# ARPA-E Costing Analysis

## BETHE Kickoff Virtual Workshop
## Aug. 11–12, 2020

Simon Woodruff, Woodruff Scientific
Ronald L. Miller, Decysive Systems
Eric Ingersoll, Lucid Catalyst
Mike Zarnstorff, Princeton Plasma Physics Laboratory

# Team members and roles

Simon Woodruff, PI (2017-)

Ronald L. Miller, Co-PI (2017-)

Eric Ingersoll, Co-PI  (2019-)

Mike Zarnstorff, Co-PI (2020-)

WOODRUFF • SCIENTIFIC

Decysive Systems

LUCID CATALYST

PPPL PRINCETON PLASMA PHYSICS LABORATORY

# High-level motivation and goals of the costing project

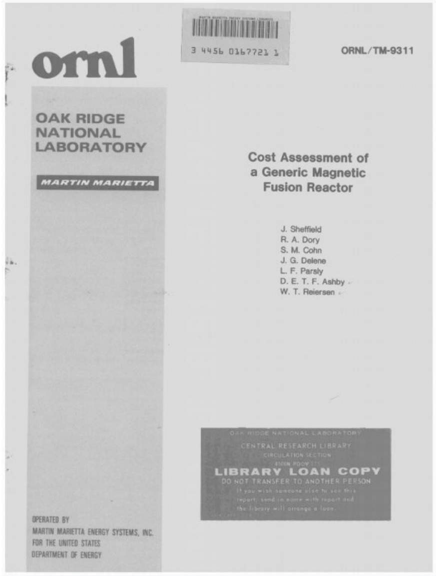
Ground up cost analysis of fusion energy technology

Cost modeling with device specific costing

Cost optimization

Cost calibration against existing systems

# ARPA-E 2017 Costing informed by prior work



ornl

ORNL/TM-9311

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Cost Assessment of a Generic Magnetic Fusion Reactor

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OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC. FOR THE UNITED STATES DEPARTMENT OF ENERGY


Journal of Fusion Energy
October 2010, Volume 29, Issue 5, pp 447–453 | Cite as

## Why Compact Tori for Fusion?

Authors | Authors and affiliations

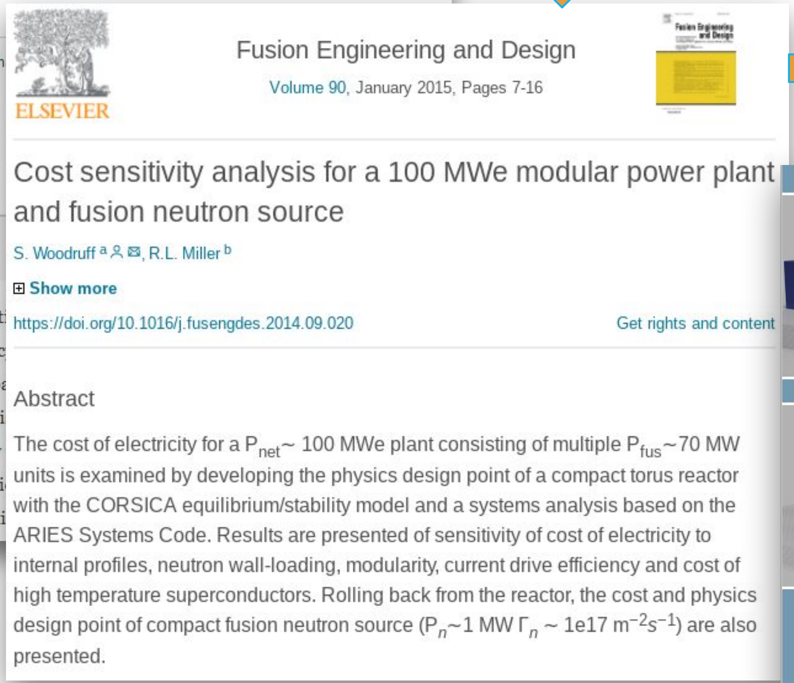
S. Woodruff, M. Brown, E. B. Hooper, R. Milroy, M. Sch

Original Research
**First Online:** 12 June 2010

104 Downloads 5 Citations

### Abstract

A compact torus (CT) has a toroidal magnet simply-connected vacuum vessel such as a c configurations fall into this category. Compa beta. The primary benefit of CTs for fusion i coils and the many problems brought on by connected geometries affords the world fusi opportunities not found in other configurati


ELSEVIER

Fusion Engineering and Design
Volume 90, January 2015, Pages 7-16

## Cost sensitivity analysis for a 100 MWe modular power plant and fusion neutron source

S. Woodruff [a], R.L. Miller [b]

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https://doi.org/10.1016/j.fusengdes.2014.09.020

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### Abstract

The cost of electricity for a $P_{net}$~ 100 MWe plant consisting of multiple $P_{fus}$~70 MW units is examined by developing the physics design point of a compact torus reactor with the CORSICA equilibrium/stability model and a systems analysis based on the ARIES Systems Code. Results are presented of sensitivity of cost of electricity to internal profiles, neutron wall-loading, modularity, current drive efficiency and cost of high temperature superconductors. Rolling back from the reactor, the cost and physics design point of compact fusion neutron source ($P_n$~1 MW $\Gamma_n$ ~ 1e17 $m^{-2}s^{-1}$) are also presented.


Stabilized Liner Compressor

Plasma Jet Driven Magneto-Inertial Fusion

Staged Z-Pinch

Sheared Flow Stabilized Z-Pinch

Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program

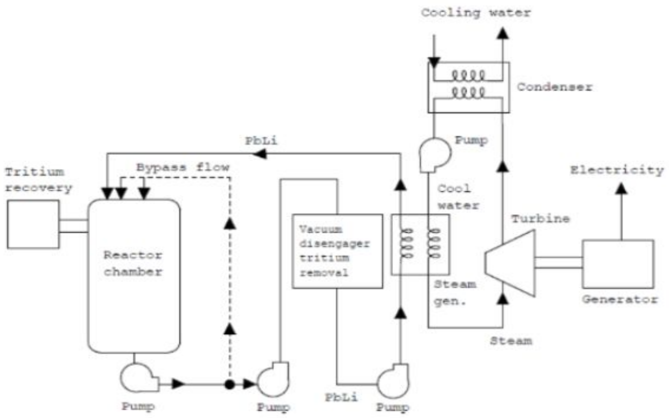
Bechtel National, Inc.
Woodruff Scientific, Inc.
Decysive Systems

Bechtel National, Inc.
Report No. 26029-000-30R-G01G-00001

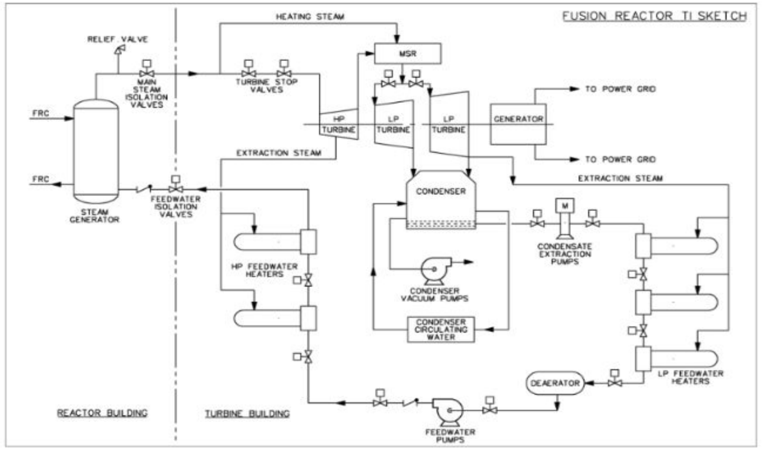
February 2017

# ARPA-E 2017 Costing analysis was performed with Bechtel

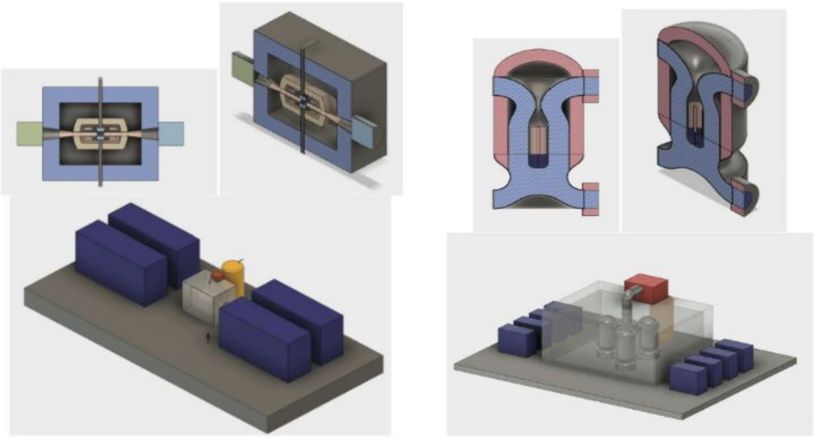
## Balance of Plant: coolant



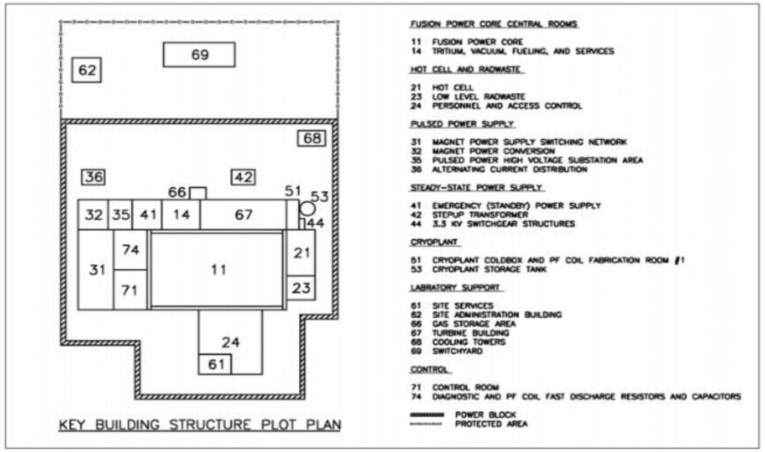

## Balance of Plant: turbines




## Fusion power cores



## Site

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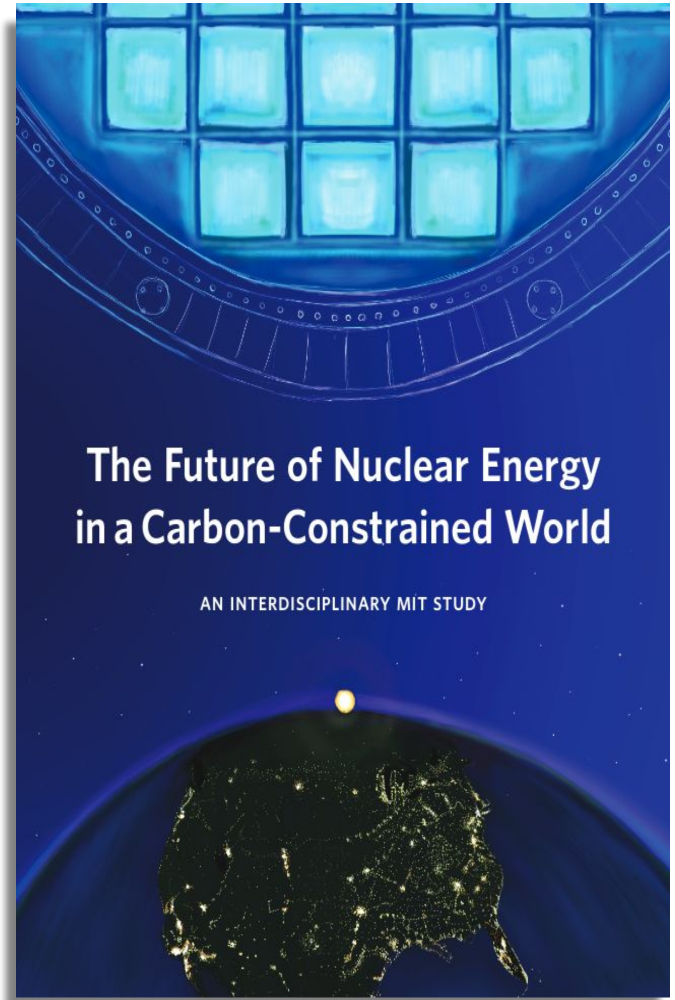
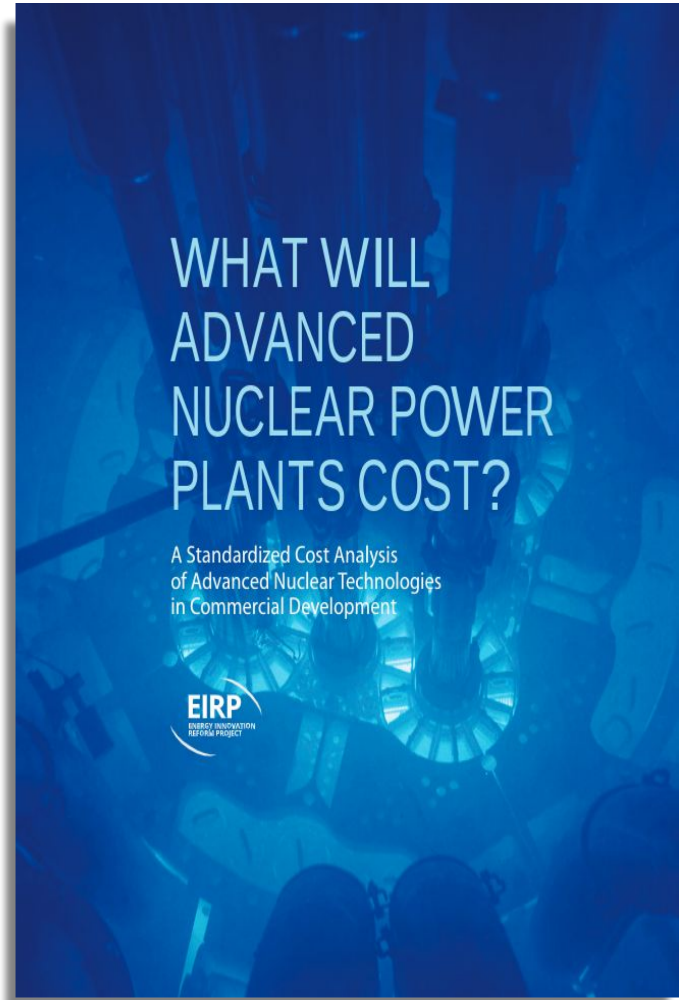
# Main results for Total Capital Cost (4 ALPHA concepts averaged)

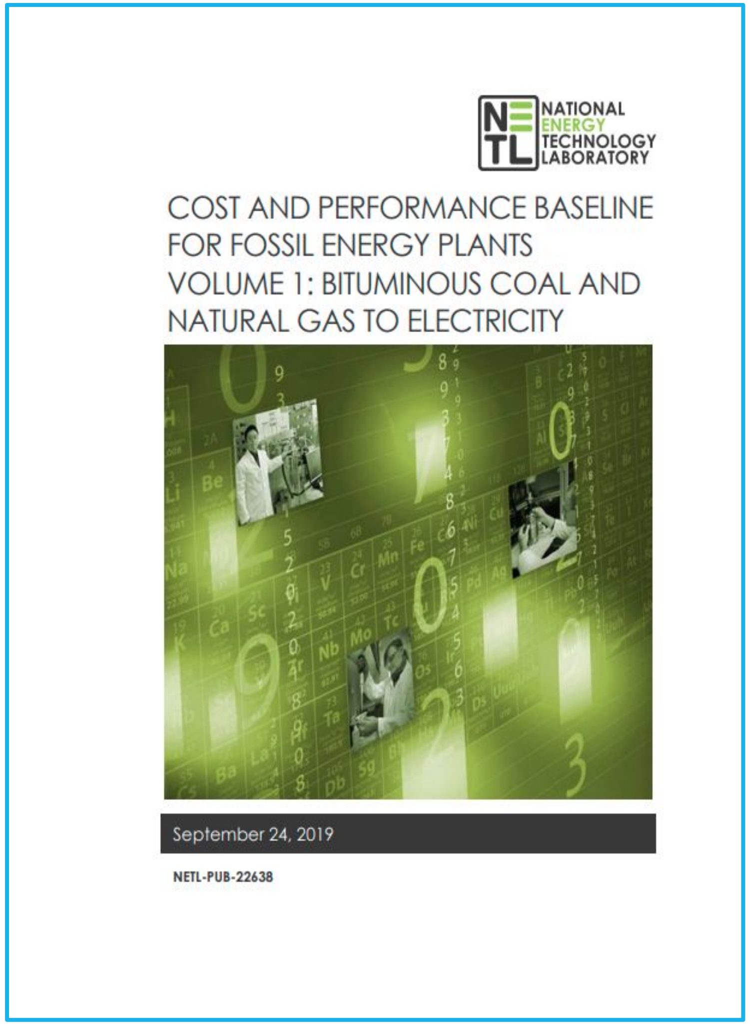
Design point was for 150MWe

| CBS # | Cost Element | Mean Estimated Overnight Cost ($M) (2016 USD) | Percent of Total Estimated Cost |
|---|---|---|---|
| 20 | Land & Land Rights | $17 | 1% |
| 21 | Structures & Site Facilities | $188 | 15% |
| 22 | Reactor Plant Equipment | $267 | 21% |
| 23 | Turbine Plant Equipment | $125 | 10% |
| 24 | Electric Plant Equipment | $46 | 4% |
| 25 | Miscellaneous Plant Equipment | $23 | 2% |
| 26 | Special Materials | $8 | 1% |
| **90** | **Total Direct Costs** | **$675** | **53%** |
| | **Indirect Costs** | | |
| 91 | Construction Services & Equipment | $101 | 8% |
| 92 | Home Office Engineering & Services | $34 | 3% |
| 93 | Field Office Engineering & Services | $68 | 5% |
| 94 | Owner's Costs | $34 | 3% |
| 95 | Process Contingency | $207 | 16% |
| 96 | Project Contingency | $149 | 12% |
| 97 | Interest During Construction | Not Included | Not Included |
| 98 | Escalation During Construction | Not included | Not included |
| **91-96** | **Total Indirect Costs** | **$592** | **47%** |
| **99** | **Total Overnight Project Cost** | **$1,268** | **100%** |

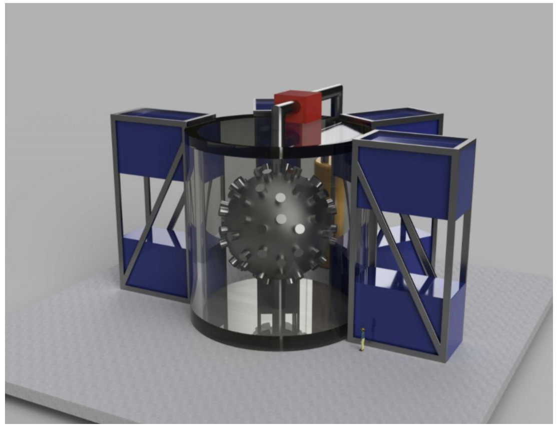
# In 2019-2020 ARPA-E revisited the 2017 study in light of new cost information

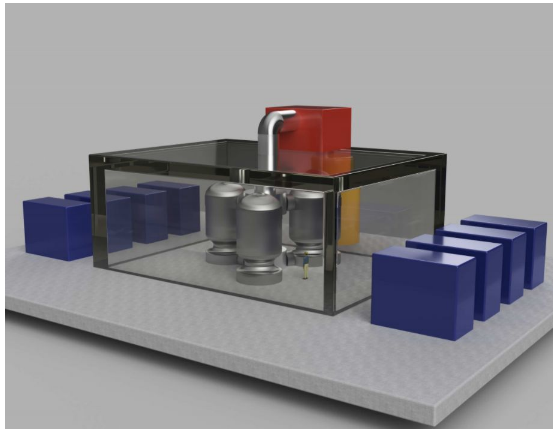


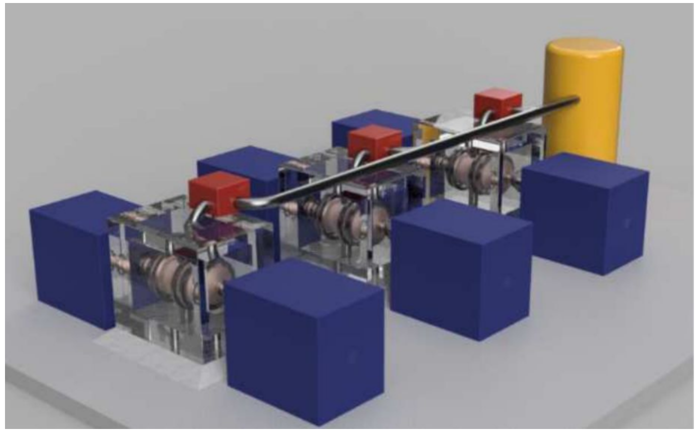



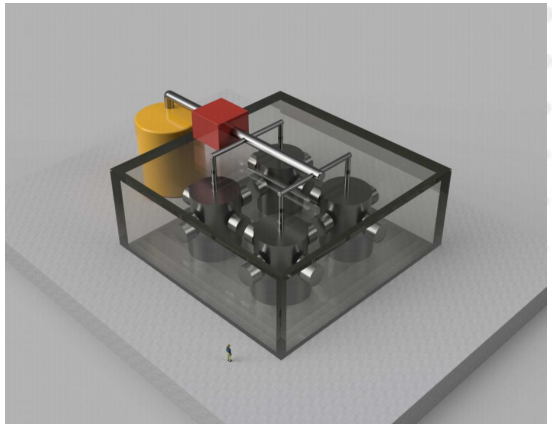



# Preliminary results for capital costs for 4 fusion plants









| | Average | Lowest | Highest | |
|---|---|---|---|---|
| N_mod | 2.75 | 1 | 4 | |
| Fusion Power | 1187.5 | 529 | 1920 | MW |
| Alpha Power | 239.45 | 118.3 | 382 | MW |
| Neutron power | 964.55 | 476.7 | 1538 | MW |
| Thermal power | 1373.625 | 702.2 | 2208.4 | MW |
| Net electric power | 399.275 | 202.8 | 714.8 | MW |

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# Preliminary results for capital costs ...

| CAS | Cost (M$) | Lowest | Highest |
|---|---|---|---|
| 20. Land/Rights | 10.7825 | 5.48 | 19.3 |
| 21. Structures/Site | 181.27 | 92.07 | 324.52 |
| 22. Reactor Plant Equip. | 286.435 | 168.07 | 430.82 |
| 22.1 Reactor Equip. | 156.26 | 60.75 | 254.24 |
| 22.1.1 First Wall/Blanket | 56.5125 | 0.35 | 116.49 |
| 22.1.2 High Temp. Shield | 19.905 | 5.04 | 28.49 |
| 22.1.3 Coils | 0.8025 | 0 | 2.28 |
| 22.1.4 Suppl. Heating | 3.1 | 0 | 12 |
| 22.1.5 Primary Structure | 25.185 | 11.35 | 40 |
| 22.1.6 Vacuum System | 0.1575 | 0.07 | 0.32 |
| 22.1.7 Power Supplies | 45.6575 | 3.98 | 140.4 |
| 22.1.8 Plasma Source | 0.85 | 0.6 | 1 |
| 22.1.9 Direct E. Conv. | 0 | 0 | 0 |
| 22.1.10 ECRH | 0 | 0 | 0 |
| 22.1.11 Assembly and installation | 4.09 | 1.25 | 7.44 |
| 22.2 Main Heat Transfer | 80.895 | 52.79 | 118.66 |
| 22.3 Auxiliary Cooling | 2.5825 | 1.32 | 4.15 |
| 22.4 Rad. Waste Treat. | 4.6025 | 2.35 | 7.4 |
| 22.5 Fuel Processing | 35.8 | 35.8 | 35.8 |
| 22.6 Other plant equipment | 4.18 | 2.14 | 6.72 |
| 22.7 Instrumentation and control | 2.115 | 0 | 3.85 |
| 23. Turbine Plant Equip. | 106.2075 | 53.94 | 190.14 |
| 24. Electric Plant Equip. | 45.5175 | 23.12 | 81.49 |
| 25. Misc. Plant Equip. | 98.37 | 43.92 | 152.42 |
| 26. Heat Rejection | 42.7225 | 21.7 | 76.48 |
| 27. Special Materials | 103.1325 | 1.37 | 266.91 |
| 90. Total Direct Cost | 874.4325 | 610.97 | 1328.89 |
| 91. Construction Serv./Mat. | 22.7975 | 15.9 | 30.42 |
| 92. Home Office Eng./Serv. | 27.36 | 19.08 | 36.5 |
| 93. Field Office Eng./Serv. | 9.12 | 6.36 | 12.17 |
| 94. Owners Cost | 32.985 | 23 | 44.01 |
| 96. Contingency | 0 | 0 | 0 |
| 97. Interest During Constr. | 45.1425 | 31.48 | 60.23 |
| 99. Total Capital Cost: | 1011.8425 | 719.91 | 1490.44 |

# … and Levelized Cost of Electricity

| | Average | Lowest | Highest | |
|---|---|---|---|---|
| Capital cost | 101.175 | 72 | 149 | M\$/annur |
| Scheduled Replacement Costs | 11.65 | 0.1 | 24 | M\$/annur |
| Operations and Maintenance Costs | 41.775 | 30.6 | 57.4 | M\$/annur |
| Fuel Costs | 0.075 | 0 | 0.1 | M\$/annur |
| Decontamination and Decommissionin | 0.5 | 0.5 | 0.5 | mills/kWh |
| | | | | |
| COE | 60.695 | 40.79 | 101.5 | mills/kWh |
| COE2 | 51.8925 | 35.72 | 82.83 | mills/kWh |

(COE2 is with learning curve costs applied to the centralized manufacture of fusion power core components).

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# Next steps for the costing team include the following:

1. Widen the scope - we now have a very flexible costing framework that can be offered to many other groups with now ‘standardized outputs’.

2. Offer cost reduction strategies

3. Provide calibration of the cost data with reference to work ongoing elsewhere.

4. Provide design-to-cost information, based on most recent work in the nuclear sector.

# Summary

ARPA-E started cost analysis for fusion concepts, working with Bechtel in 2017

In 2019, ARPA-E supported a small team to revisit the costing in light of recent cost studies elsewhere.

This lead to a cost reduction in most categories outside of the fusion power core for all previous concepts.

And a new direction to pursue for reducing uncertainties in cost analysis, and provision of cost reduction strategies for fusion development across the board.

# In 2019-2020 ARPA-E revisited the 2017 study in light of new cost information


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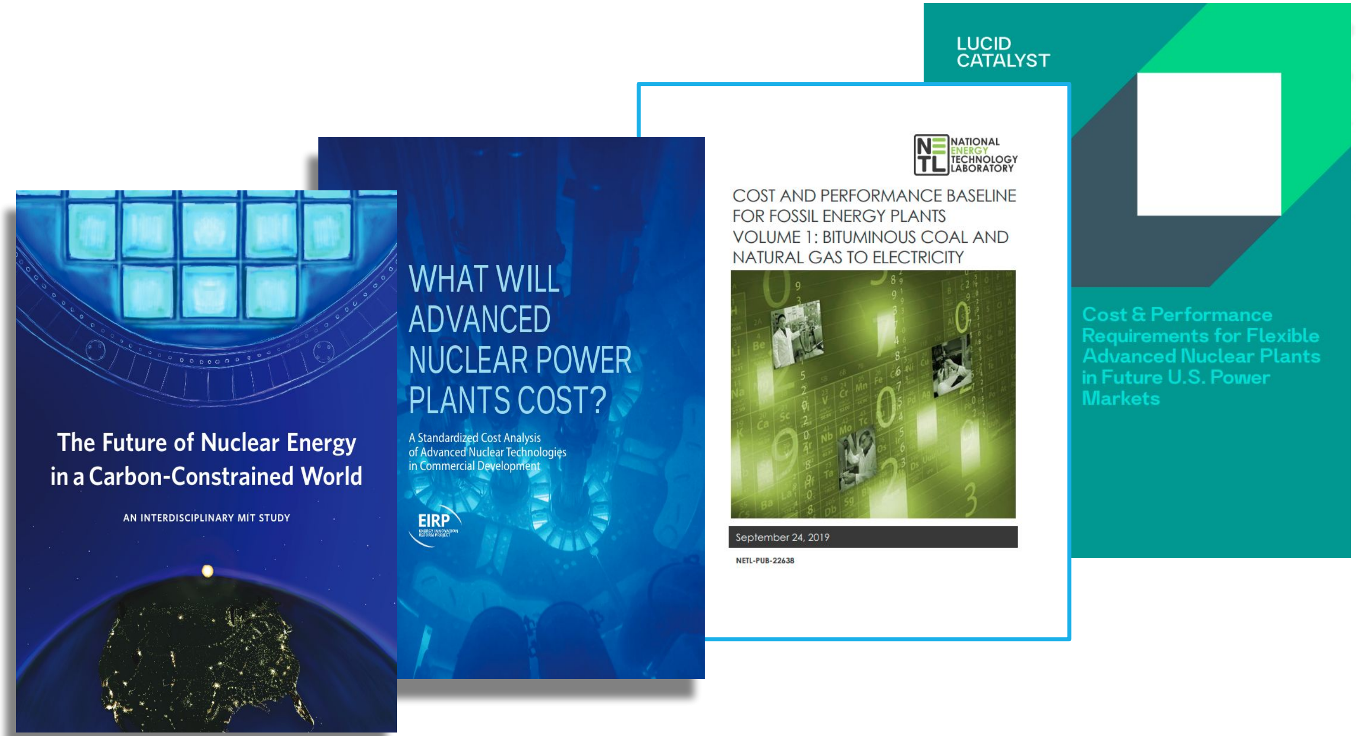


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**For $P_E$=150MWe, OCC/$P_E$=$4.9/Watt**
**5c/kWh for NOAK and centralized manufacture of modular fusion power cores**

IAEA
International Atomic Energy Agency

# The 2nd IAEA Workshop on Fusion Enterprises

## 5-6 July, 2021
## Oxford, UK

*To discuss what the market is demanding and how we can draw commercialization paths to fusion energy.*
*Mark your calendars!*

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