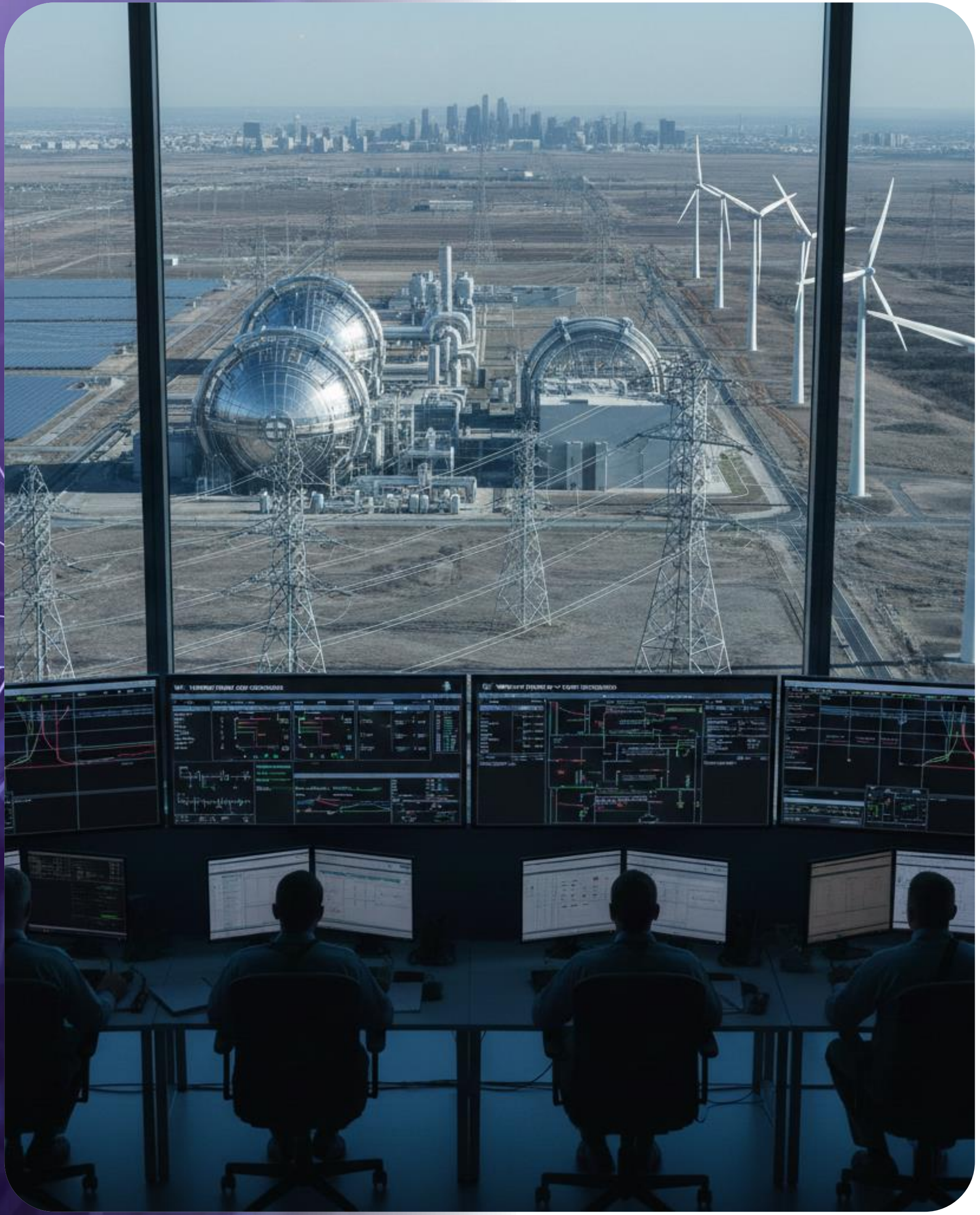


# Techno-Economic Analysis of Fusion Power Plants

Layla Araiinejad
June 12, 2026

layla00@mit.edu

# About Layla Araiinejad

**Education:**

- Master of Science in Technology and Policy (Fusion Energy) from MIT
- Bachelor of Industrial and Systems Engineering, Auburn University

**Fusion Experience:**

- Co-founder of Module12, a Nuclear Commercialization Advisory
- Research Collaborator at MIT Plasma Science and Fusion Center
- Research Associate at MIT Plasma Science and Fusion Center
- Lead of Techno-economic Analysis for the Fusion Study at the MIT Energy Initiative

**Other Work and Research Experience:**

- Industry Experience across the power sector: Transmission, Distribution, and Generation
- Product Research at VEIR (High-temperature super conductors)
- NSF-funded researcher at Auburn University, Department of Mathematics and Statistics
- NSF-funded researcher at Utah State University Department of Engineering Education
- Research Assistant, Auburn University, Department of Industrial and Systems Engineering

*Clean Air Task Force International Working Group on Fusion Cost Modeling*

*Hosting "Business of Fusion Energy Course" at MIT*

*TEA Thesis Presentation at MIT Energy Initiative*

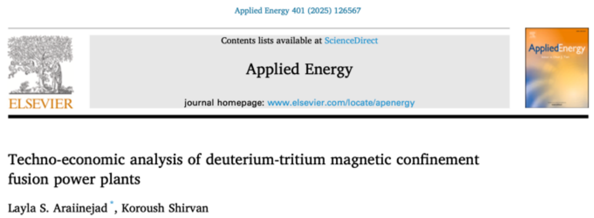
*Thesis signing day with the Director of MIT Technology and Policy Program, 2024*

# Fusion Economics Work and Talks by Layla Araiinejad

MITei
MIT Energy Initiative

THE ROLE OF FUSION ENERGY
IN A DECARBONIZED
ELECTRICITY SYSTEM

A report from the MIT Energy Initiative in collaboration with the
MIT Plasma Science and Fusion Center



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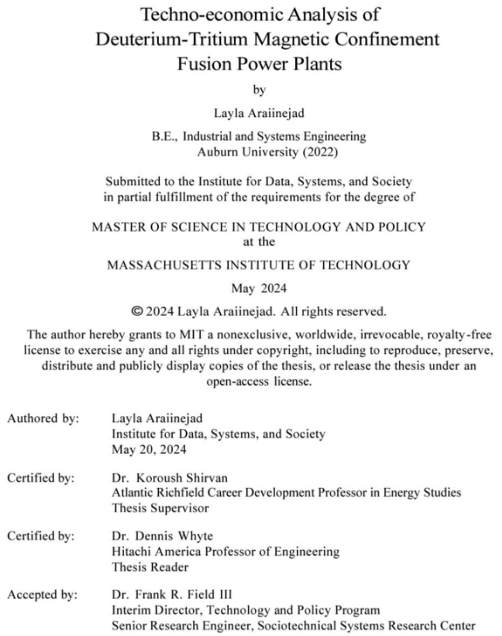
journal homepage: www.elsevier.com/locate/apenergy

Techno-economic analysis of deuterium-tritium magnetic confinement fusion power plants

Layla S. Araiinejad*, Koroush Shirvan



Techno-economic Analysis of
Deuterium-Tritium Magnetic Confinement
Fusion Power Plants

by

Layla Araiinejad

B.E., Industrial and Systems Engineering
Auburn University (2022)

Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2024

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Authored by: Layla Araiinejad
Institute for Data, Systems, and Society
May 20, 2024

Certified by: Dr. Koroush Shirvan
Atlantic Richfield Career Development Professor in Energy Studies
Thesis Supervisor

Certified by: Dr. Dennis Whyte
Hitachi America Professor of Engineering
Thesis Reader

Accepted by: Dr. Frank R. Field III
Interim Director, Technology and Policy Program
Senior Research Engineer, Sociotechnical Systems Research Center

- MIT Energy Initiative Study: *The Role of Fusion in a Decarbonized Electricity System*
    - Chapter 7: Techno-economic Analysis (TEA) of Fusion Power Plants
        - Includes Bottom-Up TEA of D-T Magnetic Confinement Fusion
        - Top-Down Assessments of Magneto-Inertial and Inertial Confinement Approaches
- MIT Master of Science Thesis : *Techno-economic-Analysis of D-T Magnetic Confinement Fusion Power Plants*
- Applied Energy Journal Paper: “Techno-economic Analysis of D-T Magnetic Confinement Fusion Power Plants"
- Many more in progress!

Talks:
- MIT Energy Initiative Seminar: “Techno-economic Analysis of D-T Magnetic Confinement Fusion Power Plants”
- Panels: FusionX Invest March 2025; FusionX Invest September 2025; FusionX Invest March 2026
- Independent Activities Period at MIT: Business of Fusion Energy
- Journal of Plasma Physics Colloquium talk on Fusion Economics

**Contact: layla00@mit.edu**

# Presentation Agenda

- Group Intro Activity
- TEA
  - Motivation for conducting TEA
- Key Terminology:
  - Overnight Capital Cost
  - LCOE
  - NOAK vs. FOAK
- Learning Curves: Wright's Law
- LCOE Comparison with DT MCF fusion
- Economic comparison of other Fusion Concepts

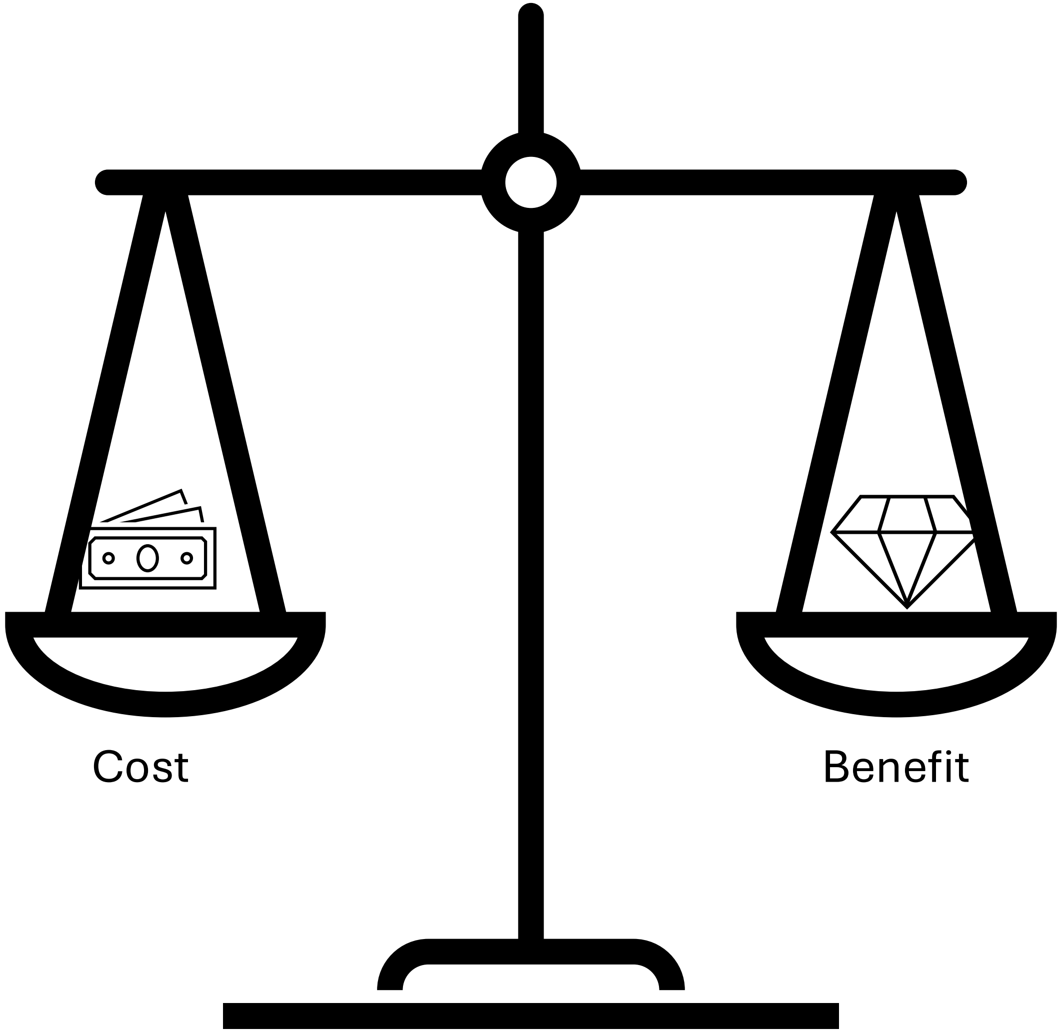
# Think of fusion as a commercial energy source.
# What do you expect to be the dominant cost driver(s) within a fusion power plant?

*This question is intentionally open-ended. Feel free to bound your answer by assumptions about fusion approach, technology readiness (FOAK vs NOAK), regulatory context, or market structure.*

*In-person attendees: please form small groups*

*Zoom attendees: answer the questions individually*

# What is Techno-economic Analysis?



# Who uses Techno-economic Analysis (TEA) & Why?

**Key Users:**

- Investors:
  - Critical to Due Diligence
  - Evaluates Commercial viability and downside risk
  - Guides Investment Strategy and Capital Allocation

- Start-ups:
  - Aligns technology development with cost and market targets
  - Tests competitiveness against incumbents
  - Guides the path to commercial viability

- Academic and Research Institutions
  - Enables system-level techno-economic modeling and analysis
  - Informs research design and R&D prioritization
  - Identifies key performance thresholds for commercial relevance

→ TEA identifies synergies between technical performance and economic benchmarks, helping reveal key sensitivities and guiding technology development toward economically meaningful milestones.

# Key Terminology

**Overnight Capital Cost (OCC):**
- Total upfront cost to build the plant, excluding financing and interest during construction
- Large "one-time" investments like property, equipment, and long-term assets

**Operations and Maintenance (O&M) Costs:**
- Recurring Expenses to operate the plant such as labor, maintenance, and consumables
- Fixed and Variable O&M costs.

**Levelized Cost of Electricity (LCOE):**
- The average lifetime cost of electricity generation ($/MWh)
- Used to benchmark economic competitiveness against other energy sources

**First-of-a-kind (FOAK) vs. Nth-of-a-kind (NOAK):**
- **FOAK:** First commercial plant; higher cost and risk due to limited experience and immature supply chains.
- **NOAK:** Mature plants; lower cost and risk from learning, standardization, and scale.

- Fusion electricity costs will be driven by **upfront capital costs**, whereas natural gas electricity costs are dominated by the **cost of fuel**.

# Bottom-up Techno-economic Analysis of Deuterium-Tritium Magnetic Confinement Fusion Power Plants

NOAK Cost Estimate

Source: **Araiinejad, L**. & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567*. https://doi.org/10.1016/J.APENERGY.2025.126567

# TEA Current Focus Justification: D-T Magnetic Confinement Reactor

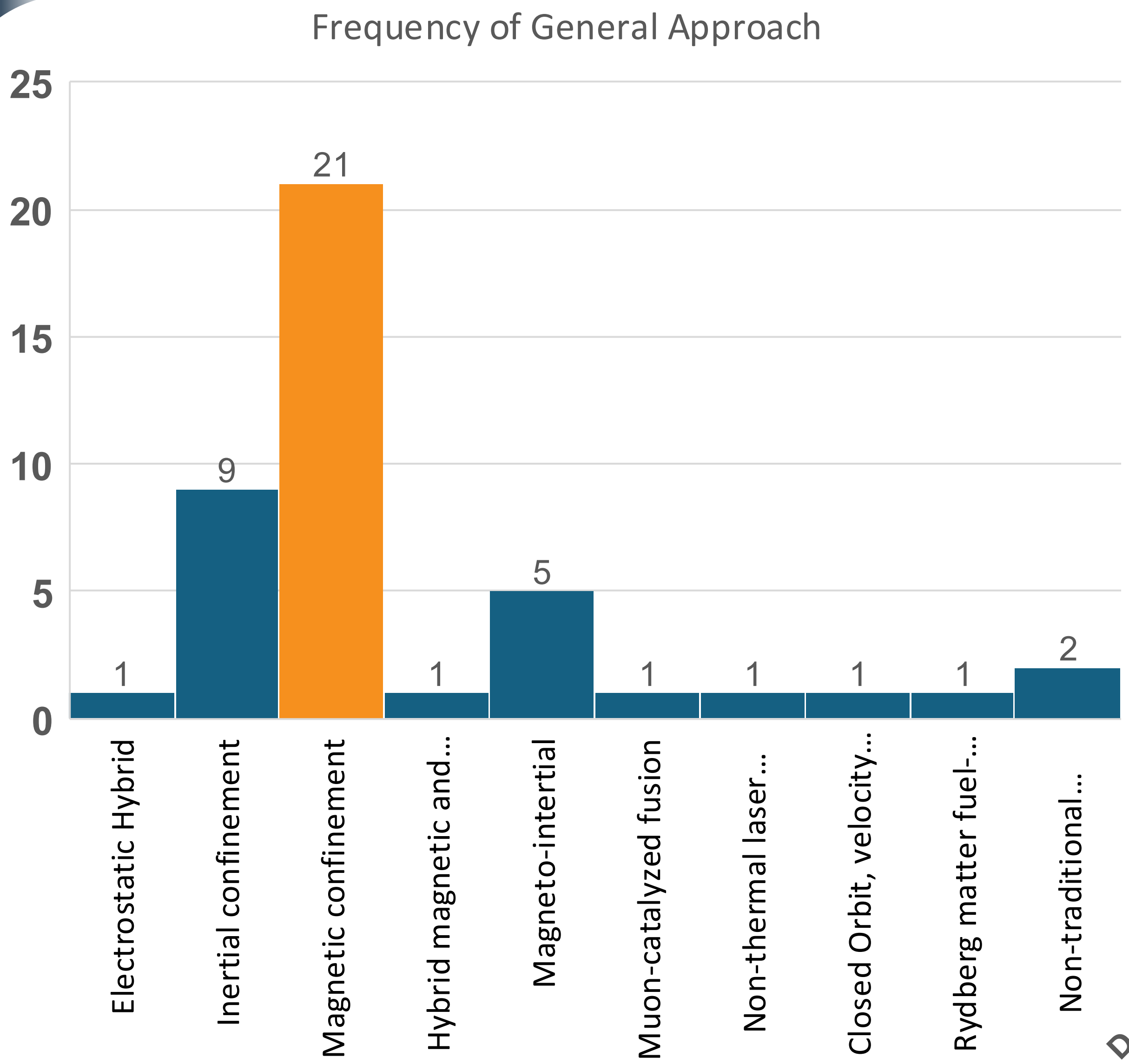


*Figure 1. Frequency of General Approach [1]*

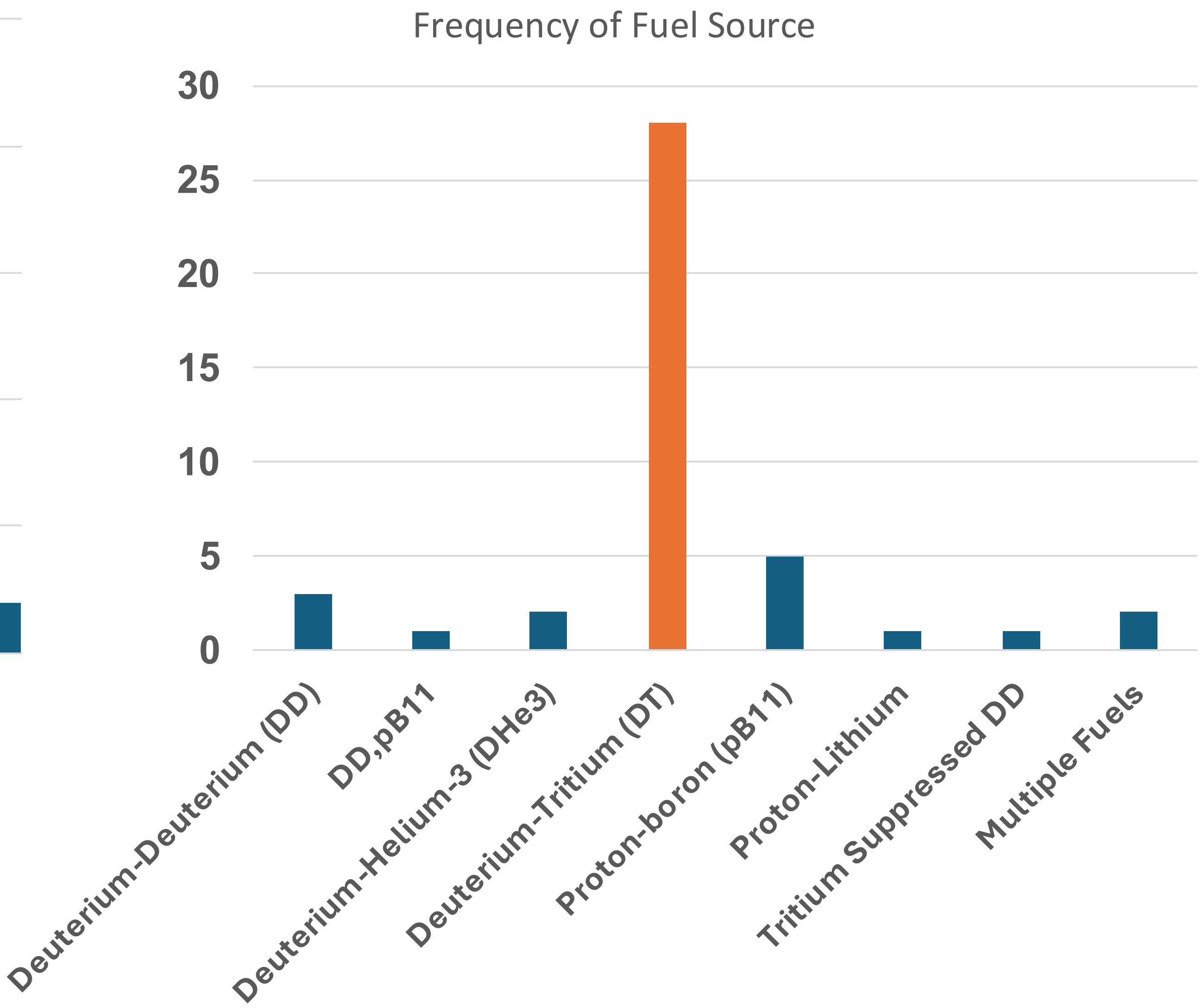


*Figure 2. Frequency of Fuel Source [1]*

[1] The Global Fusion Industry in 2024: Fusion Companies Survey by the Fusion Industry Association

# TEA Focus: D-T Magnetic Confinement Reactor (1000MW Thermal/350 MWe)

| Account # | Account Name |
|---|---|
| **20** | **Direct Costs:** |
| 21.1 | Land & Land Rights |
| 21.2 | Structures & Site Facilities |
| 22 | Reactor Plant Equipment |
| 23 | Turbine Generator Equipment |
| 24 | Electric Plant Equipment |
| 26 | Heat Rejection System |
| 27 | Misc. Plant Equipment |
| **30** | **Indirect Costs:** |
| 31 | Design services at A/E home office |
| 32 | PM/CM services at A/E home office |
| 34 | PM/CM services at plant site (field office) |
| 35 | Construction field supervision at plant site |
| 36 | Field indirect costs (rentals, temp facilities, etc.) |
| 37 | **Plant commissioning service** |
| **40** | **Plant Decommissioning Cost** |
| **60** | **Owner's Cost** |
| **70** | **Annual O&M** |

TEA Features:
- First-of-a-kind (FOAK) vs**. Nth-of-a-kind** (**NOAK)** assumptions
- Bottom-Up Cost Estimate (200+ Cost Accounts),
- Cost Driver Analysis and Sensitivity Study:
  - Impacts of Learning on the manufacturing of FOAK components
  - Nuclear Cost Escalation Factor (Regulation)

**ARAI-FPP:**

ARC-class device with updated information from FIA report & Fusion literature regarding leading candidate materials

**Araiinejad, L.** & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.* https://doi.org/10.1016/J.APENERGY.2025.126567

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| **40** | **Plant Decommissioning Cost** |
| **60** | **Owner's Cost** |
| | |
| **70** | **Annual O&M** |

Energy Economic Database (EEDB) used as the baseline for estimating costs.

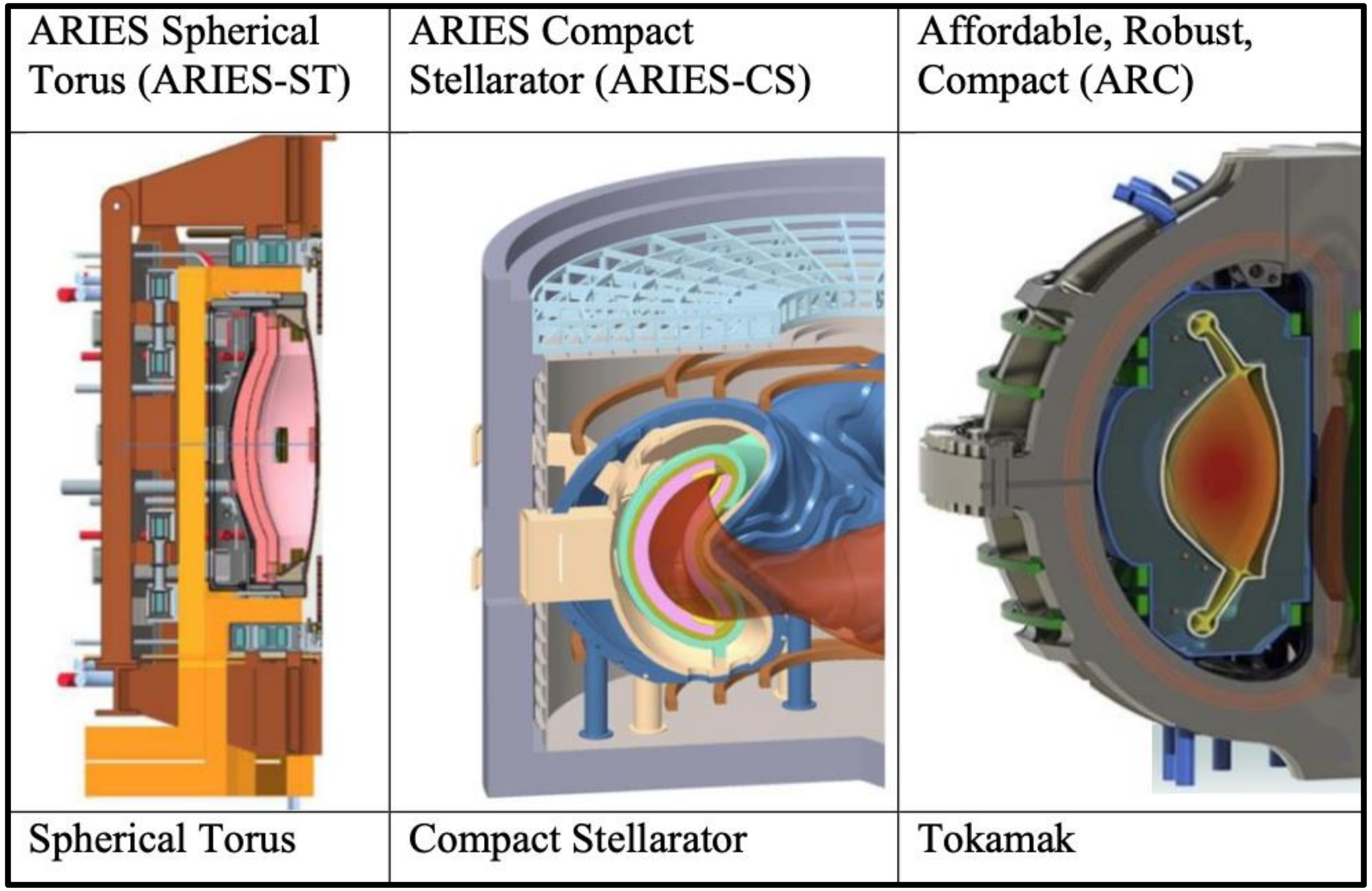
- EEDB provides a detailed cost breakdown of over 1400 cost items for a four-loop 1200 MWe Westinghouse pressurized water reactor (PWR12).
- For each cost item, the EEDB lists:
  - Factory cost
  - Site labor cost
  - Site labor hours
  - Material quantity
  - Material cost

Costs organized using a code of accounts system:

- Database contains costs for:
  - Median experience plant builds (PWR12-ME)
  - Better experience plant builds (PWR12-BE)
    - PWR12-ME capital cost is double that of PWR12-BE.
- In this analysis:
  - PWR12-ME represents the FOAK cost.
  - PWR12-BE represents the NOAK Cost *(Used in this analysis)*

- U.S. Department of Energy (DOE). (1988). Phase IX Update (1987) Report for the Energy Economic Data Base Program (EEDB-IX). DOE/NE-0091, DE88-013033. Prepared by United Engineers & Constructors Inc. under direction of Oak Ridge National Laboratory.
- Araiinejad, L. (2024). *Techno-Economic Analysis of Deuterium-Tritium Magnetic Confinement Fusion Power Plants*. MIT.

# Publicly available data sources that informed cost comparisons for Magnetic Confinement Fusion Concepts

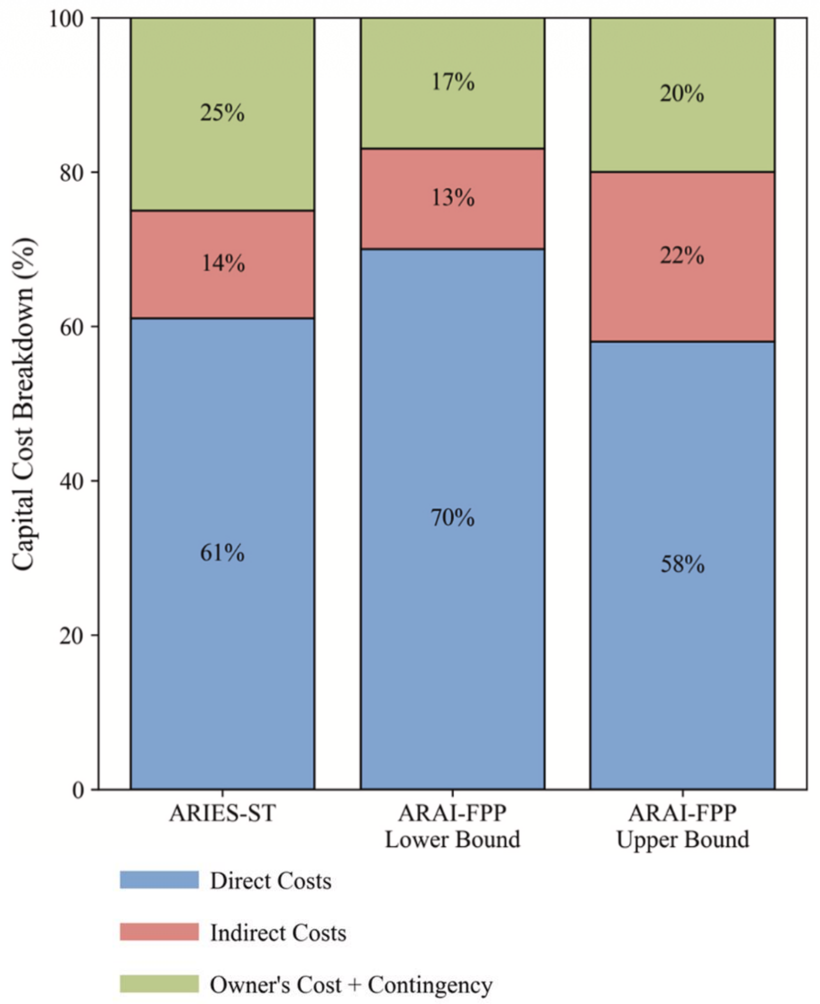


| ARIES Spherical Torus (ARIES-ST) | ARIES Compact Stellarator (ARIES-CS) | Affordable, Robust, Compact (ARC) |
|---|---|---|
| Spherical Torus | Compact Stellarator | Tokamak |

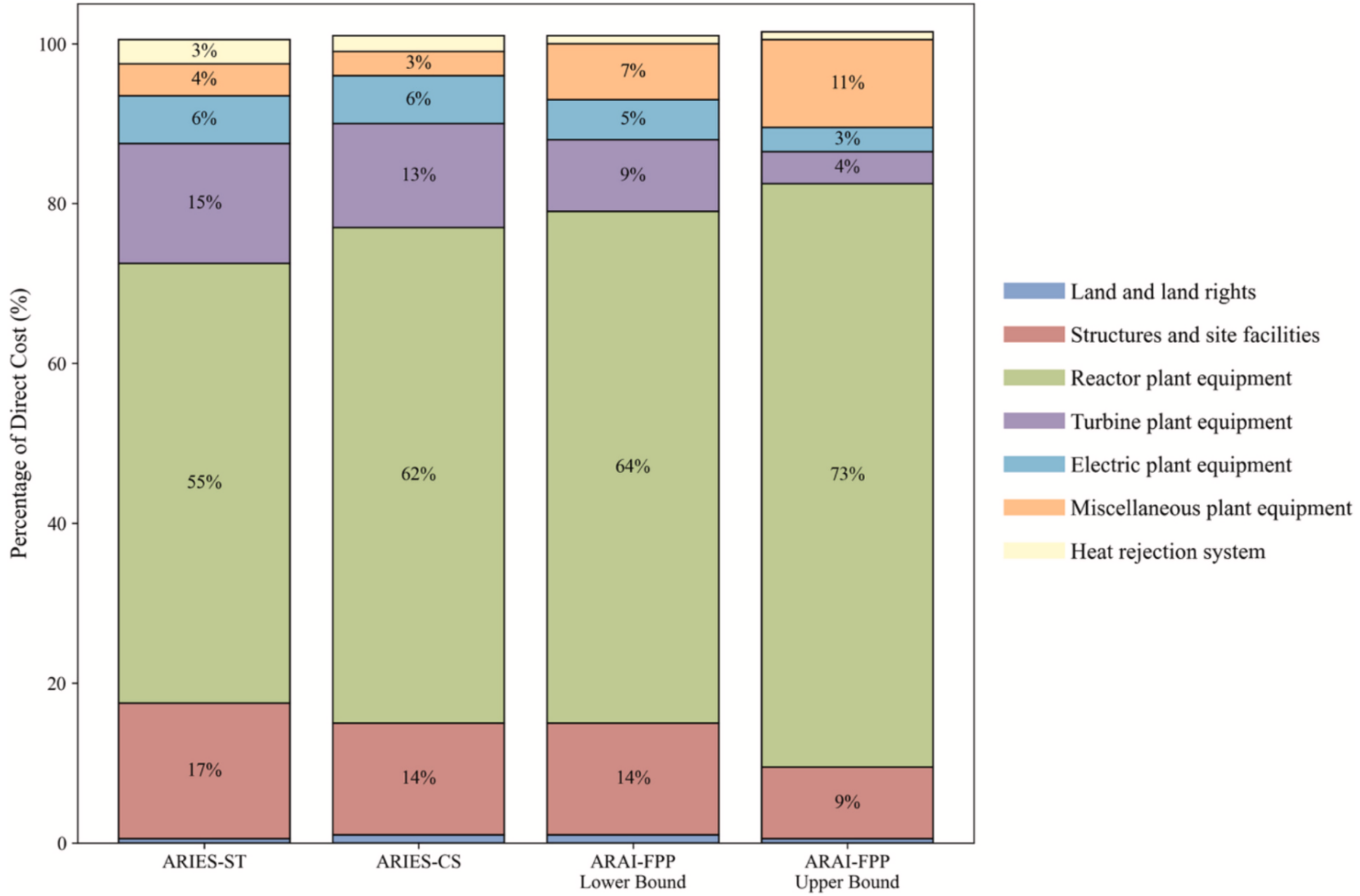
**Advanced Reactor Affordable Integration (ARAI):**
ARC-class tokamak device with updated information from FIA report & Fusion literature regarding leading candidate materials

Najmabadi, F. n.d. “The ARIES-CS-A Compact Stellarator Power Plant.”
Najmabadi, F, and The Aries Team. n.d. “Spherical Torus Concept as Power Plants: The ARIES-ST Study.”
Sorbom, B. N., J. Ball, T. R. Palmer, F. J. Mangiarotti, J. M. Sierchio, P. Bonoli, C. Kasten, et al. 2015. “ARC: A Compact, High-Field, Fusion Nuclear Science Facility and Demonstration Power Plant with Demountable Magnets.” Fusion Engineering and Design 100 (November):378–405.
Araiinejad, L. (2024). *Techno-Economic Analysis of Deuterium-Tritium Magnetic Confinement Fusion Power Plants*. MIT.

# Magnetic Confinement Capital Cost Comparison and Direct Cost Comparison



Capital Cost Comparison



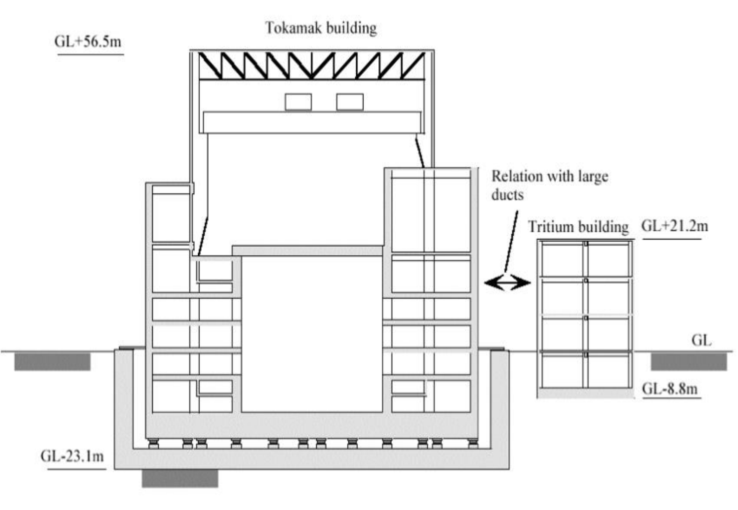
Direct Cost Comparison

**Araiinejad, L.** & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.*
https://doi.org/10.1016/J.APENERGY.2025.126567

# Cost Breakdown and Drivers

Additional Cost drivers ($/kW): Owner's Cost and Indirect costs

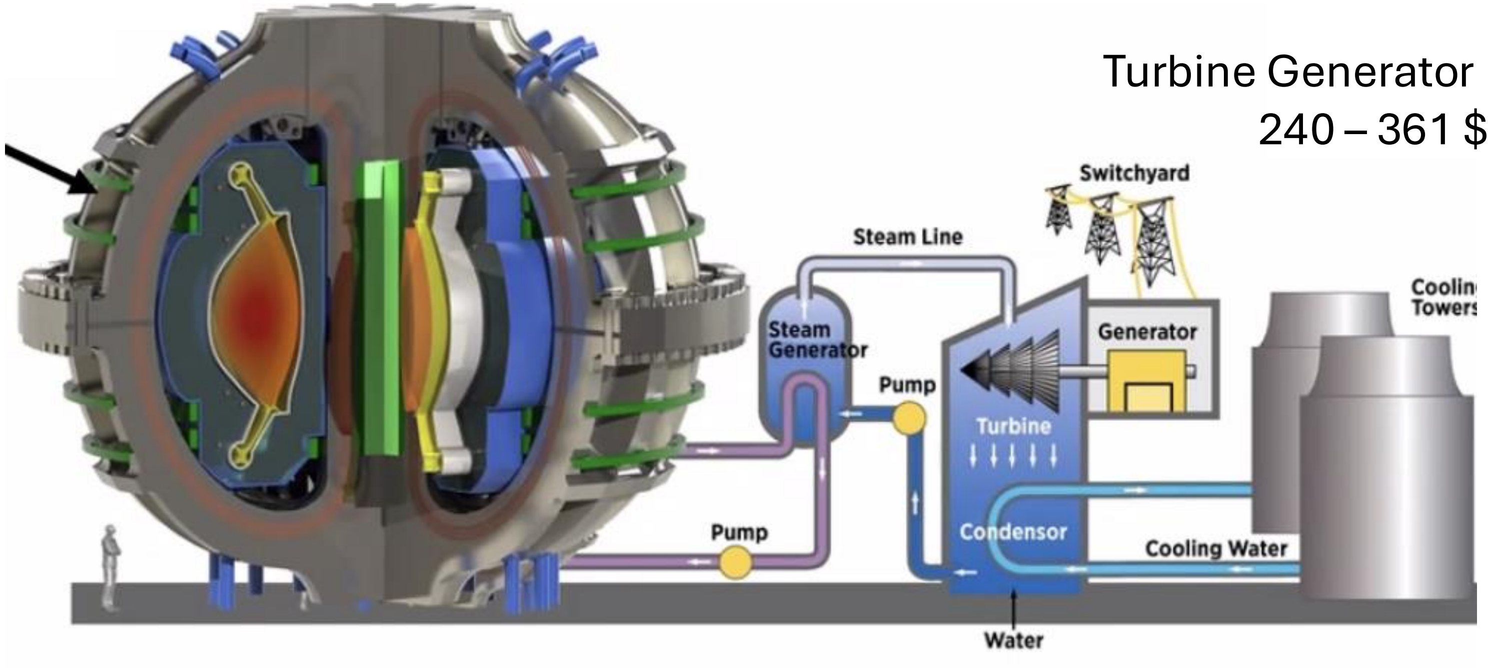
Structures and Site Facilities:
820 – 1,300 $/kW



CASE 1: Tokamak Building - Seismic Isolated
Tritium Buillding - Non-isolated

*Fig. 1 Reactor Building*

Fusion Reactor Plant Equipment:
3,870– 11,100 $/kW



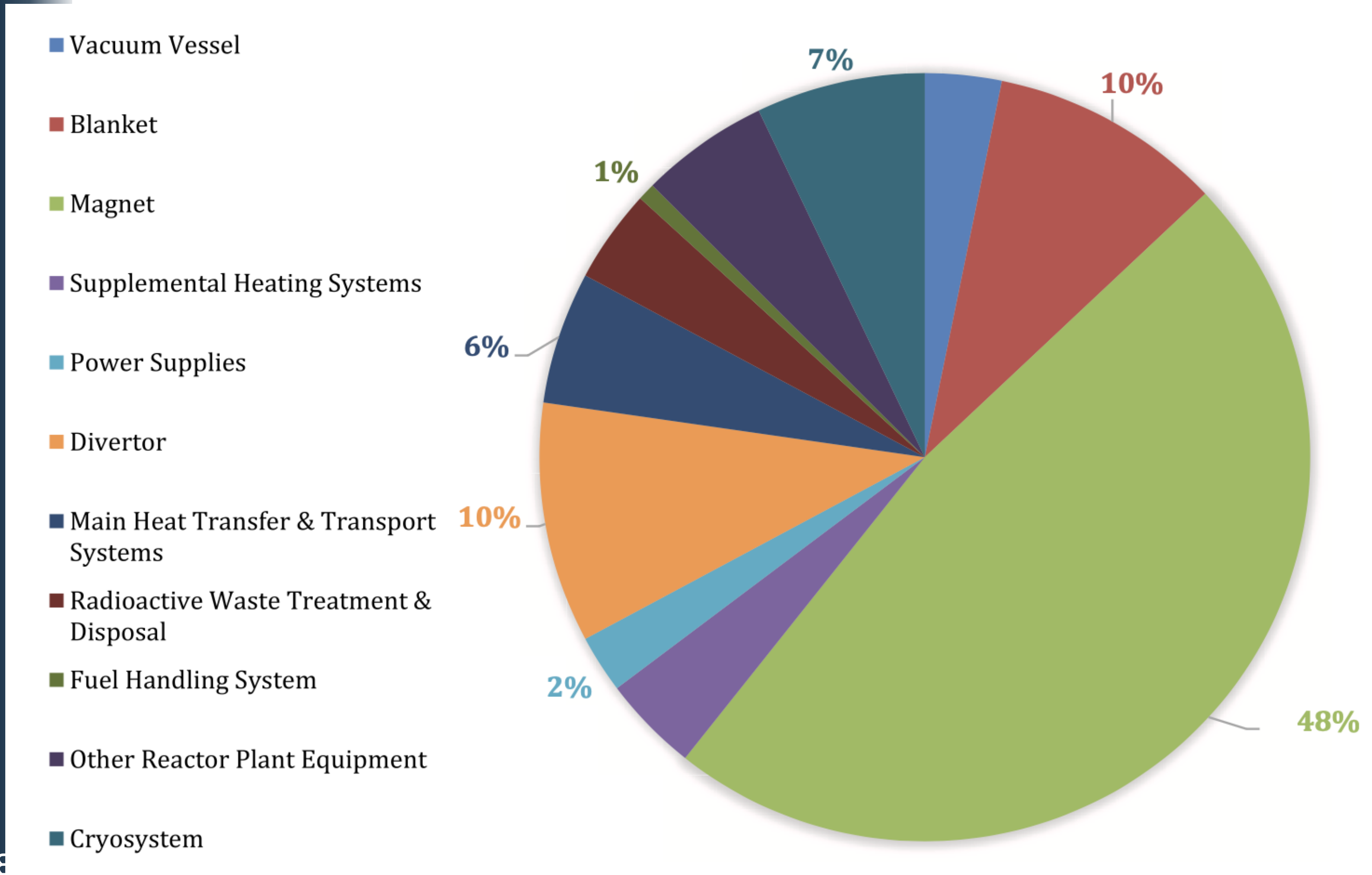
Turbine Generator Equipment:
240 – 361 $/kW

*Figure 2. ARC reactor*

Fig 1: Summary of the ITER Final Design Report (2001)
Fig. 2 : Images courtesy MIT PSFC

# Cost Driver Analysis: Reactor Plant Equipment (RPE): Fabrication

**22 Reactor Plant Equipment: 3,870 – 11,100 $/kW**



Within Reactor Plant Equipment,

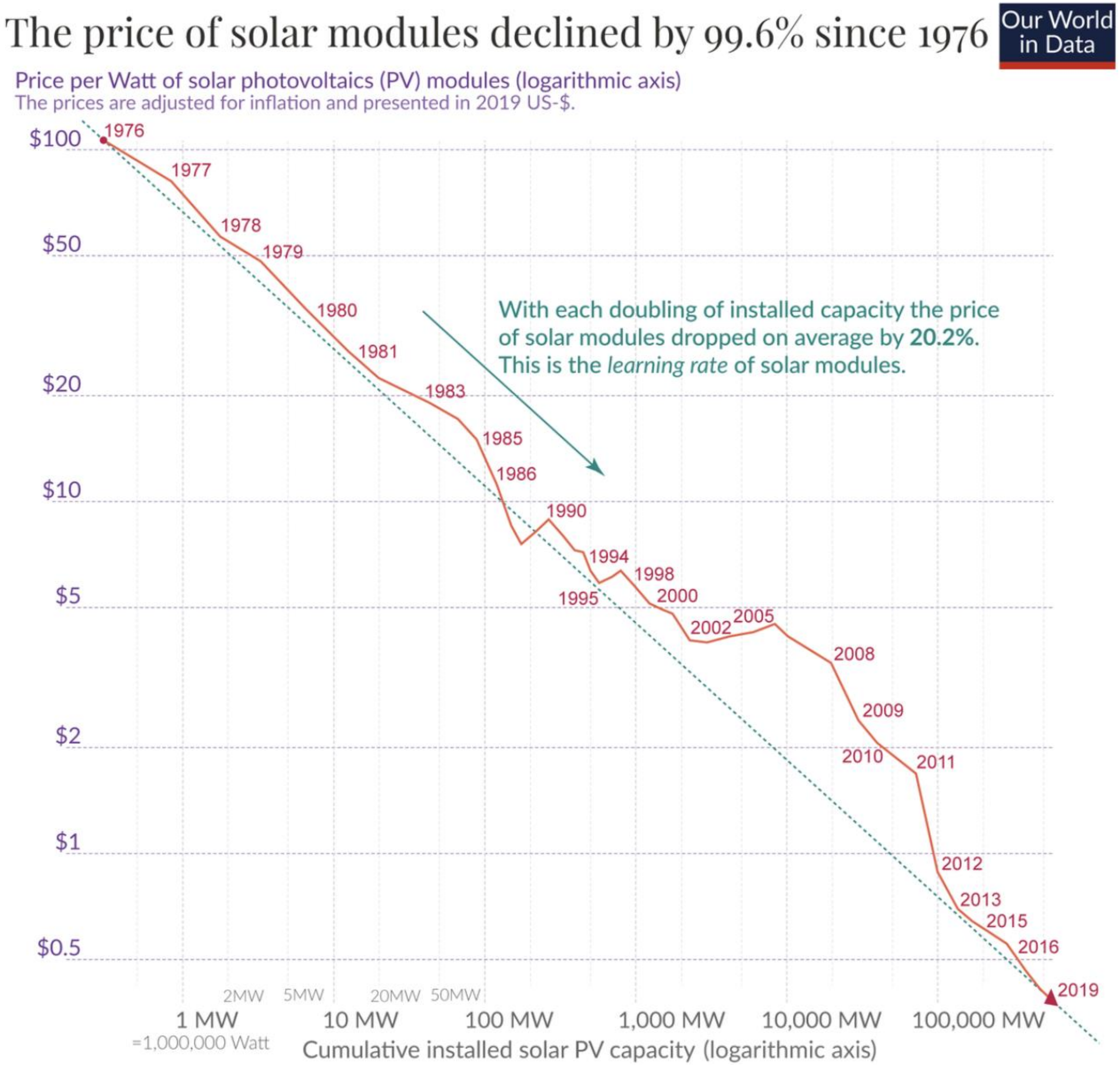
**Fabrication** is the most *sensitive* parameter and the greatest cost driver.

Range of fabrication cost is a factor 5x-9x greater than Material Cost

Fabrication Costs: 150$/kg – 603 $/kg

**Araiinejad, L.** & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.*
https://doi.org/10.1016/J.APENERGY.2025.126567

# Opportunities for learning and cost reduction:



The price of solar modules declined by 99.6% since 1976

Price per Watt of solar photovoltaics (PV) modules (logarithmic axis)

The prices are adjusted for inflation and presented in 2019 US-$.

With each doubling of installed capacity the price of solar modules dropped on average by **20.2%**. This is the *learning rate* of solar modules.

Wright's Law:

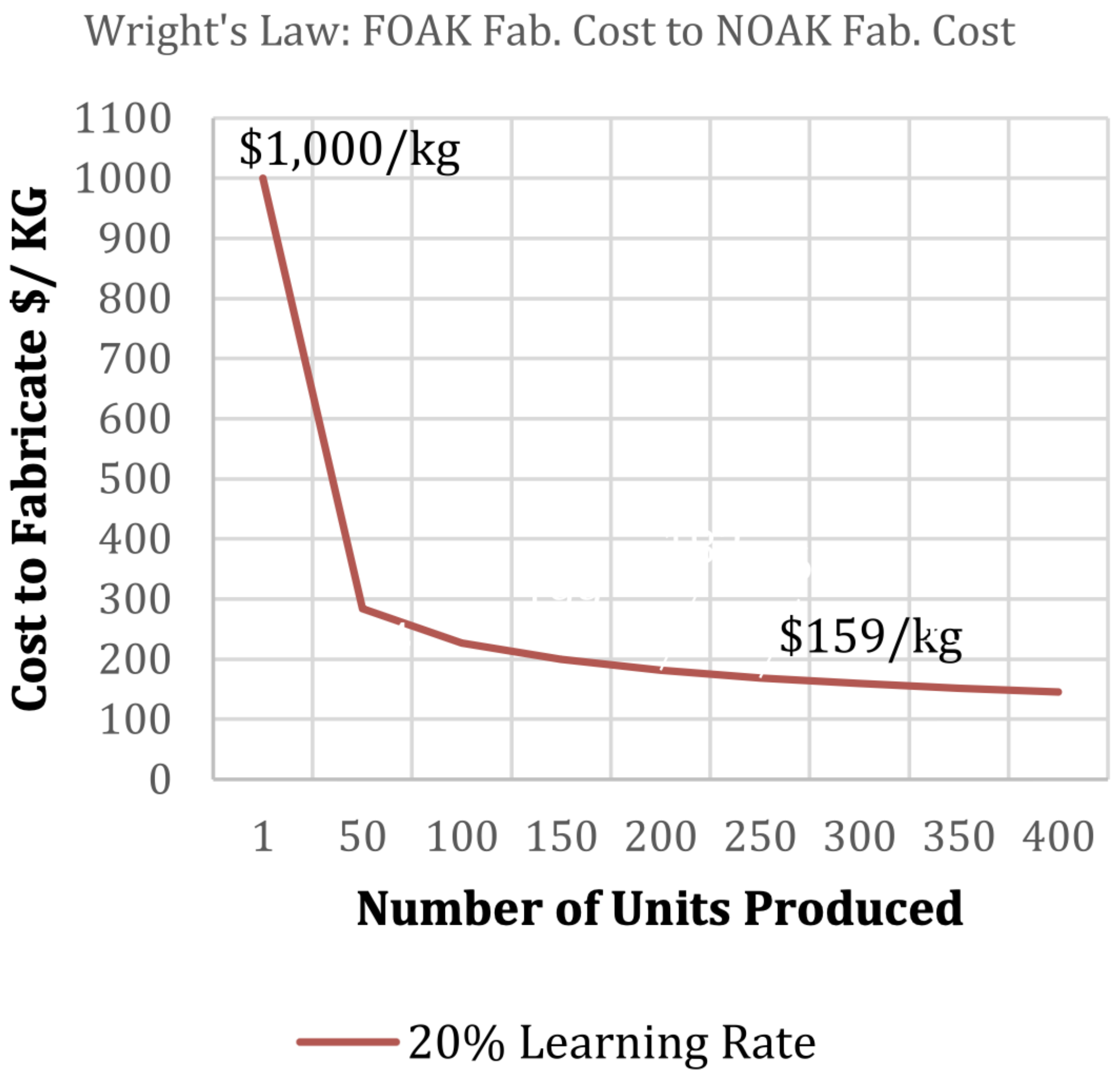
$$\frac{C_N}{C_0} = N^{\log_2(1-r\%)}$$

*Equation 1. Learning rate*

$C_N$ is the cost of the $N$th component,
$C_0$ is the cost of the first component,
$r$ is the learning rate.

Micah Zigler and Jessica Trancik (2021). Re-examining rates of lithium-ion battery technology improvement and cost decline.

# Applying Wright's Law to the Fabrication Costs



- FOAK Manufacturing: $1,000/kg
- NOAK manufacturing cost: ~$159/kg

- The NOAK estimate (~$159/kg) is in the hundreds of dollars per kilogram, consistent with reported costs (~$150/kg) for conventional fabrication methods such as welding and forging.

**Araiinejad, L.** & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.* https://doi.org/10.1016/J.APENERGY.2025.126567

# Levelized Cost of Electricity (LCOE) Equation

- The average lifetime cost of electricity generation ($/MWh)
- Used to benchmark economic competitiveness against other energy sources

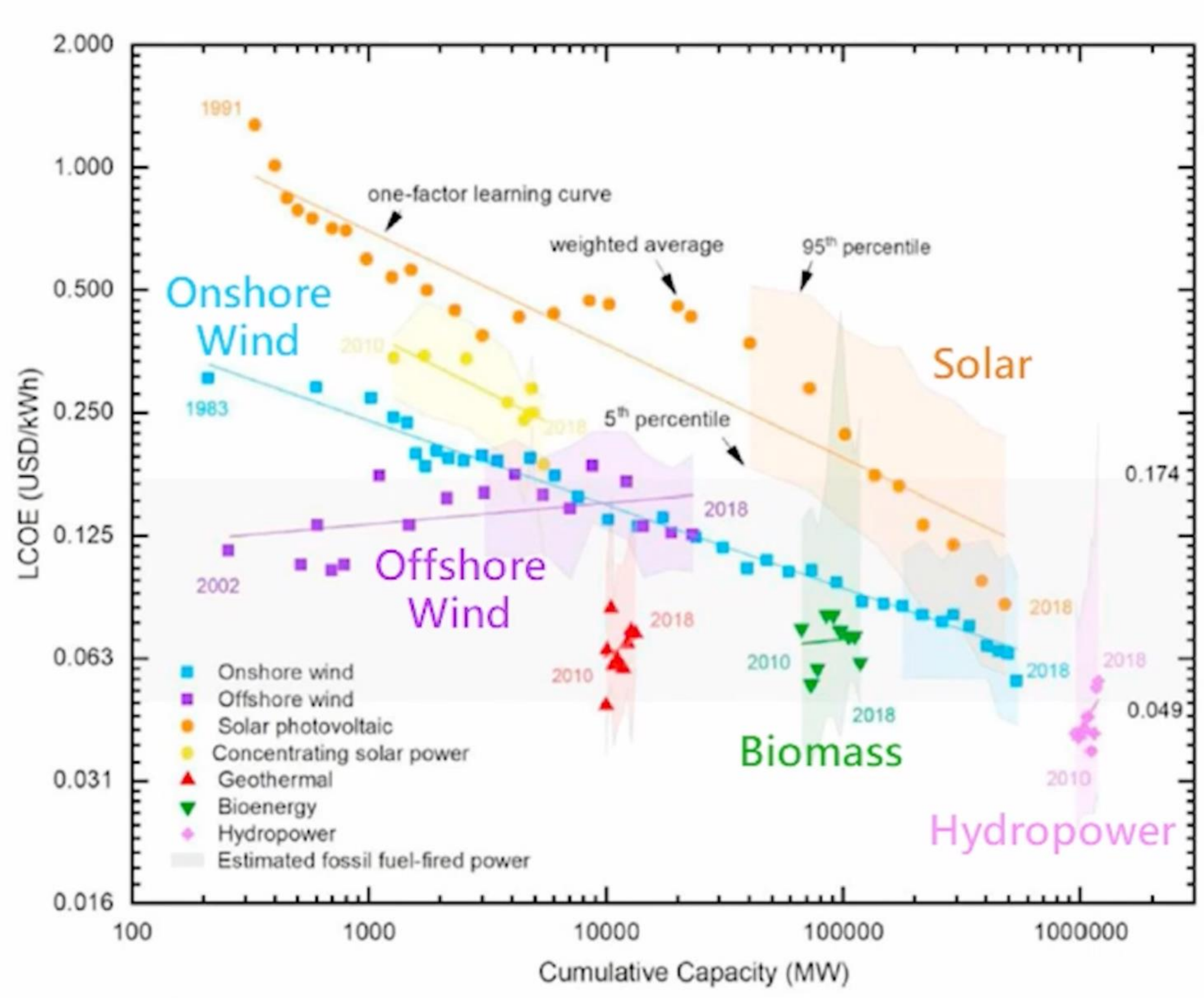
$$\text{Capital Recovery Factor (CRF)} = \frac{[r\times(1+r)]^N}{(1+r)^N-1}$$

$$\text{LCOE}\left(\frac{\$}{\text{MW}}\right) = \left(\frac{\text{OCC}\times\text{CRF}}{\text{CF}\times\text{Hours in a year}}\times 1{,}000\right) + (\text{Annual O\&M})$$

r = discount rate per year
N = total plant lifetime in years
CF = Capacity Factor
Hours in a year = 24 hours in a day x 365 days in a year
Operations and Maintenance (O&M) = annual O&M in $/MWh Overnight Capital Cost
(OCC) = total capital cost in $/kW

**Araiinejad, L**. & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.*
https://doi.org/10.1016/J.APENERGY.2025.126567

# Levelized Cost of Electricity (LCOE) and Learning Rates



Learning rates observed
Solar:

- Concentrated Solar Power: 20%

Wind:

- Onshore Wind: 20%
- Offshore Wind: 9%

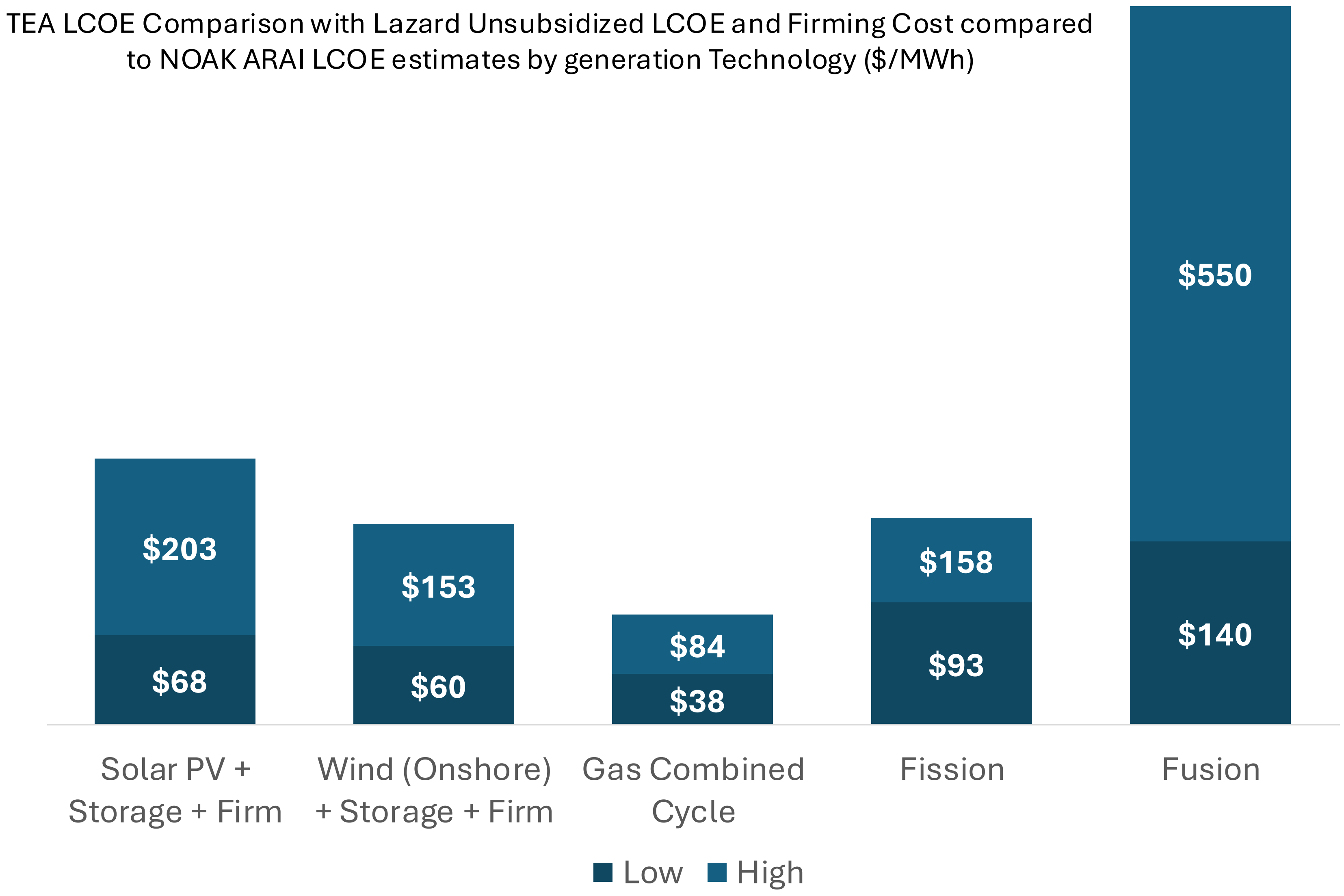
- **Costs fall with deployment, not time**
  LCOE declines primarily as cumulative capacity increases—learning-by-doing and scale drive cost reduction.
- **Modular technologies learn fastest**
  Solar (and onshore wind) show the steepest learning curves, explaining their rapid cost competitiveness.

Yao, Y., Xu, J. H., & Sun, D. Q. (2021). Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: Wind, solar, geothermal, hydropower and bioenergy. Journal of Cleaner Production, 285, 124827.

D-T

MC

# LCOE Comparison across Energy Technologies


TEA LCOE Comparison with Lazard Unsubsidized LCOE and Firming Cost compared to NOAK ARAI LCOE estimates by generation Technology ($/MWh)

**Araiinejad, L**. & Shirvan, K. (2025). **The Techno-economic Analysis of Deuterium-Tritium Fusion Power Plants**. *Applied Energy, 401, 126567.* https://doi.org/10.1016/J.APENERGY.2025.126567
“Lazard’s Levelized Cost of Energy Analysis -- Version 17.0 .” 2024. Lazard.

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MC

# LCOE Comparison across Energy Technologies

**LCOE Parameters:**

- **Capacity Factor:** 0.7
- **Plant lifetime:** 30 years
- **O&M Results**: $35/MWh to $182/MWh – Driven by Maintenance and Replacement of key Fusion Reactor Equipment

- **Methodology**: Bottom-up Cost Analysis: 1000 MW thermal/350 MWe (net)
  - NOAK Estimate is based on ~100 GW of installed by 2050.
    - Significant number of Equipment are Fusion Specific – Low TRL (High uncertainty)
  - NOAK Estimate bounds:
    - Lower Bound: non-nuclear power plant with minimal consideration for Radiation Safety
    - Upper Bound: Best in-class fission power plant scaling with minimal radiation hazard

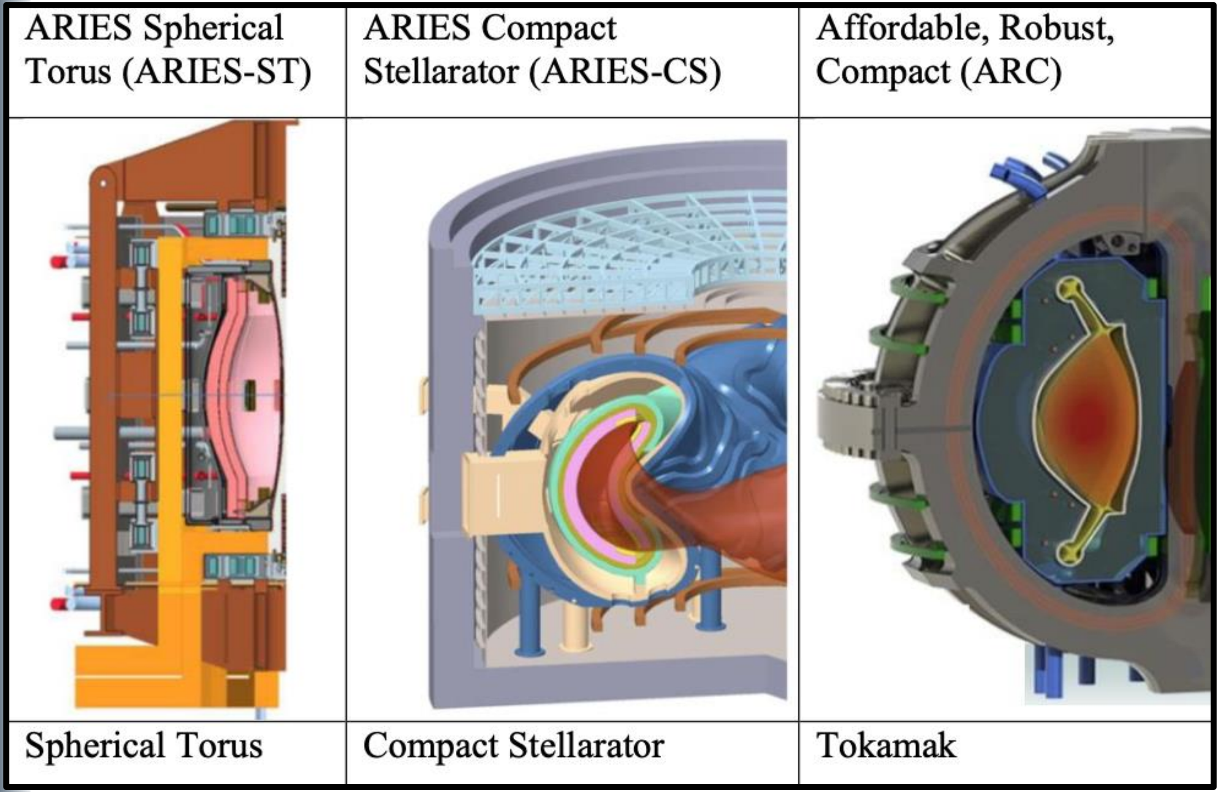
- **Results**: $8,171 -22,180 $/kW Overnight Capital Cost – Driven by Fusion Reactor (Magnet) Equipment Cost
  - Large range is driven by two main factors:
    - Uncertainty in the NOAK cost of Magnet system fabrication
    - Regulatory Treatment of Fusion relative to non-nuclear power sources (Solar Thermal)

# Normalized Cost estimates of various Fusion Technologies

Source: *The Role of Fusion in a Decarbonized Electricity System*

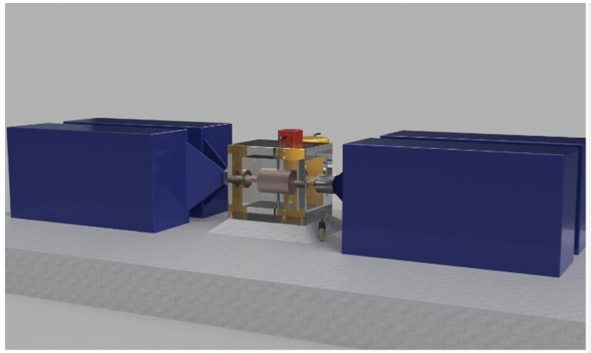
# Publicly available data sources that informed cost comparisons

Magnet Confinement Fusion

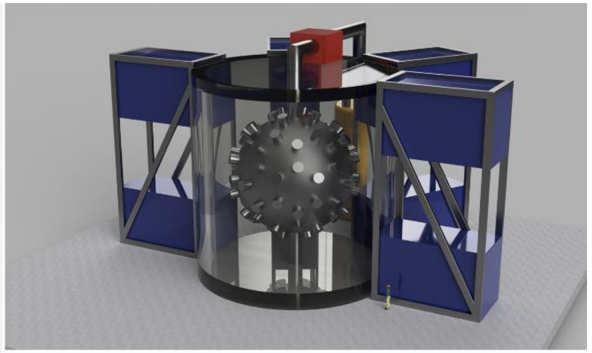


| ARIES Spherical Torus (ARIES-ST) | ARIES Compact Stellarator (ARIES-CS) | Affordable, Robust, Compact (ARC) |
|---|---|---|
| Spherical Torus | Compact Stellarator | Tokamak |

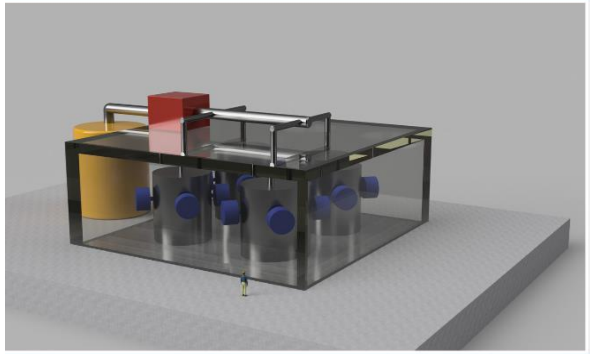
Magneto-Inertial Fusion



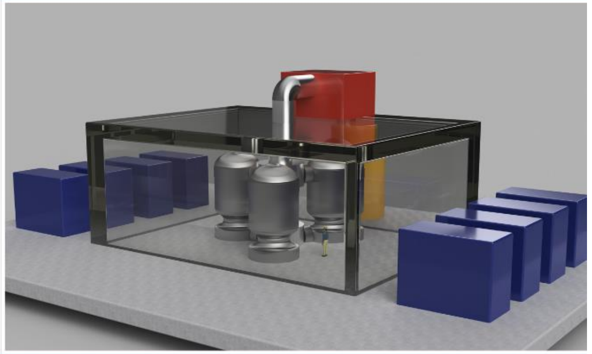
Stabilized Liner Compressor



Plasma Jet Driven Magneto-Inertial Fusion



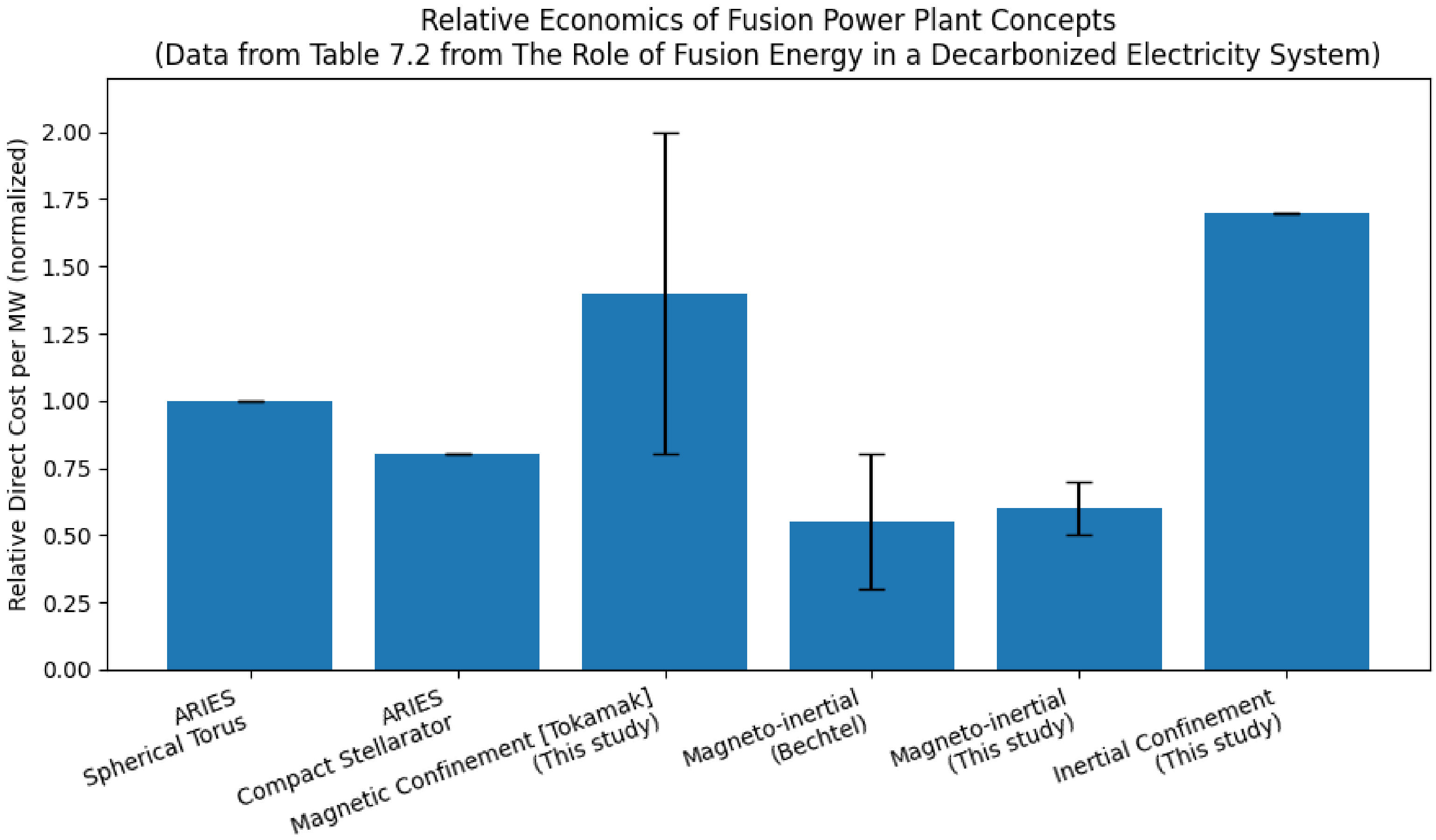
Staged Z-Pinch



Sheared Flow Stabilized Z-Pinch

Najmabadi, F. n.d. “The ARIES-CS-A Compact Stellarator Power Plant.”
Najmabadi, F, and The Aries Team. n.d. “Spherical Torus Concept as Power Plants: The ARIES-ST Study.”
Sorbom, B. N., J. Ball, T. R. Palmer, F. J. Mangiarotti, J. M. Sierchio, P. Bonoli, C. Kasten, et al. 2015. “ARC: A Compact, High-Field, Fusion Nuclear Science Facility and Demonstration Power Plant with Demountable Magnets.” Fusion Engineering and Design 100 (November):378–405.
“Conceptual Cost Study for a Fusion Power Plant on Four Technologies from the DOE ARPA-E ALPHA Program.” 2017.

# Relative Capital Cost per MW Across Fusion Power Plant Studies

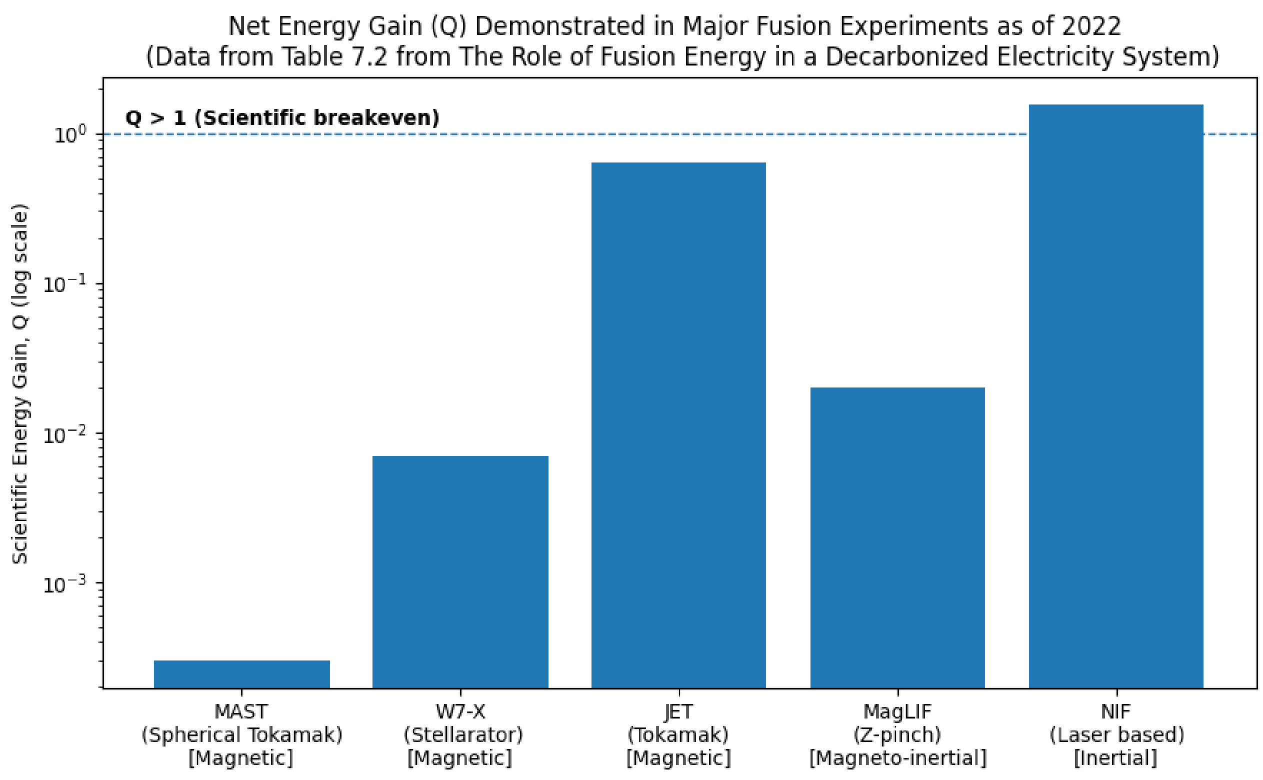


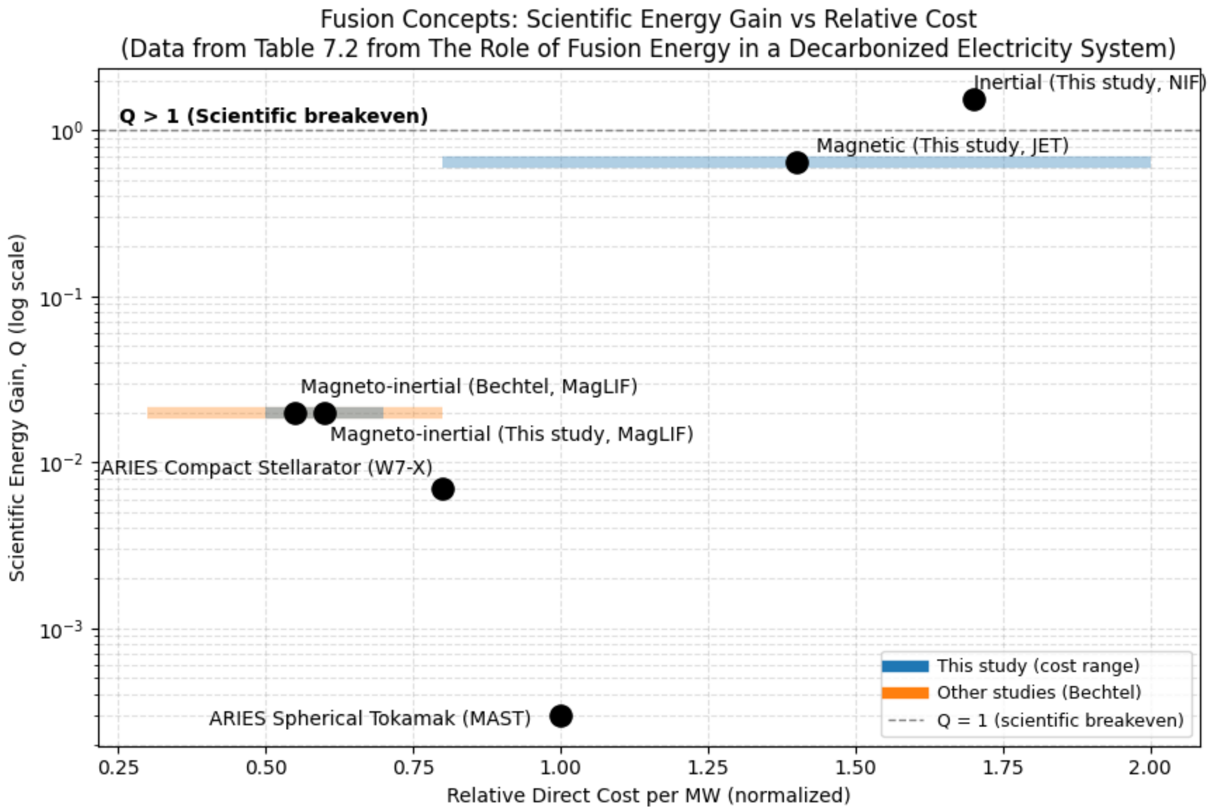
**Study Context:**
This study conducts a **bottom-up TEA** of magnetic confinement and **top-down cost estimate** to magneto-inertial and inertial concepts. Results are compared with **ARIES point estimates** and **Bechtel's range-based magneto-inertial analysis**, which evaluated multiple configurations.

**Key takeaways**

- Capital cost per MW varies strongly by fusion approach and design assumptions
- Magneto-inertial concepts consistently fall in the lower-cost regime
- Magnetic confinement exhibits a wide cost range due to design and regulatory uncertainty

# Comparison of Demonstrated Scientific Gain and Relative Cost Across Fusion Concepts





Data taken from: MIT Energy Initiative. (2024). *The Role of Fusion Energy in a Decarbonized Electricity System*.

Sources: For the ARIES Studies, see Najmabadi et al. (2006); for the Bechtel study, see Woodruff et al. (2017).Values for scientific energy gain values are from Wurzel and Hsu (2022) and Messinger (2022). They are derived from the UK's Mega Amp Spherical Tokamak (MAST), Germany's Wendelstein 7-X stellarator (W7-X), the Joint European Torus (JET), Magnetic Liner Inertial Fusion (MagLIF) experiments at Sandia National Laboratory, and the United States' National Ignition Facility (NIF).

# Conclusion

- **Techno-economic analysis (TEA) is essential** for guiding fusion to become an economically viable energy source
- **Cost uncertainty remains high**—true capital and operating costs will only be revealed with the first-of-a-kind (FOAK) fusion power plant
- **Scenario-based assumptions** enable insight into NOAK cost trajectories and potential brownfield savings
- **Both technical and capital risks must be evaluated together** to form a comprehensive view of fusion viability

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