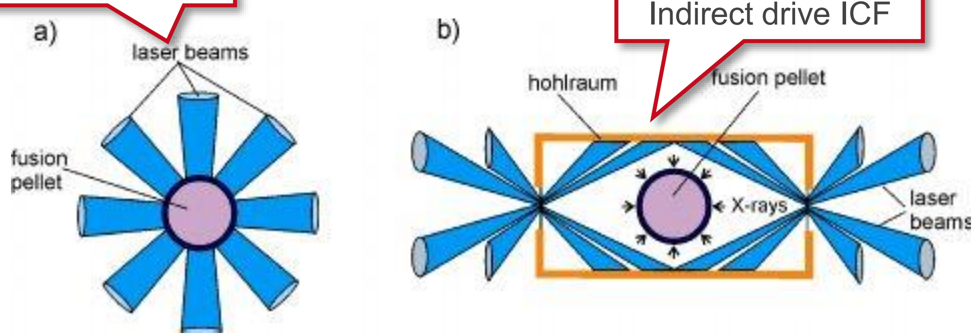
Source: Pearson and Takeda (2020), Bickerton et al. (1999)

Fusion 101 | Two general types of fusion devices exist (II/II)

Inertial confinement

- ICF does not aim to increase confinement times but aims to sufficiently increase the density of the plasma
- A small fusion fuel target is rapidly heated and compressed by one or several high-power laser beams
- Direct drive ICF heats the target to such high temperatures that the outer layers of the target are ablated and indirect drive ICF heats the target to generate “internal” x-rays that trigger a short-lived fusion reaction
- Both approaches lead to high temperatures and compression sufficiently high to ignite fusion that rapidly spreads through the fuel
- Current applications are the NIF at Lawrence Livermore Lab (US) or start-ups such as Marvel Fusion and Focused Energy (both DE, see Case Studies)
- Major challenges lie in the fuel pellet production and precise position, laser pulsing and constant energy provision for said lasers

Source: McCracken and Stott (2013), Pearson and Takeda (2020), Meier et al. (2014)



Direct drive ICF

Indirect drive ICF

Fig. 2, taken from Badziak (2012)

Inside NIF

https://www.llnl.gov/sites/www/files/styles/scaled_425h/public/28723_preamplifiersBig.jpg?itok=LMSuhDf_

Fuel pellet at NIF

https://media.diepresse.com/images/uploads_1152/e/d/9/536281/laser-fusion_v2_NIF_LLNL20100129134658.jpg

Techno-historical context | Major challenges fusion reactors will have to overcome

Tritium scarcity and fuel breeding

- Initial stockpile of tritium is required to get any DT-fusion reaction going (or restart the reactor); during operation “breeding” is supposed to ensure tritium availability
- Tritium is a scarce resource with a half-live of only 12.3 years and currently, the only production facilities are old heavy-water fission reactors in Canada and India

Resource competition

- Fuel breeding via Lithium-6 could ensure tritium availability; this has not been tested
- Lithium is an abundant material, but fierce competition from battery production will challenge assumptions
- Other materials such as beryllium are required for magnets and are scarce

Competition on energy markets

- as shown, costs of fusion plants must come way down even from today’s projections to compete with renewables
- Non-electrical applications could become viable, but nothing demonstrated yet

Reliability

- Fusion is often portrayed as a “baseload” energy, but this is yet to be demonstrated
- current tokamaks generate stable plasma of only a few seconds
- ICF approaches must be further researched regarding laser pulses and pellet positioning

Materials and technology

- Very high temperatures held over many hours in the year require heat-resistant materials capable of withstanding very steep temperature gradients
- Supraconducters and laser technologies also not yet at the required stage

Neutron radiation management

- Neutrons released from fusion processes are to be used for energy generation
- This can lead to neutron activation in blankets, which generates low- and intermediate radioactive waste
- Neutrons damage materials and long-term behavior of materials remains largely unstudied

…and more.

Source: Pearson et al. (2018), Abdou et al. (2021), Nuttall (2005), Meschini et al. (2023), Bradshaw et al. (2011), Meier et al. (2014), Nicholas et al. (2021), Reinders (2021), McCracken and Stott (2013), Grunwald et al. (2002)

Necessary background information | Capital Cost, LCOE etc.

- The levelized cost of electricity (LCOE) method allows for different types of energy generation methods to be made comparable as cost are determined per generated unit of electricity over one year
- LCOE include most costs, e.g., capital cost and operating cost, and account for availability (i.e. generating hours) of a technology
- However, external effects are not included

$$LCOE = \frac{CAPEX+Fixed\ O\&M+(FLH*Variable\ O\&M)}{FLH}$$

$LCOE$	Levelized cost in €/MWh
$CAPEX$	Annualized capital expenditure calculated with constant interest rate *i* over total expected operation time *n* in €/kW
Fixed O&M	Fixed operations and maintenance cost in €/kW
FLH	Total hours of full-load operation (full load hours)
$Variable\ O\&M$	Operations & maintenance cost depending on production volume in €/MWh, includes fuel cost
n	Assumed operating lifetime in a

- For fission reactors, capital cost account for up to 80 % of total project cost and are therefore discussed separately. We assume a similar share for fusion power plants.
- In literature, capital cost are often provided as *overnight construction cost* (OCC) that include all costs related to physical new build, but neglect construction time and interest.
- Therefore, to calculate total capital expenditure for nuclear new build construction, TCC, both construction time and interest during construction must be taken into account.
- This gives the formula

$$TCC = OCC + IDC$$

where IDC is the interest during construction calculated as

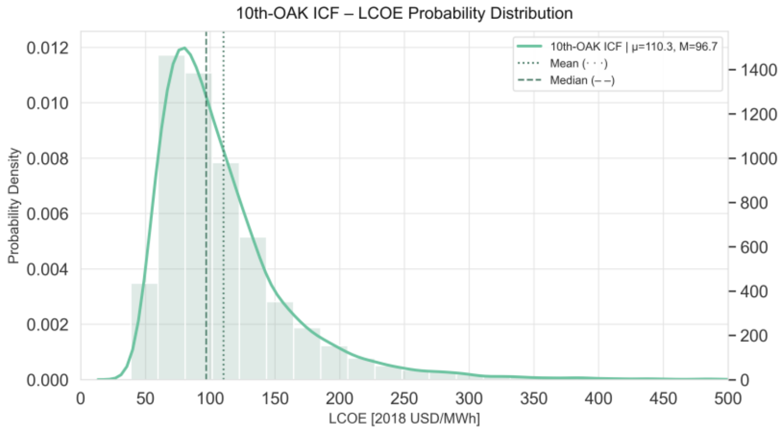
$$IDC = \frac{WACC}{2} * t + \frac{WACC^2}{6} * t^2$$

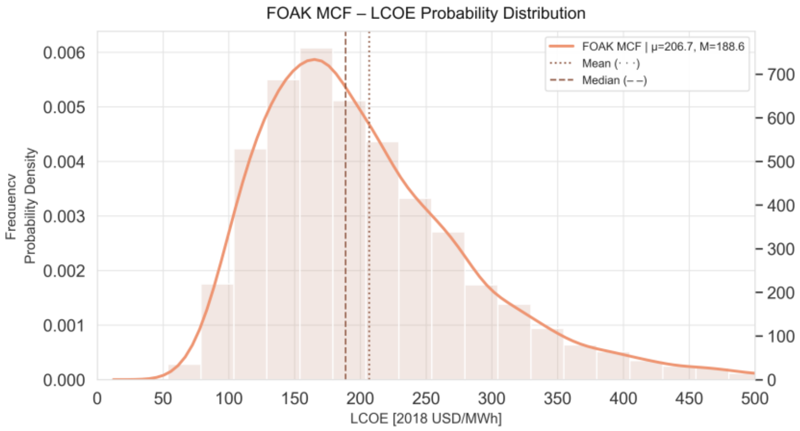
- where WACC as weighted average cost of capital (e.g. 5%) and t is the construction time in years.

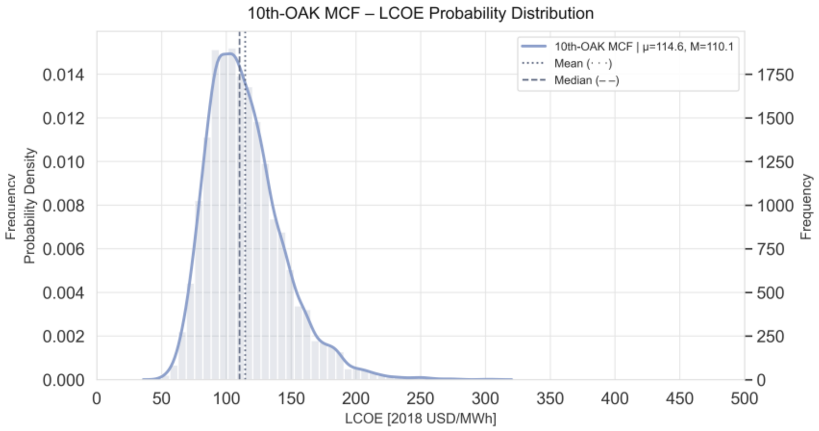
Monte Carlo Input Parameters

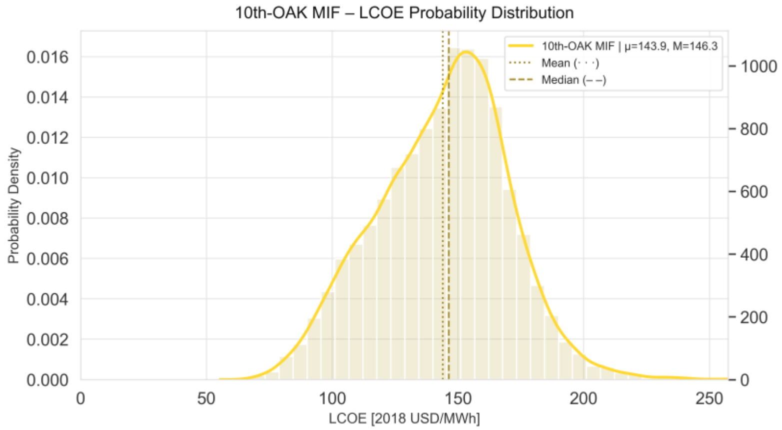
Parameter	**ICF 10th-OAK**	**MCF FOAK**	**MCF NOAK**	**MCF 10th-OAK**	**MCF Mature NOAK**	**MIF 10th-OAK**
Overnight construction costs [USD/kW]	Lognormal (μ = 8.391; σ = 0.634); [min-max: 1,718–9,122]	Lognormal (μ = 9.339; σ = 0.443); [min-max: 6,133–29,131]	Lognormal (μ = 8.735; σ = 0.506); [min-max: 2,519–15,856]	Lognormal (μ = 8.658; σ = 0.333); [min-max: 3,161–13,440]	Lognormal (μ =8.418; σ = 0.328); [min-max: 3,164–7,004]	Triangular (a = 4,889; c = 12,391; b = 13,427)
Fixed O&M costs [USD/kW]	Lognormal (μ = 4.905; σ = 0.119); [min-max: 114.77–171.81]	Lognormal (μ = 4.481; σ = 0.273); [min-max: 56.48–137.84]	Lognormal (μ = 4.588; σ = 0.305); [min-max: 70.6–190.81]	Normal (μ = 100.59; σ = 28.68); [min-max: 20.47–172.69]	95.223	Lognormal (μ = 5.206; σ = 4.833); [min-max: 125.55–265.05]
Variable O&M costs [USD/MWh]	14.858	9.990	15.012	14.858	8.604	-
Fuel costs [USD/MWh]	1.113	0.125	0.0457	0.115	0.115	0.0236
Discount rate (%)	7	7	7	7	7	7
Capacity factor	0.76	0.75	0.75	0.75	0.8	0.9
Construction time [years]	6	8	6	6	6.3	6
Plant lifetime [years]	30	30	40	30	40	30
Capacity [MW]	1,000	1,000	1,000	1,000	1,000	1,000
Number of experiments N	10,000	10,000	10,000	10,000	10,000	10,000

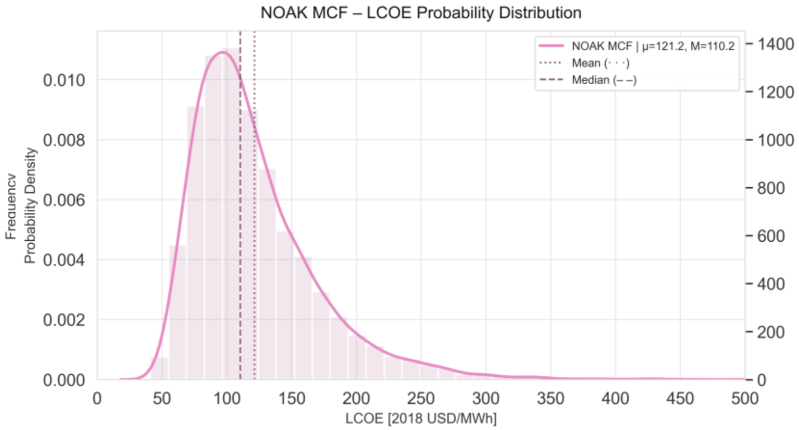
LCOE Simulation Distribution

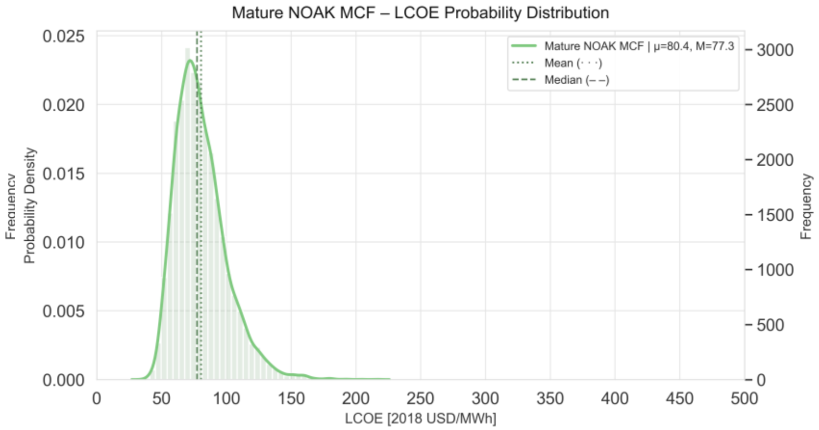




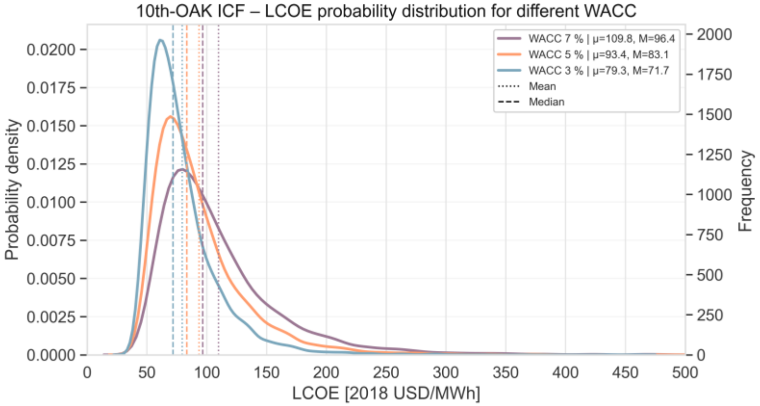


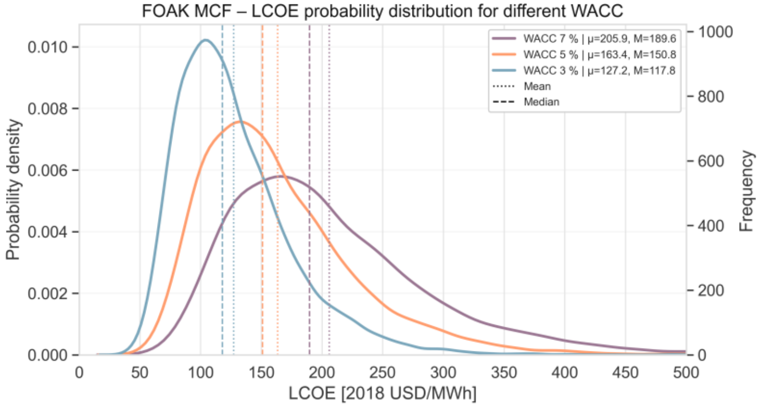


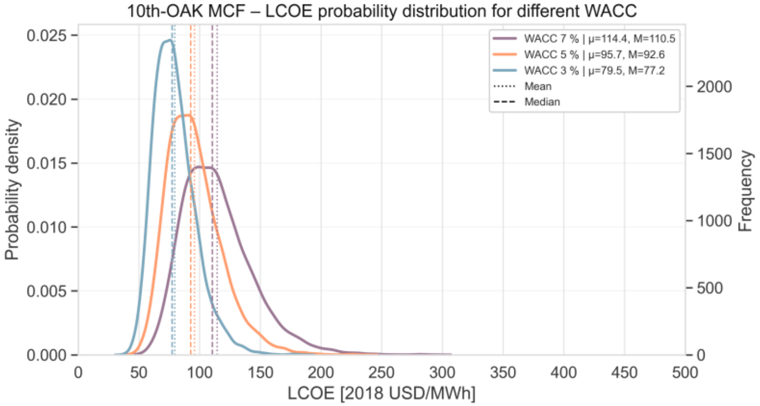


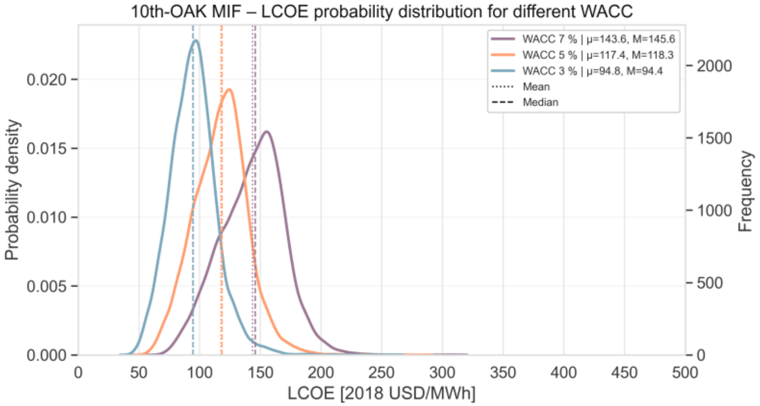


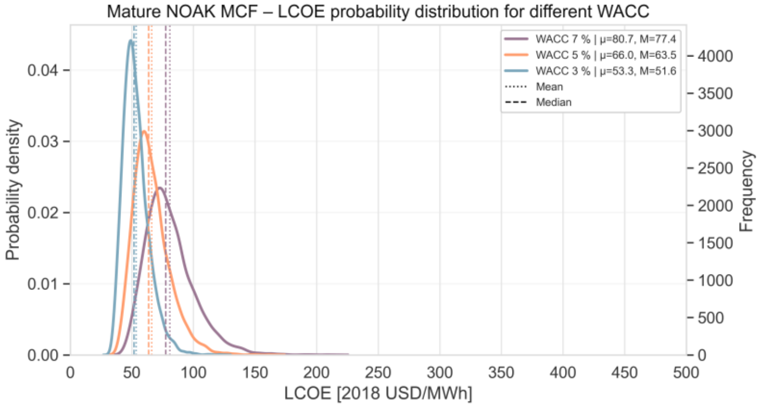
LCOE Sensitivity | WACC Variation

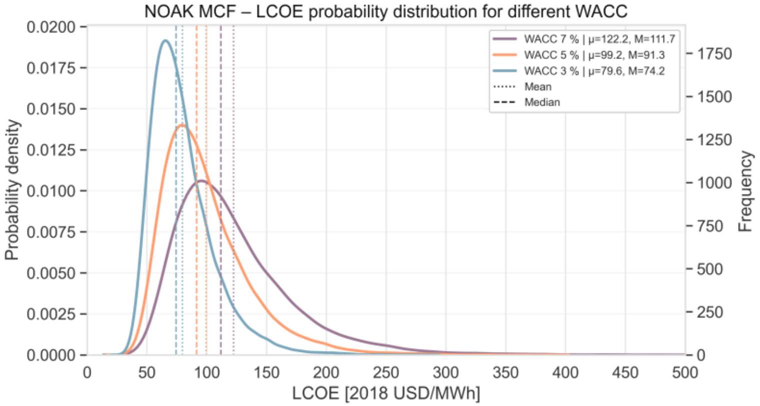

10th-OAK ICF – LCOE probability distribution for different WACC


FOAK MCF – LCOE probability distribution for different WACC


10th-OAK MCF – LCOE probability distribution for different WACC


10th-OAK MIF – LCOE probability distribution for different WACC


Mature NOAK MCF – LCOE probability distribution for different WACC


NOAK MCF – LCOE probability distribution for different WACC