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

by

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Abstract

This thesis presents the techno-economic analysis of Deuterium-Tritium Magnetic Confinement Fusion Power Plants (FPP), tailored to enhance the economic viability and scalability of FPPs in response to global energy challenges and climate change. Amidst a backdrop of substantial investments in fusion technology, totaling $6.2 billion to date, this study critically assesses the overnight capital costs of a FPP that hosts ARAI, a 350 MWe tokamak reactor based on the MIT ARC fusion concept. This research evaluates the economic viability of constructing an Nth-of-a-kind ARAI-FPP. The overnight capital costs for ARAI-FPP are estimated to range between $8,800/kW and $22,200/kW, with this variation largely driven by differing regulatory and manufacturing assumptions. The overall cost breakdown is found to be similar to past and recent fusion literature, where the direct cost of fusion reactor equipment is the largest cost driver. The Levelized Cost of Electricity is estimated to be between $140/MWh and $550/MWh. The findings aim to deepen the understanding of absolute and relative cost drivers in fusion energy and suggest strategies to improve its economic feasibility. The analysis highlights the significant role of fabrication costs and regulatory frameworks in influencing cost dynamics.

Thesis Supervisor: Dr. Koroush Shirvan
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This thesis is dedicated to my father, *a constant force in my life.*

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Abbreviations

ARAI	Advanced Reactor Affordable Integration
ARAI-FPP	Advanced Reactor Affordable Integration Fusion Power Plant
ARC	Affordable Robust Compact
ARIES-AT	Advanced Research Innovation and Evaluation Study – Advanced Tokamak
ARIES-CS	Advanced Research Innovation and Evaluation Study – Compact Stellarator
ARIES-ST	Advanced Research tor Innovation and Evaluation Study – Spherical Torus
BE	Better Experience
CF	Capacity Factor
COA	Code of Accounts
DOE	Department of Energy
D-T	Deuterium-Tritium
EEDB	Energy Economic Data Base
FOAK	First-of-a-kind
FPP	Fusion Power Plant
FPY	Full Power Years
HTS	High-Temperature Superconductor
IAEA	International Atomic Energy Agency
ITER	International Thermonuclear Experimental Reactor
kW	Kilowatt
LCOE	Levelized Cost of Electricity
MC	Magnetic Confinement
MIT	Massachusetts Institute of Technology
MWe	Megawatts Electric
MWh	Megawatt-hour
NCET	Nuclear Cost Estimation Tool
NRC	U.S. Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NOAK	Nth-of-a-Kind
NPP	Nuclear Fission Power Plant
OCC	Overnight Capital Costs
O&M	Operation and Maintenance
PWR12	1200 MWe Westinghouse Pressurized Water Reactor
REBCO	Rare-earth barium copper oxide
R&D	Research and Development
TEA	Techno-Economic Analysis
W	Watt

A. Introduction

1. Overview

1.1 Background and Motivation

Climate change poses a significant challenge to humanity, threatening the environment, public health, and economies worldwide. As a major contributor to global CO_2 emissions, the United States actively engages in global initiatives to reduce its carbon footprint and decarbonize its electric power systems to achieve net-zero carbon goals (Schreurs 2016). Energy use, through the burning of fossil fuels, is the largest driver of greenhouse emissions globally (Environmental Protection Agency 2024). In response, the U.S. calls for a clean energy transition and the pursuit of carbon-free energy to meet increasing energy demands while decreasing environmental impact.

Renewable energy sources such as wind and solar are imperative for this transition but suffer from low power density, inefficient baseload performance, and a lack of energy storage solutions. Meanwhile, nuclear fission, while supplying a remarkable portion of the non-carbon-emitting energy in the world, faces high capital costs, cost overruns, and regulatory burdens, mainly due to long permitting processes and safety requirements for fission reactors and extended permitting processes (MIT Energy Initiative 2018). These challenges prevent renewables and fission from displacing fossil fuels in the existing energy system. Fortunately, fusion energy provides a solution. Fusion energy mimics the sun's energy-producing processes and will generate virtually unlimited, clean energy. Its development may revolutionize power generation, altering our reliance on carbon-based fuels and facilitating a sustainable future in the U.S. and globally.

In 2022, the Biden-Harris Administration initiated a strategy to expedite the advancement of fusion power, setting a clear objective to exceed the break-even point (where the fusion system generates more energy than it consumes)(Office of Science and Technology Policy 2022). This approach represents a substantial change from the 1970s, when most fusion research was predominantly confined to colleges and national laboratories. Today, this landscape has altered notably due to the increase in private-sector investments and improved public-private partnerships, which have fostered meaningful progress toward the commercialization of fusion energy. To date, the fusion industry has accumulated over $6.2 billion in investments; Commonwealth Fusion Systems has led the charge, raising over $2 billion based on MIT's ARC concept, a Deuterium-Tritium Magnetic Confinement reactor (Fusion Industry Association 2023b).

This analysis will present a methodology used to construct a techno-economic model for costing an Nth-of-a-kind (NOAK) Fusion Power Plant (FPP). Additionally, this analysis addresses the impact of regulatory frameworks on capital costs, identifying how these requirements can contribute to cost escalations. By integrating the latest technological innovations, including advanced materials, superconducting magnets, and advanced manufacturing capabilities, this thesis assesses how these innovations can reduce anticipated cost drivers. Moreover, this research will contribute its findings as a part of a new study by the MIT Energy Initiative aimed at assessing the role of fusion energy in a decarbonized electricity system.

1.2 Thesis Overview

Part A, which contains Chapters 1 and 2, serves as an introduction to the thesis and provides context to the reader about the motivation for pursuing this research as well as assumptions made that impact the design and power parameters discussed. Chapter 1 provides the motivation for pursuing fusion energy and the role of this analysis within the fusion landscape. Chapter 2 provides justification for the focus of this thesis as well as an overview of the primary assumptions made about the reactor design and power parameters.

Part B, consists of Chapter 3, presents the methodology used in this techno-economic analysis. It discusses costing strategies, assumptions, and information about the technology needed to perform the tasks carried out in an ARAI-FPP.

Part C, composed of Chapter 4, 5, and 6, evaluates the results and provides discussion. Chapter 4 showcases the overnight capital costs and contextualizes the results of the analysis by comparing the LCOE computed through the TEA with the LCOE of other energy generation technologies. Chapter 5 is a cost driver analysis where the cost drivers in Chapter 4 are further analyzed and discussed within context. Chapter 6 identifies social acceptance as a lever impacting economic viability that should be achieved before the deployment of FPPs.

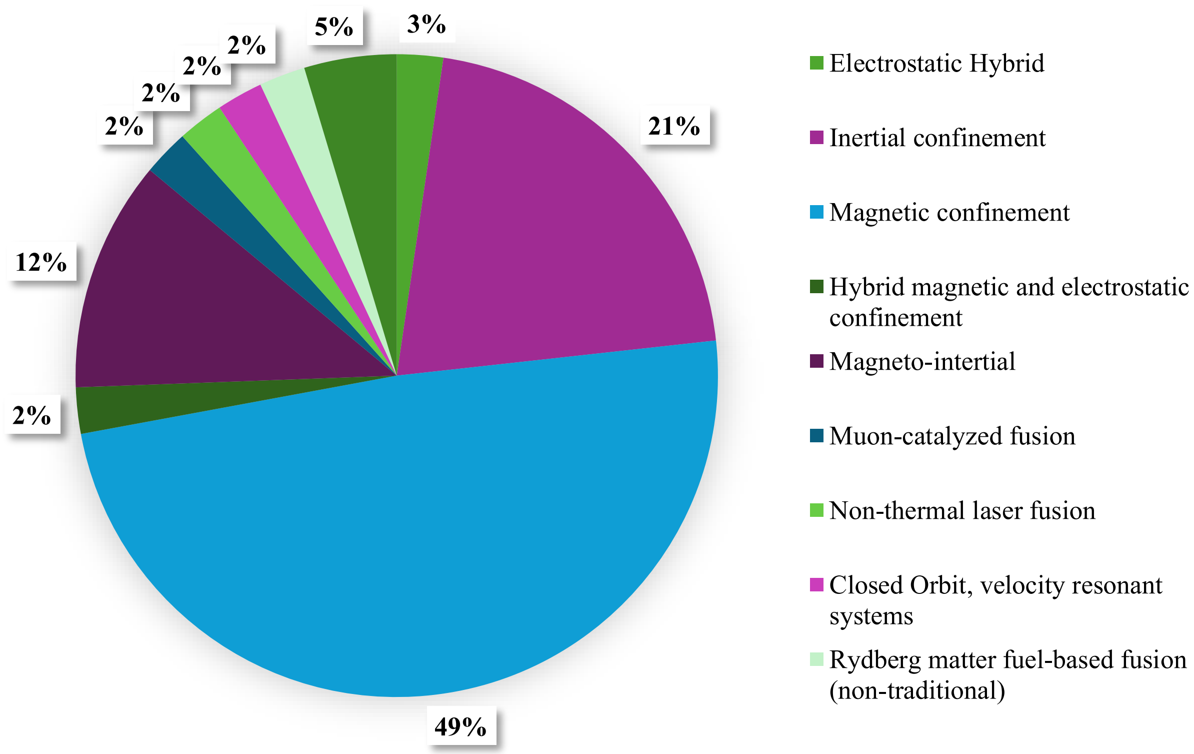
Part D hosts the conclusion, reiterating the analysis's key findings and how the results can impact future work.

2. D-T MC FPP Overview

2.1 Justification of Focus

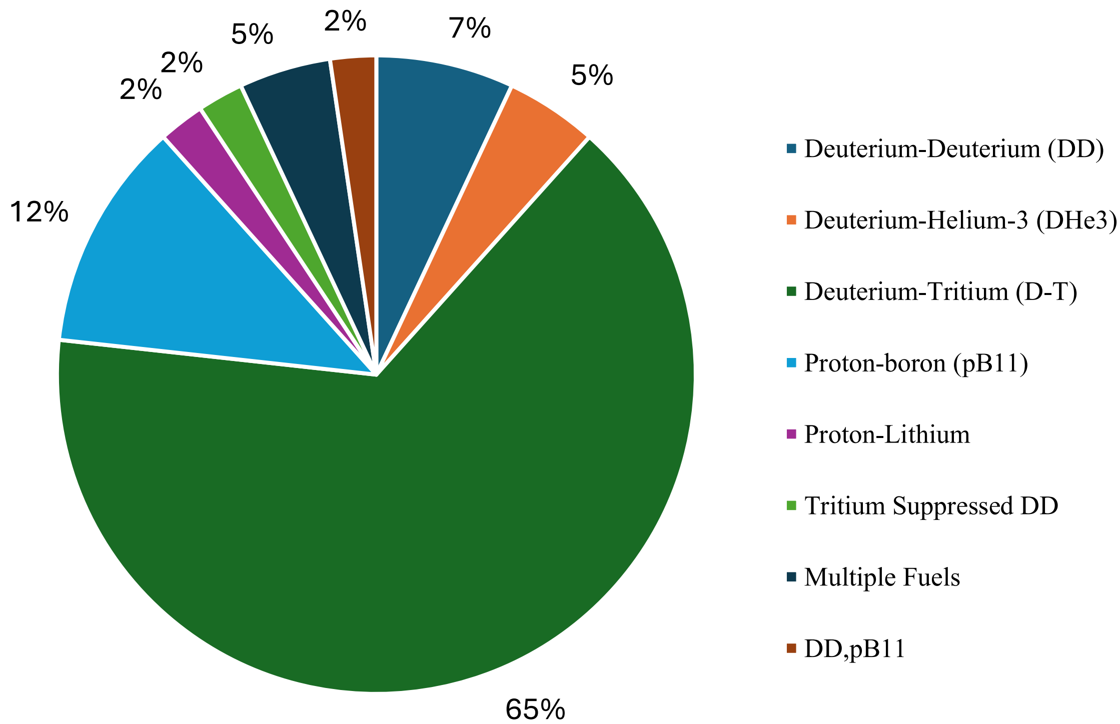
To determine the possible range of capital and operating costs for fusion technologies, this Techno-Economic Analysis (TEA) was designed to provide an estimate of capital costs associated with a Fusion Power Plant. According to the Fusion Industry Association, as shown in Figure 1, the Magnetic Confinement (MC) approach (49%) represents the most adopted approach by the private Fusion Industry.

Figure 1. Approaches taken by Fusion Companies



Similarly, the most pursued fuel source is Deuterium-Tritium (D-T); Figure 2 depicts the degree to which D-T is being pursued in the fusion industry (Fusion Industry Association 2023b). Moreover, D-T MC approaches have the most data available in the literature due to the extent to which MC Reactors have been studied in universities and laboratories. The D-T MC reactor technologies proposed by the ARIES studies and MIT's ARC conceptual design are parameterized for cost comparison (F Najmabadi, n.d.; F Najmabadi and Team, n.d.; Sorbom et al. 2015). As such, this analysis attempts to provide a bottom-up capital cost estimation of a D-T MC FPP.

Figure 2. Fuel Sources adopted by Fusion Companies



Despite the numerous publications on experimental FPP configurations, substantial uncertainty remains in cost estimates due to the absence of a demonstration FPP and a commercial supply chain for essential components. In order to respect this uncertainty, the TEA work focuses on the NOAK cost and provides a cost estimation of FPPs given their proposed architectures. Postulating a NOAK cost avoids consideration of highly uncertain and sometimes controversial First-of-a-kind (FOAK) costs for initial demonstration power plants such as the International Thermonuclear Experimental Reactor (ITER), a fusion research and engineering megaproject (Fusion Industry Association 2023a). Additionally, various existing studies of FPPs, Fission, and other renewable energy sources will be leveraged to arrive at a range of possible capital and operating costs for FPPs. In particular, a discussion on the impact of regulation on cost relative to a fission power plant will be made, given the merits of FPPs and lower overall radioactive inventory. Sensitivity to the identified cost drivers is also applied where deemed appropriate.

2.2 Concepts and Assumptions

There are several assumptions affecting the FPP costs, its supporting equipment, and the facilities that house it. Table 1 depicts relevant assumptions regarding the D-T MC FPP considered in this study. Many features of the MC reactor discussed within the analysis are based on the leading candidate materials shown in the annual Fusion Industry Association report, where companies self-report their progress (Fusion Industry Association 2023a). This analysis acknowledges the amount of uncertainty within the system and highlights the need for technological advancements to advance economically critical features.

Table 1. General reactor parameters of D-T Magnetic Confinement Reactor

Parameters	**Symbol**	**Base Case Values**
Thermal Power	P_{tot}	1000 MW
Fusion Power	P_f	800 MW
Net Electric Output (MWe)	P_{net}	350
Efficiency (%)	η_{elec}	0.4
Capacity Factor	CF	0.7
Tritium Breeding Ratio	TBR	$1 \leq x \leq 1.1$

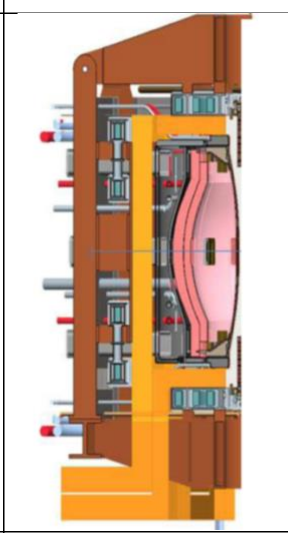
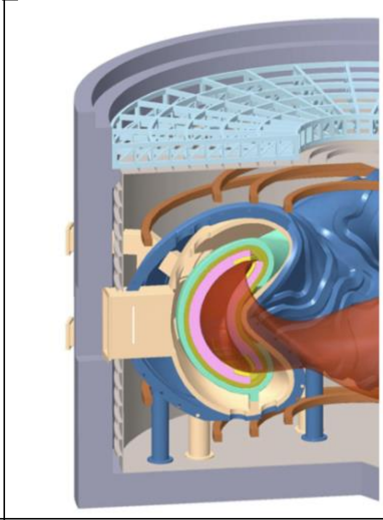
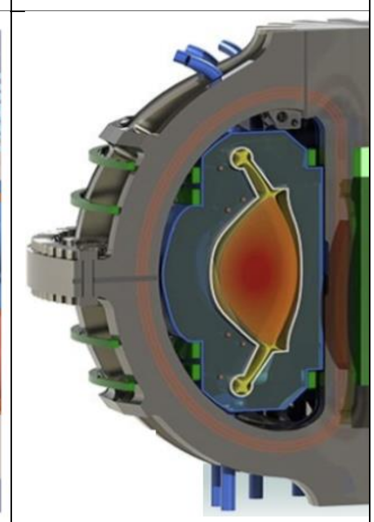
The following are noteworthy assumptions in the TEA:

- Publicly available data was used for the costs of materials involved in construction and annual operation of a FPP. Therefore, it cannot, by definition, capture recent improvements in science or manufacturing held by private companies, yet will still provide a relative basis from which to assess fusion economics.
- This TEA analysis does not reflect the business plans of any particular fusion company. Instead, concepts will be explored based on their popularity.
- The Fusion Industry requires significant novel technologies and concepts to be developed in order to ensure economically feasible deployment, and this analysis does not aim to capture the future state of Fusion R&D.
- All Civil, mechanical, and electrical work are costed based on a thermal plant that has a 1000 MWth and a 350 MWe electrical power output.
- Fusion-specific technology possesses great uncertainty, so assumptions about materials needed were based on experimental fusion concepts and the Fusion Industry Association Report.

D-T Concepts

Given that MC concepts have been researched for decades, there is extensive literature describing various MC designs. Advanced Reactor Innovation and Evaluation Study (ARIES) presented several capital cost studies for various MC concepts which will be referenced in this thesis, including the Spherical Torus (ARIES-ST) and Compact Stellarator (ARIES-CS). The costs of those concepts will be discussed in the results section. Affordable, Robust, Compact reactor (ARC), piloted out of MIT, utilizes rare-earth barium copper oxide (REBCO) high-temperature superconductors (HTS), and within the original ARC study, a FOAK cost for 70kA REBCO cables was provided (Sorbom et al. 2015). Table 2 depicts the power core of ARIES-CS, ARIES-ST, and ARC, respectively. All ARIES concepts were intended to produce P_{net} = 1000 MWe. The ARIES-ST power core weighs approximately 8,613 tonnes, and the ARIES-CS power core weighs roughly 12,555 tonnes (Miller 2003; Lyon et al. 2008). Meanwhile, ARC was designed to produce a P_{net} = 190 MWe, and its power core weighs a total of 7,190 tonnes. Therefore, ARC features a significantly higher mass-to-power ratio compared to the ARIES reactor series. Given HTS's impacts and continued presence in the fusion industry, this TEA modifies the ARC concept as a basis for the bottom-up estimate. Modifications were made to the ARC concept to apply leading candidate materials such as vanadium alloys to the design of the replaceable components, vacuum vessel, and plasma-facing components. Within ARC, a total of 5,730 kilometers of 70kA REBCO cables was utilized, and thus, the same will be assumed within this analysis. Each cable consists of a stack of REBCO tapes, each tape measuring 12 mm in width and 0.1 mm in thickness. Again, these modifications were based on the leading candidate materials discussed in the Fusion Industry Supply Chain report; further discussion is in the results section (Fusion Industry Association 2023a). The modified ARC concept will be redefined as the Advanced Reactor Affordable Integration (ARAI). ARAI will be compared to ARIES-ST and ARIES-CS to demonstrate the flexibility and inclusivity of the bottom-up approach.

Table 2. Features of MC reactor architectures compared

Name:	ARIES Spherical Torus (ARIES-ST)	ARIES Compact Stellarator (ARIES-CS)	Affordable, Robust, Compact (ARC)
Image:			
Type of Magnetic Confinement:	Spherical Torus	Compact Stellarator	Tokamak
Net Power (MWe):	1000	1000	190

Power Core Weight (Tonnes):	8,613	12,555	7,190

Components of ARAI

ARAI will employ the following materials for its assembly. The blanket tank and magnet structure will be crafted from stainless steel SS316 LN. Enclosing the blanket tank, a neutron shield composed of titanium dihydride (TiH_2) will be designated as the TiH_2 shield. The vacuum vessel will utilize the vanadium alloy V-4Cr-4-Ti, and the first wall will be made from tungsten. Additionally, the blanket will consist of the molten salt fluorine, lithium, and beryllium (FLiBe). While the Code of Accounts and other reactor plant equipment components will be discussed in detail in the methodology, the following volume and material assumptions below are made about ARAI in Table 3. The relevant volumes are specified. The major radius assumption is consistent with the assumption made in ARC. The power core of ARAI, composed of the vacuum vessel, blanket, and magnet, weighs 4,291 tonnes. The term "ARAI-FPP" will refer to the constructed plant costs that host ARAI.

Table 3. Components of ARAI

Account #	Component	Tonnes	Material assumed
22.11	**Vacuum Vessel**	**201**	
22.11.1	First wall	3.72	Tungsten
22.11.2	Inner Vacuum Vessel wall	100	V-4Cr-4-Ti
22.11.3	Outer Vacuum Vessel wall	86.4	V-4Cr-4-Ti
22.11.4	Vacuum Vessel ribbing	6.8	V-4Cr-4-Ti
22.11.5	Vacuum Vessel posts	4.14	V-4Cr-4-Ti
22.11.6	Vacuum Pumps		
22.12	**Blanket**	**731.5**	
22.12.1	Blanket tank	97.1	SS316 LN
22.12.2	TiH2 shield	26.4	TiH_2
22.12.3	Channel FLiBe	8.1	FLiBe
22.12.4	Blanket tank FLiBe	300	FLiBe
22.12.5	Heat exchanger FLiBe	300	FLiBe
22.13	**Magnet**	**3,358**	
22.13.1	Magnet structure	3,000	SS316 LN
22.13.2	REBCO tape structural materials	358	Copper
22.13.3	REBCO	~ 0	REBCO

There exists great uncertainty pertaining to the cost of FLiBe, Vanadium Alloys, tritium, REBCO, and other specialized materials needed for the power core and for operation, but due to the immature market of these materials, there is an absence of publicly accessible data. Hence, the material costs were obtained from several sources. A FOAK cost of FLiBe was taken from an internal source, and its NOAK cost was derived by applying a 20% learning rate (justification explained in Chapter 5). The raw material costs of most of the components except the vacuum vessel were obtained from the ARC paper but not scaled to $2021, and those costs are comprised of both historical data and private quotes obtained from vendors (Sorbom et al. 2015). For the Vacuum Vessel material, V-4Cr-4-Ti was created through an original estimate shown in Table 4; the costs of Vanadium, Chromium, and Titanium were obtained through separate sources ("Ferro Vanadium 80% Price USD / Kg" 2024; "TITANIUM AND TITANIUM DIOXIDE" 2022; "CHROMIUM" 2022). It should be noted that material costs are a sensitive parameter, and impacts on it inevitably will affect the total cost of the lifetime and replaceable components. Table 5 depicts the material costs utilized.

Table 4. Cost and Composition of Vanadium Alloy

V-4Cr-4-Ti		Composition
Vanadium		0.92
Titanium		0.04
Chromium		0.04
Material Cost ($/kg)		Cost based on Composition:
Vanadium:	34	31
Titanium:	11.7	0.47
Chromium:	7.5	0.30
Sum of Costs:		32.05
15% Premium for removal of impurities		4.81
Total Cost per kg (rounded)		**37**

Table 5. Material Cost Assumptions

Material Type	**Material Cost ($/kg)**
V-4Cr-4-Ti	37
SS316 LN	10
FLiBe	154
Tungsten	29
TiH_2	26
Copper	8.3

B. Methodology

3. Techno-economic Analysis Methodology:

3.1 Code of Accounts and Scaling

A cost accounting system used in nuclear fission power plant (NPP) cost estimates is the Code of Accounts (COA) from the U.S. Department of Energy (DOE) Economic Data Base (EEDB). The COA has been accepted by the International Atomic Energy Agency and formalized by the Generation IV International Forum Economic Modeling Working Group (Economic Modeling Working Group of the Generation International Forum 2007) and adapted for some fusion applications ("Conceptual Cost Study for a Fusion Power Plant on Four Technologies from the DOE ARPA-E ALPHA Program" 2017). A widely used cost accounting methodology facilitates uniformity and consistency when comparing the capital costs of NPPs across designs over time. The flexibility of the COA system allows for applications across nearly all nuclear power designs, which simplifies comparisons between NPP technologies. This flexibility explains why it has been used in many studies to estimate the costs of new power plants and compare costs across different nuclear and conventionally used power plant designs (Asuega, Limb, and Quinn 2023; Stewart and Shirvan 2022).

However, despite its flexibility and usage for comparisons across conventional power generating facilities, the COA system itself was not designed for specific fusion concepts. As a result, the COA was modified to accommodate the differences between an FPP and NPP. These modifications are somewhat in line with previous adaptations of EEDB COA to fusion reactors (F Najmabadi, n.d.; "Conceptual Cost Study for a Fusion Power Plant on Four Technologies from the DOE ARPA-E ALPHA Program" 2017; F Najmabadi and Team, n.d.). The Overnight Capital Costs within this TEA fall into Account 20: Direct Capital Costs, Account 30: Indirect Capital Cost, Account 40: Plant Decommissioning Cost, Account 60: Owner's Cost, and Account 70: Annual Operations and Maintenance.

The Direct Capital Costs (shown in Table 6) were determined through a variety of methods, including bottom-up and top-down assessments. While bottom-up assessments provide a robust estimate by considering fabrication, material inputs, and site labor, top-down assessments were employed when assessing bottom-up quantities was challenging. The bottom-up estimate employs a combination of methods in order to compute a range of capital costs, and the Nuclear Cost Estimation Tool (NCET) was referenced because it provides a bottom-up cost estimation tool for fission Nuclear Power Plants (Stewart and Shirvan 2022).

Within this analysis, the scaling methodology from NCET, which was developed at MIT, was utilized and modified to gauge the costs associated with a Fusion Power Plant. NCET has been used to model ~45-1500 MWe fission modular power plant from FOAK to NOAK. Similar to fission, nuclear fusion demonstrates a high initial capital cost with specialized equipment while benefiting from low fuel costs by leveraging the high energy density of the nuclear reactions. The cost estimate tool within NCET utilizes power law scaling to adjust direct costs from the EEDB. The power law exponent used varied based on the parameter scaled but generally was around 0.6.

In the EEDB, there are several baseline costs for different NPPs. The lowest cost, known as the "Better Experience Plant," was used for this NOAK fusion cost analysis. As it will be seen, the "Better Experience Plant" (BE) cost estimates for the non-nuclear part of the NPP are similar to the costs for NOAK thermal power plants constructed today, justifying its utilization. Given that an FPP has never been constructed, no historical data exists to validate the fusion-specific cost numbers. Thus, I use this methodology to examine the relative economics of a D-T MC FPP. This thesis does not attempt to project absolute values for the cost of MC fusion concepts. The EEDB lists a component-by-component breakdown of a 1200 MWe Westinghouse pressurized water reactor (PWR12). The costs include factory costs, site labor hours, material costs, and quantity. The COA was organized into direct and indirect costs. The top-level direct accounts are structures and improvements (representing the civil works), reactor plant equipment (will be replaced with FPP specific equipment), turbine generator equipment (assumes steam Rankine cycle similar to FPP), electrical plant equipment, miscellaneous equipment, and the main heat rejection system. The top-level indirect costs are construction services, engineering and home office services, and field supervision and offsite services. The direct costs are comprised of 7 top-level accounts and 38 subaccounts, and the indirect costs are comprised of 6 top-level accounts.

Table 6. Direct Costs

Account Number	Account Name	Account Description
20	**Direct Costs**	
21.1	Land & Land Rights	
21.2	Structures & Site Facilities	*Described in Section 3.2*
22	Reactor Plant Equipment	Vacuum Vessel, Blanket, Magnet, Fuel Handling System, Tritium Extraction and Removal, Auxiliary Cooling Systems, Cryostat , Other Reactor Plant Equipment (e.g., divertor), Instrumentation and Control
23	Turbine Generator Equipment	Rankine Cycle assumed: Turbine Generator, Condensing Systems, Feed Heating System, Other Turbine Plant Equipment
24	Electric Plant Equipment	Switchgear, Power and Control Wiring, Switchboards, Station Service Equipment, Electrical Structures and Wiring Containers, Electrical Lighting

26	Heat Transfer Equipment	Heat exchangers and steam generators for steam production. Pumps, piping, valves required for heat removal.
27	Misc. Plant Equipment	Costs for transportation and installation of the reactor plant equipment

3.2 Structures and Site Facilities

Through a combination of scaling methods from NCET and looking at the facility layout of ITER, relevant buildings needed for the design of MC concepts were identified and scaled (IAEA 2000). Structures and Site Facilities, Account 21.2, is the second greatest cost driver in the analysis. A significant cost faced by fission structures and sites is related to safety requirements induced by regulation. ITER was licensed similarly to a Fission power plant. However, there are strong indications that in the U.S., fusion may be regulated under a significantly more simplified regulatory framework. This provides an opportunity to both reduce and perform a sensitivity study on the impact of regulation on fusion cost. Generally, these regulatory requirements increase the cost of buildings by a factor of 2.2 (Stewart and Shirvan 2022). Thus, in the "lower bound" of the capital cost, this analysis divides the reactor building costs in EEDB by a cost factor of 2.2. In general, it should be noted that regulatory requirements can drive the costs of FPPs, so throughout this analysis, there will be brief discussions of how regulation that has impacted nuclear fission could impact nuclear fusion. Based on the NCET, the PWR12-BE was used as a basis to estimate the costs of the MC reactor containment buildings.

Detailed descriptions of the containment buildings were taken from design documents from the ITER design layout as it represents the most detailed architecture in open literature of buildings for a D-T MC system. A key distinction between the assumptions in this analysis and the ITER site layout pertains to the size of the reactor building, including cryo-cooling. The ITER reactor is particularly larger than ARAI because it uses low-temperature superconductors. The low magnetic field strength requires a larger reactor to achieve positive energy. Magnetic confinement reactors designed to use HTS are physically smaller. Given the smaller size of the reactors for ARAI, ARIES-ST, and ARIES-CS, the ITER Tokamak Hall was scaled down accordingly to represent these compact reactors. The cryogenic cooling facilities were also scaled accordingly.

After reviewing the buildings needed in an FPP, the total volume and surface area of walls, floors, and roofs were calculated for sections of the buildings and relative quantities of materials—including concrete, reinforcement steel, structural steel, form-work, etc.—were found using the rates from the EEDB reactor building. The quantity of each material was categorized into super-structure or substructure and exterior or interior since the cost of these sections varies. From these quantities, labor rates and the cost of materials from the PWR12-BE reactor building were used to generate bottom-up estimates. This method was also used to estimate the costs of the control room building and radioactive waste process building. The turbine generators for FPPs are assumed to be functionally equivalent to those used by the EEDB and conventional power-generating systems.

3.3 Conventional Equipment Assumptions

When beginning a bottom-up estimate, it is important to distinguish NOAK assumptions relevant to existing technology and processes with available cost data. Thus, several assumptions in this analysis rely on cost data for conventional thermal plants. The costs used in this analysis are shown and compared to a coal plant for reference in Table 7.

A coal plant with a superheated steam cycle has components and costs that are applicable within a FPP (Table 7). The sum of component costs in Table 7 represents roughly ~23% of the total coal plant cost (Schmitt et al. 2022). The Turbine Generator Equipment and Building costs within the coal plant represent NOAK systems, so these costs are compared with the independent TEA of the equivalent systems. Table 7 shows that the TEA cost breakdown and total cost for a thermal plant align with the literature.

The data in Table 7 is also useful in estimating the savings that can be achieved through brownfield siting. By pursuing brownfield siting, existing facilities can be used and, therefore, will not need to be repurchased or reconstructed, so the sum of the components mentioned in Table 7 gives a rough approximation of how much can be saved by not having to re-purchase those components.

Table 7. Relevant conventional thermal plant costs: comparison between fusion cost assumptions and coal thermal plant costs (Schmitt et al. 2022)

	Direct Cost Accounts of TEA	Lower Bound ($/kW)	Upper Bound ($/kW)	Supercritical Coal Thermal Plant Cost Accounts	$/kW
26	Heat Rejection System	70	88	Cooling Water System	182
23	Turbine Generator Equipment	535	550	Steam Turbine & Accessories	581
24	Electric Plant Equipment	274	402	Accessory Electric Plant	144
	Sum Of Costs	879	1,040	Sum of Costs	907

3.4 Reactor Plant Equipment

This analysis assumes that ARAI will be comprised of the following leading materials: HTS, Vanadium alloys, and SS316 LN, as discussed in the previous chapter. Fusion companies benefit from decades' worth of research to evaluate candidate materials for their conceptual designs. As mentioned, in the ARAI-FPP COA, Vanadium alloys are assumed for the vacuum vessel, including the inner vacuum vessel wall, outer vacuum vessel wall, vacuum vessel ribbing, and vacuum vessel posts. Vanadium alloys have also been assumed in selected ARIES concept (Farrokh Najmabadi et al. 2006). Thus, the base case cost analysis is based on a Vanadium alloy, "V-4CR-4Ti" (Chung et al., n.d.). Previous ARC studies that have estimated vacuum vessel lifetime were focused on Inconel 718 as the material of construction. In one such study, the lifetime of the vacuum vessel is estimated to be two years (Segantin, Testoni, and Zucchetti 2019). However, Inconel 718 has been ruled out as the best long-term choice for vacuum vessel material because the nickel content would result in long-life activated materials. Vanadium has much lower activation than nickel, but it has its own set of challenges. Lifetime analysis for vanadium alloy vacuum vessels is required, and the absence of this information represents another area of uncertainty. ARAI utilizes a FLiBe blanket and SS316 LN as the base material for the magnets. In addition to these components, there are several other relevant costs within the reactor plant equipment, as shown in Table 8.

The justification for accounts 22.11 (except 22.11.6), 22.12, and 22.13 were discussed in Section 2.2. Several cost accounts remain within the reactor plant equipment, and the methodologies for computing cost estimates are as follows.

Account 22.11.6 Reactor vacuum systems

To calculate costs for 22.11.6 a series of assumptions were made based on other fusion concepts such as the STARFIRE and ITER-FEAT(Baker and Abdou 1980; IAEA 2000). The STARFIRE high vacuum pumping system consists of 48 cryopumps on 24 vacuum ducts (Baker and Abdou 1980). The cost of a cryopump was taken from a commercial company that sells cryopumps for roughly $14,000 each ("CTI Cryo-Torr 500 Cryo Pump, Rebuilt," n.d.). Thus, it is assumed that the cost of 48 cryopumps will be $0.7 M.

Account 22.1.4 Supplemental heating

For the purposes of this analysis, it is assumed that the supplemental heating/current drive systems will cost approximately 2.5 $/Watt (Blank et al., n.d.; Casey 1990).

Account 22.1.6 Power supplies

This analysis assumes that the power supplies for the supplemental heating would cost roughly 1.5 $/Watt (Blank et al., n.d.; Casey 1990).

Account 22.1.8 Impurity control (divertor)

The costs for 18 Tungsten tiles were assumed for the costs of the divertor. The costs were obtained from an MIT internal source.

Account 22.7 Cryosystem

The cost of the cryosystem is composed of the cost of the cryostat and cryocooling system for ARAI. The cryostat cost calculation involves determining the volume of stainless steel needed by calculating the surface area of the cryostat and then using the material's density and price to find the material cost. It also accounts for fabrication costs. The cryocooling system cost calculation is more straightforward: it multiplies the required cooling power (in kW) by a fixed cost per kW at 20K. Relevant input parameters included the minimum radius of the cryostat, the number of toroidal field magnets, and the fusion power output to calculate the overall costs of the cryostat and the cryocooling systems.

The costs for accounts 22.2, 22.4, 22.5, and 22.6 were derived from the NCET tool discussed (Stewart and Shirvan 2022).

For other equipment where fission and other technology-specific examples could be found such as a Tritium handling equipment and salt-to-steam heat exchanger, appropriate scaling and engineering judgment was applied. If fission cost is used, only the NOAK with minimal regulatory escalation factors was assumed. From the cost of magnets, different learning rates and factors were applied to reduce the costs noted in the ARC design paper (Sorbom et al. 2015). The original ARC reference magnet cost numbers are likely more representative of FOAK fabrication. For the lower bound, I assumed conventional manufacturing, while for the upper bound, I inflated this cost to respect the specific manufacturing complexity of high-field magnets. The distinguishing factor between NOAK and FOAK costs is within the fabrication cost assumptions which will be discussed in the results section. The specific costs are outlined and compared to ARIES-ST and ARIES-CS in Section 4.1. The breakdown of the Reactor Plant Equipment is listed in Table 8.

Table 8. Reactor Plant Equipment Cost Accounts

22	Reactor Plant Equipment
22.11	**Vacuum Vessel (201 Tonnes)**
22.11.1	First wall (3.72 Tonnes) - Tungsten
22.11.2	Inner Vacuum Vessel wall (100 Tonnes) - Vanadium Alloy
22.11.3	Outer Vacuum Vessel wall (86.4 Tonnes) - Vanadium Alloy
22.11.4	Vacuum Vessel ribbing (6.8 Tonnes) - Vanadium Alloy
22.11.5	Vacuum Vessel posts (4.14 Tonnes) - Vanadium Alloy
22.11.6	Vacuum Pumps
22.12	**Blanket (731.5 Tonnes)**
22.12.1	Blanket tank (97.1 Tonnes) - SS
22.12.2	TiH2 shield (100 Tonnes) -TiH2
22.12.3	Channel FLiBe (8.1 Tonnes) - FLiBe
22.12.4	Blanket tank FLiBe (300 Tonnes) - FLiBe
22.12.5	Heat exchanger FLiBe (300 Tonnes) - FLiBe
22.13	**Magnet**
22.13.1	Magnet structure (3,000 Tonnes) - SS
22.13.2	REBCO structure (358 tonnes)
22.13.3	REBCO tape
22.14	Supplemental Heating Systems
22.16	Power Supplies
22.18	Divertor
22.2	Main Heat Transfer & Transport Systems
22.4	Radioactive Waste Treatment & Disposal
22.5	Fuel Handling System
22.6	Other Reactor Plant Equipment
22.7	Cryosystem

Account 27: Misc. Plant Equipment:

Transportation and installation costs of the reactor plant equipment are listed under Account 27: Misc. Plant Equipment. In addition to adding tax and fees, the costs depend on the origin of the materials, whether they are sourced internationally or domestically. However, due to immature supply chains and uncertainty, a combination of assumptions of material origin was made based on available data.

3.5 Indirect Costs

The Indirect Costs were estimated as a percentage of direct costs. The percentages given based on Gen 4 fission data sets that approximate indirect costs reflect the experience of the design and construction techniques (D. E. Holcomb, Peretz, and Qualls 2011). The indirect cost will depend on ranges for direct cost, learning rate, modularization (percent of work onsite vs offsite) and standardization of design. The indirect costs have great potential to be a cost driver within the analysis, as experience and regulatory constraints can impact indirect costs. In many FPP cost studies noted in literature, indirect costs align with direct costs (F Najmabadi and Team, n.d.). For fission power plants, indirect cost as percentage of total cost can be as much as ~80% of the cost (Eash-Gates et al. 2020) while for natural gas plants are about 20% of the total cost ("Annual Technology Baseline," n.d.). In the EEDB database, the better experience plant realizes about 40% indirect cost as a portion of the total cost. In this TEA, it was assumed that the natural gas plant's indirect cost percentage would be representative of the indirect costs that NOAK FPP would face (Table 9), recognizing that such an assumption may be optimistic given FPPs will likely realize indirect costs in the range between a natural gas plant to an advanced fission power plant. The values in Table 9 sum to 0.38, which is roughly equivalent to the 40% of the better experience plant cost assumptions used for indirect costs, and this serves as the upper bound assumption for indirect costs. For the lower bound indirect cost assumption, the percentages in Table 9 were divided by 2, making the indirect costs for the lower bound in line with the indirect costs for a natural gas plant.

Table 9. Indirect Cost Formulas

30	**Indirect Costs**	Formula Used
31	Design Services at Home Office	.14 × **Direct Costs**
32	Project & Construction Management at Home Office	.01 × **Direct Costs**
34	Field Construction Management at Plant Site	.01 × **Direct Costs**
35	Field Construction Supervision at Plant Site	.05 × **Direct Costs**
36	Field Indirect Costs	.16 × **Direct Costs**
37	Plant Commissioning Service	.01 × **Direct Costs**

3.6 Operation and Maintenance and Fuel Costs

Operation and Maintenance

Several candidate maintenance approaches and strategies have been considered throughout fusion research. Because different reactor concepts discuss the usage of different materials coupled with different designs, there is not a "one-size-fits-all" approach, and it is not within the scope of the TEA to create an optimized maintenance schedule; instead, several overall concepts and features of an optimal maintenance scheme were evaluated. An ARAI-FPP should be designed to be able to be demounted and reassembled in order to maximize maintenance efficiency. Given that the reactor equipment design and installation greatly impact the maintenance, it is necessary to understand where R&D needs to be concentrated to achieve the developments necessary to maintain a high availability and, ultimately, a high-capacity factor.

To provide a standard functional maintenance scheme, the replaceable components should have nearly identical lifetimes to maintain plant availability (Wang et al., n.d.). A non-optimized maintenance schedule would result in more frequent plant shutdowns (Lester M. Waganer et al. 2006). In terms of completing the maintenance tasks in a timely manner that also ensures worker health and safety, remote maintenance strategies on reactor components are being explored and have been the focus in the fusion industry for decades across several concepts (JET, ITER, DEMO, ARIES). While the plant is nonoperational, the level of neutron-induced radioactivity from the hot cell still exceeds levels that permit hands-on maintenance, hence the need for remote maintenance.

Different reactor designs necessitate different maintenance approaches, horizontal or vertical integrated maintenance strategies being prominent contenders. Within the reactor building, the bottom-up estimate assumes a vertical maintenance approach where the reactor vessel would be lifted by a crane to perform certain maintenance tasks. The reactor building layout allows for remote O&M operations through a combination of vertical and port-based maintenance. An optimized maintenance schedule would comprise planned and unplanned maintenance timeframes for the reactor and Balance of Plant elements. Again, given the amount of uncertainty in the maintenance schemes and material lifetimes, it's difficult to estimate an annual O&M. Thus, for this analysis, O&M Costs are based on a percentage of costs in the Reactor Plant Equipment, Turbine Generator Equipment, and Electrical Plant Equipment. The modularity of replaceable components is critical to efficient maintenance. The O&M costs consist of three categories:

1) **Fixed O&M**
2) **Annual Variable**
3) O&M **Replaceable** component **costs (specific to Fusion Reactor)**

Fixed O&M (Account 71) costs pertain to the number of full-time-employees (FTE) expected to be at a NOAK FPP. Numbers from other industries were utilized to estimate the number of FTEs at a NOAK FPP. For instance, a thermal solar plant, whose power production system closely resembles D-T fusion energy systems (molten salt storage with superheated power cycle) currently employs 85 FTEs at a site in the U.S., which will be used as the lower bound assumption. An advanced nuclear fission plant has been noted to potentially require 200 FTEs, half of which are dedicated to security forces (Shirvan K., 2022). 95 FTEs are assumed for the upper bound in recognition of the added complexity of operating a fusion power plant compared to a solar thermal. As the lower bound, approximately half that number is assumed based on a scenario in which multiple reactors are installed at the same site to enable the staff to more efficiency to support multiple plants. All these assumptions are outlined in Table 10.

Annual Variable O&M (Account 72) represents the sum of the Annual Equipment Maintenance and the Replaceable Components Costs. Table 10 details these assumptions.

Annual Equipment Maintenance consists of roughly 3% of the costs associated with Reactor Plant Equipment (not including replaceable Fusion reactor components), Turbine Generator Equipment, and Electric Plant Equipment without including transportation and installation costs.

Replaceable Component costs and frequency of replacement will depend on the specific design of the FPP. Choices such as fusion fuel, containment method, material of construction, and neutron flux for each component are key differences. D-T compact FPP concepts will have more frequent first wall component replacement rates than aneutronic FPP concepts. In the ARIES-AT, the vacuum vessel (Ferritic Steel) is among the components that are designed to last the lifetime of the plant, but the replaceable components which need to be replaced are the inboard first wall/blanket, outboard first wall/blanket, and the divertor. The ARIES-ST has a large center post that will likely need to be replaced every 2-3 Full Power Years (FPY), due to poor inboard shielding. Unlike ARAI, the vacuum vessel for ARIES-ST was assumed to be a life-of-plant component. In ARAI, the replaceable components of the reactor core include the Vacuum Vessel and plasma-facing components.

Table 10. O&M Cost Assumptions

Account #	Category	Lower Bound	Upper bound
71	**Fixed O&M:** **FTE Costs (Assuming each employee has a Salary of $200,000)**	50 Employees	95 Employees
72	**Annual Variable O&M**	$\sum(\text{Annual Equipment Maintenence} + \text{Power Core Replaceable Components})$	
72.1	**Annual Equipment Maintenance** (without Replaceable Components)	3% × {Reactor Plant Equipment (not including replaceable components) + Turbine Generator Equipment Cost + Electric Plant Equipment Cost}	
72.2	**Annual Power Core Replaceable Components** (Including Transport and Installation)	$\left(\frac{\text{Cost of Replaceable Components}}{\text{Frequency of Replacement}}\right) \times (\text{Transportation} + \text{Installation})$	

Fuel Costs

The Fuel Costs discussed in this analysis pertain to a D-T Fuel Cycle. As mentioned in Section 2.1, the Fusion Industry Association Report shows that the D-T Fuel Cycle is the most adopted fueling approach within the private Fusion Industry (Fusion Industry Association, 2023b).

For all D-T FPPs, the blanket needs to have breeding capabilities that allow it to achieve self-sufficiency and not be reliant on external sources of tritium (Meschini et al. 2023). Annual Fuel Costs pertain to the Deuterium-Tritium Cycle. Research regarding tritium breeding optimization suggests that the type of structural material and blanket's Li-6 enrichment greatly impact TBR outcomes. Ongoing research regarding the fuel cycle is focused on evaluating the extent to which a high Li-6 enrichment degree is needed. Replenishing the Li-6 enrichment is necessary to achieve the tritium breeding properties of the blanket (Segantin, Testoni, and Zucchetti 2019). The cost of start-up tritium is not part of this analysis, but in general, for a compact reactor, a kilogram may be the upper limit of tritium able to be stored on-site given its radiological hazard profile. The annual cost of deuterium was omitted as it was considered small.

The tritium plant cost used is associated with ITER-FEAT due to the similarities in fusion power assumptions (IAEA 2000). Regardless of the amount of tritium expected to be consumed, the capital cost of the tritium plant is not significantly impacted by a particular operating schedule, so the capital cost of the tritium plant can be applicable in ARAI-FPP. After being scaled to $2021, the cost of the ITER-FEAT tritium plant is approximately $96M and falls within Account 22.5 Fuel Handling System, but this cost does not include the cost of startup tritium or cost of tritium extraction. Thus, the tritium extraction system is included as a cost related to radioactive waste processing in Account 22.4 Radioactive waste treatment and disposal, which was taken from NCET.

The FPP site must have enough tritium storage capacity to ensure that if power plant operations are paused, the tritium fuel can be stored until the power plant restart. Also, if the fuel reprocessing, tritium extraction system, or other components in the fuel handling system have a temporary performance problem such that the tritium supply is less than the feed rate, tritium reserves from storage can be tapped. Furthermore, FPP will be designed and operated to generate excess tritium to be used in starting up additional new FPPs. Tritium storage systems will hold that tritium and will periodically be used to transport the excess tritium to a new FPP. The total storage capacity at each FPP site will be on the order of a kg.

3.7 Decommissioning and Owner's Cost

Decommissioning costs (Account 40) were computed by assuming 3% of the total Capital costs. It should be noted that the amount of solid waste created by the disposal of replaceable components is an important topic in terms of both worker health and public safety (Di et al. 2012). The decommissioning of FPPs is an area that has not been significantly researched, but lessons can be learned from the fission industry.

Owner's Cost (Account 60) is bundled with typical contingency costs and computed by multiplying the direct cost lower bound by 25%, and thus, owner's cost represents ~17% of the capital costs. This amount is similar to a typical thermal power plant assumption. For NPPs, this value is closer to 45% (National Renewable Energy Laboratory 2012). Therefore, for the upper bound, the direct cost was multiplied by 35% to capture limited nuclear safety escalation.

3.8 Capacity Factor and Levelized Cost of Electricity

Capacity Factor

As of 2023, water-cooled NPPs have shown to have a capacity factor (CF) exceeding 90% for the past decade (EIA 2023). Within the same time period, offshore wind power hasnot exceeded a capacity factor of 45%, and solar PV's capacity factor hasnot exceeded 18% (IRENA

2023a; 2023b). Compared to other low-carbon energy technologies such as wind and solar, nuclear poses as extremely promising when evaluated solely by CF. While NPPs did not immediately achieve this high of a CF, the industry proved able to achieve benefits from learning and sustaining a high-capacity factor. The fixed cost of an NPP when non-operational is larger than that of other energy sources, so the industry was particularly motivated to achieve a high CF.

Within this TEA, the upper bound CF is assumed to be 0.7, while the lower bound is assumed to be 0.5 for NOAK. While a NOAK CF assumes the physics and engineering challenges of sustained fusion have been overcome, the upper bound is adopted from the NOAK estimate for CF of non-water-cooled NPPs which is similar to the average CF of fossil plants that fusion will look to replace in the grid (EIA, n.d.). For the lower bound, a 0.2 penalty is then applied to the upper bound. The assumed capacity factor is then used to inform the Levelized Cost of Electricity (LCOE).

The CF of a FPP directly influences its competitiveness with other energy sources. Recognizing that both high recirculated power and low CF can significantly undermine plant efficiency, it is crucial for FOAK steady-state tokamaks to address these challenges (Mulder, Melese, and Lopes Cardozo 2021). In contrast, NOAK devices should strive for both low recirculated power and high CF to ensure economic competitiveness in the evolving energy landscape.

Levelized Cost of Electricity (LCOE)

The LCOE is characterized as the price at which the generated electricity should be sold for the system to break even at the end of its lifetime (Papapetrou and Kosmadakis 2022). A simplified LCOE calculation was taken from National Renewable Energy Laboratory (NREL, n.d.) and adapted for an equation that calculates an LCOE based on the following inputs:

r = discount rate per year (6%)
N = total plant lifetime in years (30 years)
Capacity Factor = between 0.5 and 0.7
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

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

$$LCOE\left(\frac{\$}{\text{MW}}\right) = \left(\frac{\text{Overnight Capital Cost} \times \text{Capital Recovery Factor}}{\text{Capacity Factor} \times \text{Hours in a year}} \times 1{,}000\right) + (\text{Annual O\&M})$$

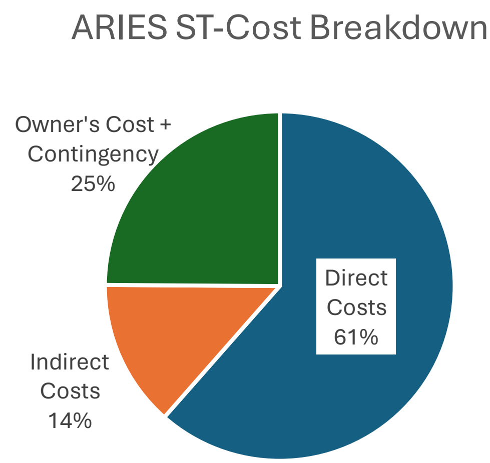
C. Assessment and Results

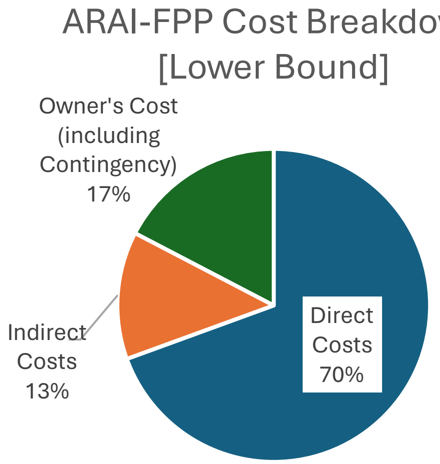
4. Overnight Capital Costs

4.1 Direct and Indirect Cost Breakdown

The economic viability of fusion energy is paramount to its successful commercial deployment. Aside from ongoing technical and engineering challenges, critiques of fusion's deployment pertain to its cost. However, the field of fusion economics remains largely unexplored, particularly considering new technology developments. Thus, this analysis employs the unique discussed methodology to examine the relative cost of a D-T MC FPP concept labeled "ARAI" and compare it to other MC concepts such as the ARIES Spherical Tokamak and the ARIES Compact Stellarator. Again, the term "ARAI-FPP" will refer to the constructed plant costs that host ARAI. Great uncertainty remains regarding what the NOAK plant will entirely be composed of. Still, this analysis attempts to anticipate the costs associated with the conventional equipment and fusion-specific technology within the plant. The assumptions of the ARAI-FPP are based on the direction of the industry, which includes the usage of specialized materials and complex manufacturing capabilities. Thus, while NOAK costs have been attempted to be extrapolated, they are accompanied by a vast uncertainty. As discussed, the primary capital costs within the overnight capital costs (OCC) are the direct, indirect, and owner's costs. Thus, in Figure 3, there is a comparison of the direct cost breakdown among the ARAI-FPP Lower Bound, ARIES-ST, and ARIES-CS.

Figure 3. High-level capital cost breakdown for the ARIES-ST from literature compared to this study's ARAI-FPP lower and upper bound





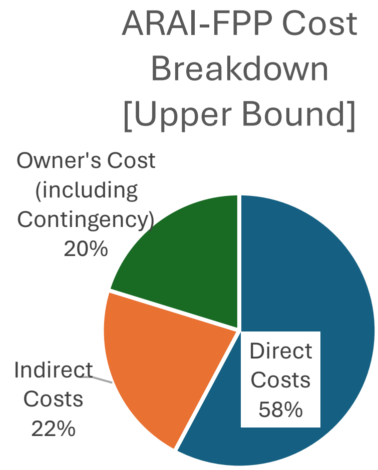


Figure 3 shows the capital cost breakdown of the independent bottom-up estimate compared to the selected literature. The ARAI-FPP upper and lower bounds show similar breakdowns of direct, indirect, and owner's cost + contingency to literature findings. These comparisons demonstrate areas of relative importance provided in the fusion literature. In the lower bound breakdown, the percentages imply an optimistic view relative to the literature. Indirect cost percentage is typically driven by the amount of engineering and project management needed. For fission, indirect costs are higher than thermal plants because of regulatory oversight. For the lower bound, I assumed an indirect cost that reflects a NOAK natural gas plant, whereas for the upper bound, I assumed minimal nuclear fission regulation would apply given the reduced hazard expected for ARAI-FPP. Similarly, I assumed very limited contingency for the lower and upper bound contingency that reflects the assumption of minimal regulatory oversight.

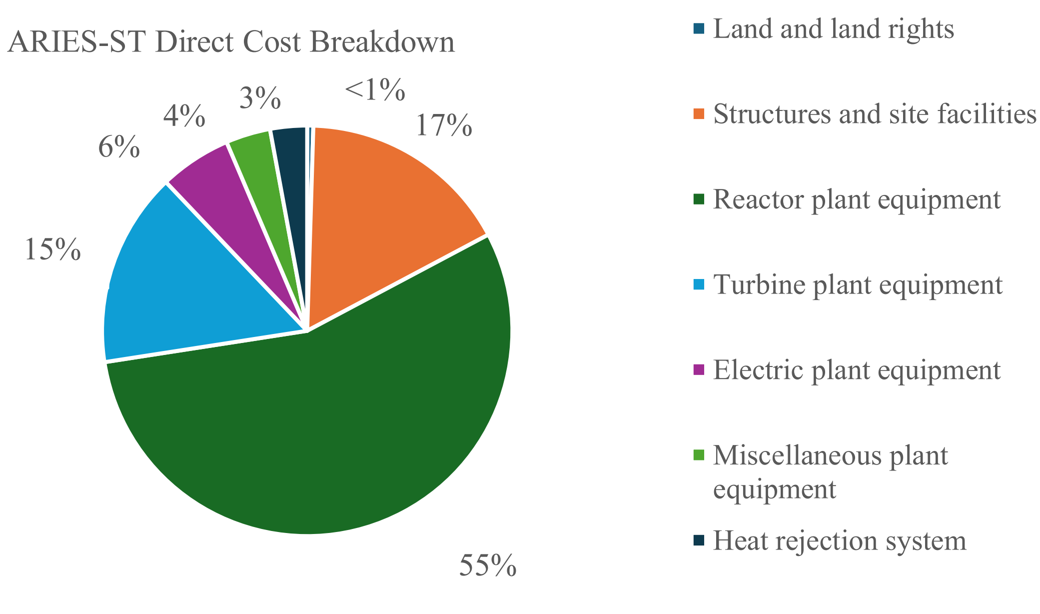
In the MC cases discussed, the direct cost constitutes most of the cost, as shown in Figure 3. Table 11 compares the total direct cost for the MC concepts divided by the respective kW power output assumption. Figure 4 shows the relative breakdown of this direct cost. These results ignore the potential of each approach in reaching viability from the point of view of physics and engineering. The lower bound direct cost estimate for ARAI-FPP aligns with the literature values of ARIES-ST and ARIES-CS. This consistency and similarity amongst the lower bound cost are expected since the ARIES costing analysis and the literature both assumed a conventional manufacturing cost per kg of material input for the cost analysis.

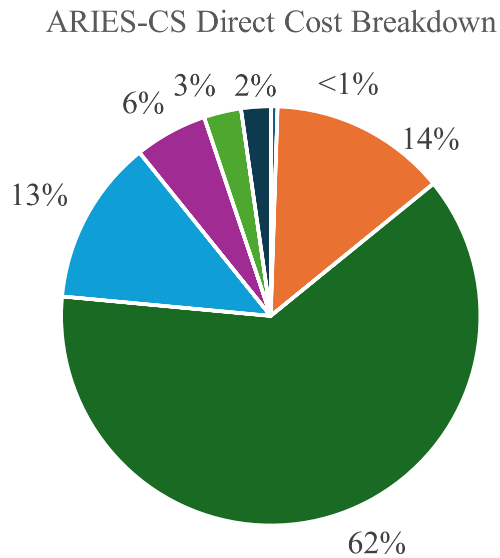
Table 11. Direct plus Indirect cost comparison for the ARIES-ST, ARIES-CS, and ARAI-FPP lower and upper bound

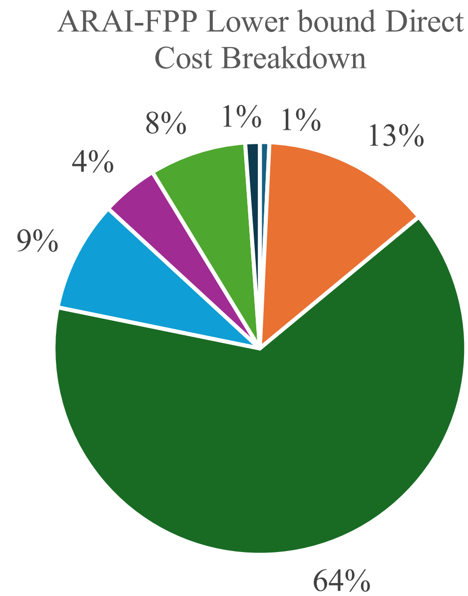
Magnetic Confinement Concept	Direct + Indirect Cost ($/kW)
ARIES-ST	9,800 $/kW
ARIES-CS	8,200$/kW
ARAI-FPP Lower Bound	7,100 $/kW
ARAI-FPP Upper Bound	18,500 $/kW

The upper bound ARAI-FPP is nearly 3x the cost of the lower bound and about double the cost of the ARIES-ST. This is due to the differences in direct and indirect cost assumptions. To better understand this source of difference, it is necessary to further break down the direct costs to understand the origin of these costs. To have a similar comparison between the ARIES-CS, ARIES-ST, and ARAI-FPP, the direct cost accounts have been modified to reflect a similar structure to the ARAI-FPP. For example, the special materials cost account was removed. According to the ARIES Systems code, the special materials cost account would contain materials such as lithium, and for this analysis, the fuel costs, including the cost of lithium, are excluded. Thus, the ARIES-ST and ARIES-CS diagrams in Figure 4 reflect this removal of the special materials cost, which accounts for the intention of being compared to ARAI-FPP. As shown, the direct cost accounts of ARAI-FPP align with the ARIES-ST and ARIES-CS. The cost drivers of the analysis primarily reside in the reactor plant equipment. Thus, a cost driver analysis in Chapter 5 was conducted to further understand the cost driver within the reactor plant equipment.

Figure 4. Direct Cost Breakdown Comparison amongst Lower bound of ARAI-FPP, ARIES-ST, and ARIES-CS







While the structures and sites have not been built specifically for a fusion power plant, the materials, and structures can benefit from the experience in constructing both non-seismically protected and seismically protected facilities. Additionally, the costs of the structures and site facilities do not factor in the costs associated with the concrete needed to seismically protect these structures; that decision will depend on regulatory requirements. The cost accounts related to Land & Land rights, Turbine Plant Equipment, and Heat rejection systems have NOAK cost values, and the costs are taken from the literature that depicts these as costs that thermal plants have. The electric plant equipment primarily consists of conventional components, but it should be acknowledged that fusion-specific additions could be needed. As mentioned in the methodology, conventional equipment and systems costs can be saved if the FPP adopts a brownfield siting approach. Additionally, most of the past fusion cost literature does not include the costs for transportation, installation, and tax associated with the equipment. Still, within this analysis, these costs are within the Misc. Plant Equipment cost category.

4.2 Replaceable Components and Operations and Maintenance Cost

Since D-T FPPs are assumed to include a tritium handling facility onsite, the fuel costs are negligible. Therefore, capital costs and operation and maintenance costs will drive the cost of FPP-produced electricity. In D-T MC FPPs, reactor components are impacted by material damage induced by neutrons, corrosion, or high-temperature operation, which shortens the lifetime of components, particularly plasma-facing components, including first-wall components. Different fusion concepts have proposed a range of lifetimes for the first wall: 1.5 – 4 FPY.

Replacing these components results in downtime for the power plant. Different fusion power plant concepts have different first-wall strategies. Most have blanket materials in front of the vacuum vessel, while others have the vacuum vessel in front of the blanket, and other concepts use a liquid first wall. Therefore, the components most exposed to neutron damage vary based on the FPP concept, and the frequency of component replacement depends on the neutron flux and material properties. Section 3.6 explains how a range of potential O&M costs for ARAI-FPP were calculated, and Table 12 shows the calculated O&M costs based on that methodology. The O&M costs for the ARIES reactors were estimated to be lower than ARAI-FPP since the vacuum vessel in those designs have low neutron fluxes relative to the ARAI-FPP concept. Most of the existing literature, including ARIES, quotes O&M cost in the range of $20-30/MWh when inflated to $2021, they are line with the lower bound for ARAI-FPP.

Table 12. Potential range of O&M costs for ARAI-FPP

Account #	O&M Items	Lower Bound	Upper Bound
71	**Fixed annual O&M**	5 $/MWh	12 $/MWh
72	**Variable general O&M**	30 $/MWh	170 $/MWh
72.1	Annual Equipment Maintenance (**without Replaceable Components**)	19 $/MWh	63 $/MWh
72.2	**Annual Power Core Replaceable Components** (Including Transport and Installation)	11 $/MWh	107 $/MWh

Given that a FPP has not been deployed, data related to availability has not been developed. All commercial and experimental fusion concepts pose great uncertainty, and the power core elements and maintenance equipment have not been tested to determine component lifetimes based on operational experience. Proposed maintenance approaches and remote handling technology still possess great uncertainty and unknowns. The maintenance of power core components must be efficient and timely to minimize maintenance downtimes. A considerable amount of R&D is required in order to have a remote handling system capable of effectively and efficiently evaluating, diagnosing, removing, and installing power core components.

4.3 Decommissioning and Owner's Cost

The Decommissioning and Owner's Costs were calculated based on the methodology discussed in Section 3.7. As shown in Figure 3, the owner's cost assumption of the ARAI-FPP is in line with the costs posed in the ARIES studies. Table 13 shows the lower and upper bound Decommissioning and Owner's Costs.

Table 13. Potential range of Plant Decommissioning Cost and Owner's Cost for ARAI-FPP

Account #	Account name	Lower Bound	Upper Bound
40	**Plant Decommissioning Cost**	$64.4 M	$96.6 M
60	**Owner’s Cost**	$528 M	$1, 176 M

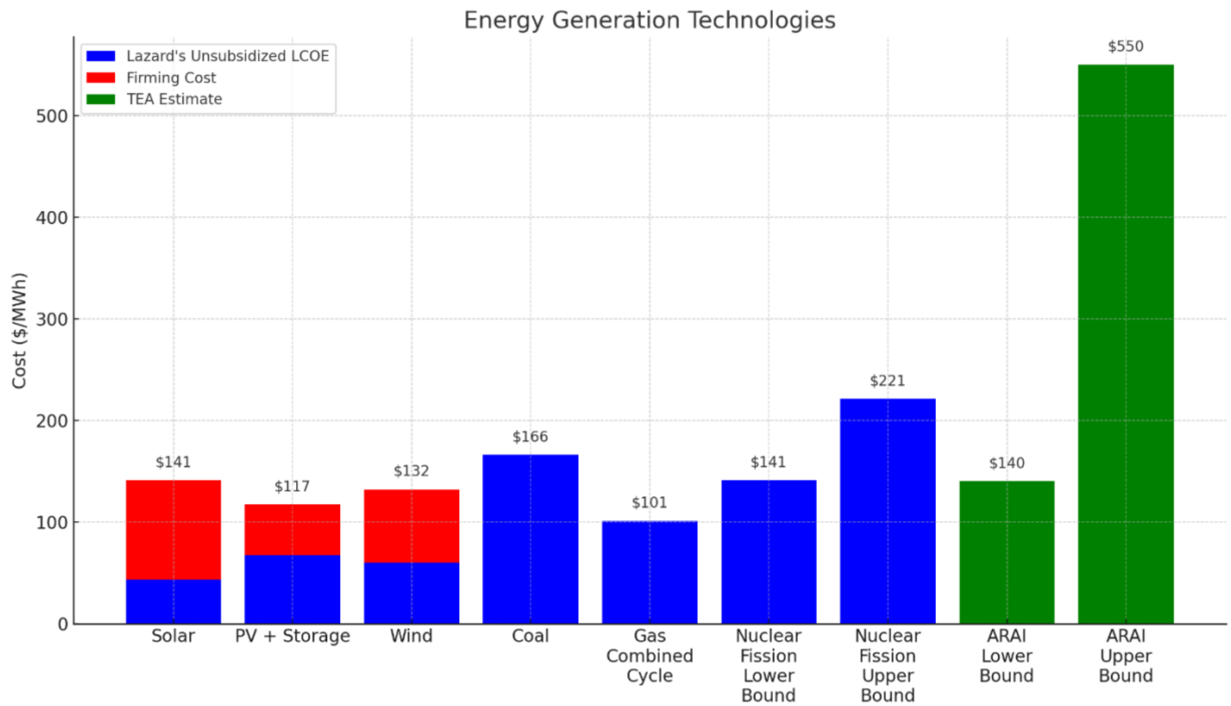
4.4 LCOE

LCOE was calculated based on the methods in Section 3.8 and the lower and upper bound LCOEs are listed in Table 14. Looking at the LCOE of other energy generation technologies through an unsubsidized cost analysis provides a more suitable point of comparison for the cost of a FPP to both renewable and conventional energy technologies. Figure 5 depicts the lower and upper bound LCOE of the ARAI-FPP alongside the LCOEs computed through an unsubsidized cost analysis by Lazard where the cost of Wind, Solar, and PV + Storage reflect the cost of firming their intermittency (“Lazard’s Levelized Cost of Energy Analysis -- Version 16.0 ” 2023).

Table 14. Levelized Cost of Electricity Calculation

	Lower Bound	Upper Bound
Levelized Cost of Electricity ($/MWh)	140	550

Figure 5. TEA LCOE Comparison with Lazard Unsubsidized LCOE and Firming Cost compared to NOAK ARAI LCOE estimates



4.5 Discussion

Given that an FPP has never been built and that more than 85% of fusion companies anticipate deployment of their first FPP after 2030, there is great uncertainty in estimating the cost of a NOAK FPP ("The Global Fusion Industry in 2023 Fusion Companies Survey by the Fusion Industry Association" 2023). The analysis in this study embraces uncertainty and identifies existing costs and technologies that allow us to understand the differences and similarities between a FPP and a conventional thermal power plant. Rather, this literature-based analysis was used to examine key drivers and the direction of the field.

Having said that, the following points briefly summarize the TEA findings:

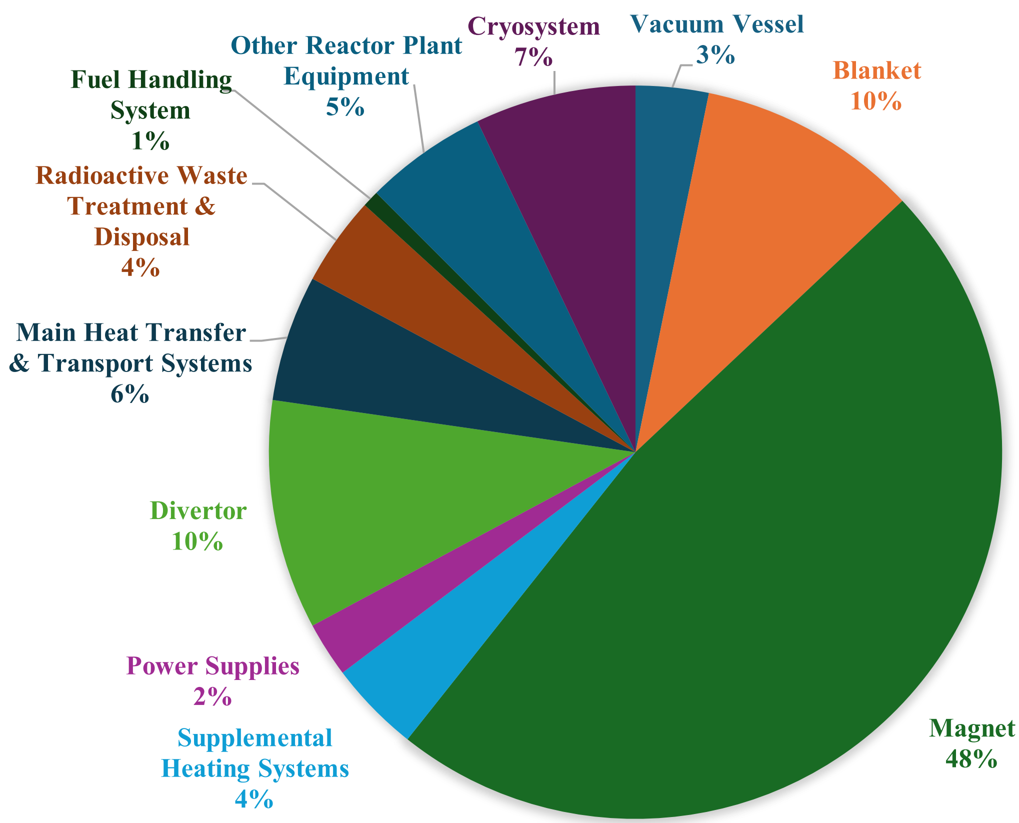
- Relative to the literature, this TEA revealed similar conclusions on the expected cost breakdown of a D-T MC FPP, including that the reactor plant equipment continues to be the main cost driver for capital and O&M costs.
- Various degrees of uncertainty steer this analysis, particularly in relation to fusion-specific components.
- Reducing uncertainties within the Reactor Plant Equipment, which hosts the most fusion-specific technology and consists of over 50% of the direct costs, would significantly impact the overnight capital cost.

5. Cost Driver Analysis

5.1 Overview and Reactor Plant Equipment Breakdown

This chapter delves into the cost drivers outlined by the ARAI-FPP. A more in-depth examination of these cost drivers is essential, given that our current cost estimates for the tokamak are based on a nascent understanding of the technology and processes required to build FPPs. Outside of the potential cost escalation borne by regulatory requirements, the most significant capital cost components within MC concepts are related to the reactor plant equipment. This chapter will discuss the cost driver analysis results, including the reactor plant equipment breakdown and the potential cost escalation due to regulation. To start, I will discuss the breakdown of the reactor plant equipment shown in Figure 6.

Figure 6. Reactor Plant Equipment Breakdown



The power core is composed of the vacuum vessel, blanket, magnet system (toroidal field coils, poloidal field coils, auxiliary coils, superconductors), and divertor. The power core components are the cost drivers of the reactor plant equipment. However, upon further investigation, it is apparent that most of the costs of the power components pertain to the manufacturing and fabrication of raw materials used in the components mentioned.

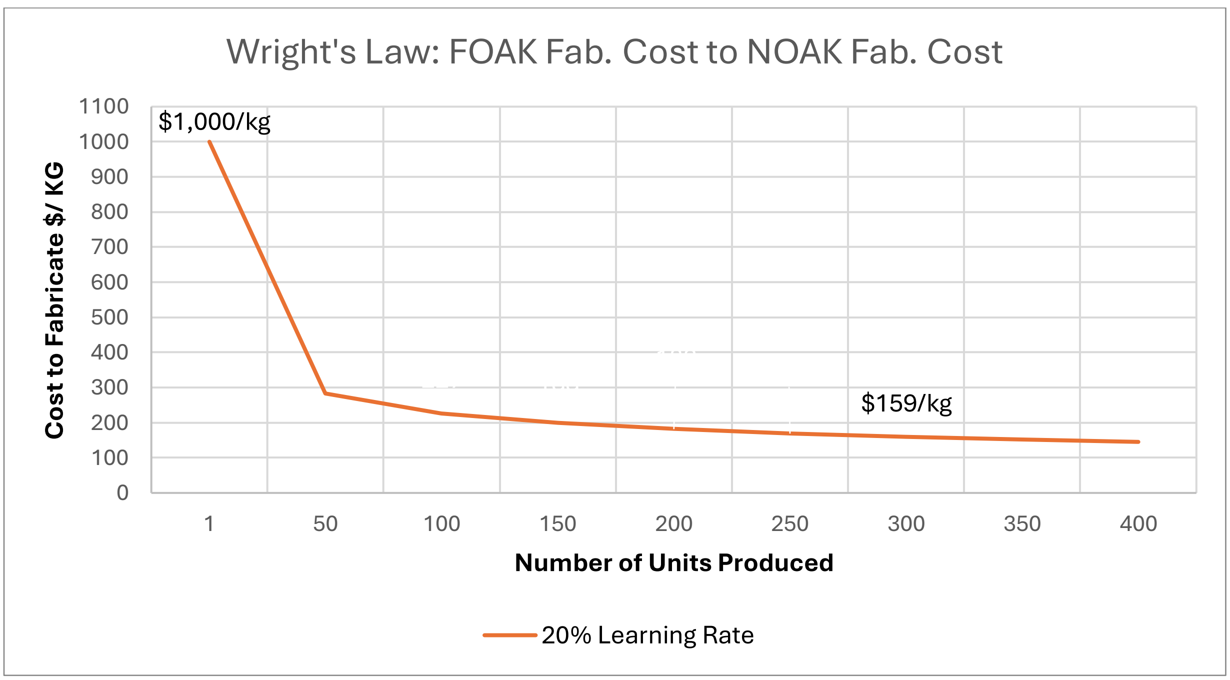
The magnet system represents ~48% of the Reactor Plant Equipment costs (Figure 6). While tokamaks have transitioned to adopting smaller devices, thus reducing the mass of magnet structures per fusion power produced by more than 50% compared to ITER, magnet components remain significant cost drivers. The magnet structure, unlike other reactor components, has established supply chains, and its raw material cost is comparatively lower than the raw material costs for the vacuum vessel and blanket. The difference between the fabricated cost of a component and its material cost is notable. In the 2015 ARC paper, the fabrication costs were estimated to be a factor of 20x greater than the raw material cost (Sorbom et al. 2015). Thus, in addition to providing an overview of the ARC fabrication costing, the deduction of the FOAK cost will be made and compared with NOAK fabrication cost assumptions. Subsequently, I will discuss the current NOAK fabrication cost assumptions outlined in the TEA. Given that Fusion's deployment of the NOAK plant is expected on 2040-2050 timeframe, it is important to understand how advanced technologies can alter standardized manufacturing processes and costs. Thus, there will be a discussion about different cost assumptions, such as alternative low-cost fabrication methods through different manufacturing approaches and the costs of mass-manufactured components. Finally, this section will explore alternative costing methods to understand the impacts on the overall capital cost by applying a new lower bound to the fabrication costs. But first, it is important to understand the fabrication costs included within fusion literature.

5.2 Assumptions in Fabrication Cost Estimation and FOAK Fabrication Costs

Existing fusion economics models often lack clarity regarding the assumptions underpinning the cost of component fabrication. Additionally, existing simplified fabrication cost methods can bring large uncertainty in fabrication cost estimates because they are nonspecific to reactor components or materials ("FIRE Lighting the Way to Fusion A Comparison of Unit Costs for FIRE and ITER" 2002). Highly referenced sources such as *ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets* utilize these simplified fabrication methods, and as a result, the fabrication costs represent 93% of the total costs associated with the vacuum vessel, blanket, and magnet systems (Sorbom et al. 2015). The method used involved comparing the overall projected costs of four burning plasma designs, namely FIRE, BPX, PCAST5, and ARIES-RS, against the weight of each device from the cryostat inward ("FIRE Lighting the Way to Fusion A Comparison of Unit Costs for FIRE and ITER" 2002). The methods used in the ARC paper result in the cost of manufacturing being roughly $1,000 per kilogram, which likely more closely represents a FOAK fabrication cost than a NOAK fabrication cost. Thus, for this TEA, the 1,000 $/kg assumption will be used as an approximate FOAK cost. This chapter will demonstrate how a NOAK cost can be derived from this FOAK cost.

A variety of methods were employed to derive the lower and upper bound of the NOAK fabrication cost. To understand the timeline of the NOAK plant, the following assumption will be made: there will be a 100 GWe installed capacity by 2050, and at 100 GWe, there will be ~300 350 MWe FPPs (Lerede et al. 2023). There are several ways to take the FOAK cost and arrive at the lower bound fabrication cost of ~150 $/kg. Firstly, by applying Wright's Law to the FOAK cost assumption (Figure 7), by the 300th unit, fabrication cost per kg is in line with my lower bound assumption. To assess the full impact of a learning rate, the learning rate of solar technology, which follows Wright's Law, was considered; thus, the impact of applying a 20% learning rate is shown in Figure 7 (Roser 2023). The magnets are expected to be mass-produced in a factory-like environment, similar to Solar PV, and as such, the application of this learning rate is somewhat justified. However, applying this learning rate to the entire ARAI-FPP is not justifiable. In addition, for context, even highly modularized thermal power plants, like natural gas plants, experience learning of about 15% (Rubin et al. 2015).

Figure 7. FOAK to NOAK fabrication cost reduction vs. number of FPPs.



Similarly, the lower bound cost of approximately 150 $/kg for fabrication represents costs associated with conventional fabrication of low-alloy steel for NPP pressure vessel costs, inclusive of labor, factory equipment costs, quality assurance, and qualification (Holcomb, Peretz, and Qualls 2011; Ganda, Taiwo, and Kim 2018). Hence, 150 $/kg was selected as the lower bound NOAK fabrication cost. Table 15 shows the cost of the fabricated power core components with this assumption.

Table 15. Cost of Fabricated Power Components

Fabricated Power Core Components	Lower bound
Fabricated Magnet Cost (SS316 LN)	1,371 $/kW
Fabricated Blanket Tank Cost (TiH2)	63 $/kW
Fabricated VV Cost (V-4Cr-4-Ti) + First Wall (Tungsten)	109 $/kW
HTS Fabricated Costs	162 $/kW
Lifetime of Components	24 months
Lower bound replacement cost of VV + First Wall over lifetime of Plant (30 years)	4,352 $/kW

5.3 Sensitivity on Fabrication Cost

Applying fabrication costs (assuming NOAK) based on conventional fabrication methods such as welding dramatically reduces fabrication costs from what is estimated in ARC (Sorbom et al. 2015). However, two additional assumptions can be made to further reduce the existing fabrication costs lower bound of 150$/kg. 1) Apply the lower bound fabrication cost of mass-manufactured technologies to the lower bound fabrication costs of the TEA. 2) Assume that with advanced manufacturing or additive manufacturing, the fabrication cost will drop significantly. Both cases reduce the cost of fabrication by a factor of 10.

The ARIES-ST fabrication Study outlines a method of applying additive manufacturing techniques the most critical component of the reactor, which is also a replaceable component, the centerpost (L M Waganer et al. 2003). Unlike ARAI, the ARIES-ST has a large centerpost that will need to be replaced every 2-3 FPY. The lifetime of power core components differs based on reactor design. An example of this difference is related to the blanket in this ARIES-ST approach, where the blanket serves as a replaceable component. While the vacuum vessel in the ARIES-ST is designed to last the lifetime of the plant, the TEA assumes that the vacuum vessel and plasma-facing components are replaceable. Within the ARIES-ST studies, a low-cost fabrication approach and conventional fabrication approach were studied and applied to specific power core components and the costs and processes were compared. All costs reported pertaining to the ARIES-ST fabrication study will be inflated to $2021 unless noted otherwise (L M Waganer et al. 2003).

The ARIES-ST fabrication study approximated the centerpost to cost 132 $/kg (compared with 5 $/kg material cost) if fabricated by conventional means which is inclusive of the material cost. The study also detailed the cost to conventionally fabricate a vacuum vessel using welding, and the Unit Cost of finished mass (39776 kg) was estimated to be 160 $/kg. This is in the same order of magnitude as the lower bound assumption of fabrication in the TEA, 150 $/kg. Using the low-cost fabrication method, they were able to cost the fabrication of the centerpost using the Laser (or plasma Arc) advanced technology, making the Unit Cost approximately 13.19 $/kg. The costs of conventional and advanced technology approaches both assume NOAK assumptions that reflect costs associated with mature design and NOAK fabrication processes. The study concluded that the cost of the centerpost would be "approximately ten times higher" if constructed using conventional fabrication approaches. The Laser forming process, allowing a generous allowance for downtime resulted in a fabrication of 8 months or so. The study recommends the fabrication of the centerpost to be done on the reactor site because shipping would be challenging. If one were to take the conclusions of the low-cost approach to fabricating the centerpost and apply it to the other fabricated components, one would see a tremendous reduction in capital costs**. Reducing the lower bound fabrication cost by a factor of 10 would cause the FPP to reduce capital costs by roughly 1,200 $/kW over the plant's lifetime.**

To understand the potential ARAI-FPP cost reduction by driving down fabrication costs, it's necessary to understand the *ultimate* minimum fabrication costs. It is reasonable to assume that the $/kg of fabrication cannot be less than the cost of fabrication of solar PV panels or common mass-produced products such as cars, which is about 15 $/kg. Reducing the reactor component fabrication costs by a factor of 10, from $150 to $15/kg, could decrease the total direct cost by a factor of 1.6 relative to the lower-bound cost for ARAI-FPP.

The findings and application of cost reduction from the ARIES-ST fabrication study corresponds with the lower bound $/kg of fabrication of a solar panel or common mass-produced products such as cars, which is about 15 $/kg. Table 16 depicts the costs after applying this factor, which will be labeled as "Advanced Manufactured Cost." Future R&D, learning rates, and production path for the reactor equipment for ARAI-FPP will determine its cost potential. However, Wright's law has limitations and must be applied cautiously by fusion industry business planners to relevant components. Again, applying Wright's law for the entire ARAI-FPP is incorrect since mature components such as the steam turbo-generator set already have an established NOAK supply chain.

Table 16. Applying a factor of 10 cost savings to Lower Bound Fabrication Cost

DT Magnetic Confinement Reactor Base Case	Conventional fab. Cost (150 $/kg)	Advanced Manufactured cost (15 $/kg)
Fabricated Magnet Cost ($/kW)	1,371 $/kW	131 $/kW
Fabricated Blanket Tank + TiH2 Shield Cost	63 $/kW	8 $/kW
Fabricated VV + First Wall Cost	109 $/kW	30 $/kW
HTS Fabricated Costs	162 $/kW	24 $/kW
Lifetime of Replaceable Components	24 months	
Replacement of VV + First Wall over lifetime of Plant (over 30 years)	1, 632 $/kW	448 $/kW

There are other considerations that drive learning and capital cost considerations; for example, CF impacts these costs. With any new technology with high capital costs, achieving high a CF for the first several years of operation will be challenging, as demonstrated by the fission and carbon-capture fossil power plants as well as many solar thermal power plants and offshore wind. Slower deployment rates for these technologies lead to a slower decline in their FOAK costs. In addition, wind turbines, photovoltaic, and lithium-ion batteries have realized very steep learning rates, as assumed for the lower bound TEA, because they lend themselves to rapid prototyping, R&D, and manufacturing at reasonable investment.

5.4 Impact of Regulatory Framework on Cost

Regulatory Considerations are also relevant when understanding the sources of capital cost escalation. As noted in this thesis, the lower and upper bounds for the cost estimates mainly differ in the assumed regulatory oversight required for the construction and installation of FPPs. Table 17 depicts the impacts of the regulatory assumptions on the relevant cost accounts. The significant financial impacts induced by regulation can motivate the fusion industry to reduce its nuclear footprint as much as possible. Fusion energy systems do not pose the same risks as fission energy because fusion does not require fissile materials, and fusion fuel cannot undergo a chain reaction. Thus, major portions of the regulatory framework for fission energy are not germane to fusion. In addition to regulatory considerations, social acceptance can play a critical role in the deployment and cost of fusion energy projects. Drawing on lessons from the fission industry, where a lack of social acceptance has resulted in higher capital costs and regulatory burdens, the fusion industry should proactively engage the public to build trust and understanding (Hoedl 2023). By creating open dialogues about the benefits and risks, fusion can differentiate itself from fission, potentially easing regulatory paths and reducing costs.

In April 2023, the U.S. Nuclear Regulatory Commission (NRC) approved NRC's staff option to regulate fusion technology under 10 CFR part 30, "Rules of General Applicability to Domestic Licensing of Byproduct Material," which focuses on material that may pose a hazard (Clark 2023). The fusion industry has been supportive of this NRC decision. Note that this decision calls for a new volume of "Consolidated Guidance About Materials Licenses" dedicated to fusion energy systems and leaves open that additional regulations may be required if the "anticipated fusion design presents hazards sufficiently beyond those of near-term fusion technologies" (Clark 2023). However, the regulatory details of the NRC rulemaking are presently being worked on and are expected to evolve as industry stakeholders and regulatory bodies continue to collaborate and refine the guidelines to better align with the unique characteristics and safety profile of fusion energy technologies.

While the focus of this TEA has been on D-T MC reactors, it should be noted that both D-T and non-D-T designs can realize reduced regulatory burdens compared to fission. The recent ruling by the U.S. NRC changed the past thinking that only non-D-T fusion could leverage regulatory benefits. If D-T FPPs maintain a low radioactive inventory by relying on low activation materials in the construction of FPPs and reduced tritium usage, they have the potential to be regulated under the same framework as non-D-T fusion. This reduced scope is expected to result in significantly (>2×) lower costs of fusion-related equipment and civil structure, as shown by the sensitivity of the lower and upper bound costs for ARAI-FPP. All in all, the fusion industry should work to strike a balance between economy of scale, fusion fuel type, regulatory oversight, and engaging public support, which is instrumental in navigating the path to commercial technology.

Table 17. Parameters Impacted by Regulatory Assumptions

Parameters Sensitive to Regulatory Assumptions	Lower Bound	Regulatory Impact on Lower Bound
Structures & Site Facilities ($/kW)	819 $/kW	1,317 $/kW
Direct Costs ($/kW)	6,005 $/kW	6, 958 $/kW
Indirect Costs ($/kW)	1,146 $/kW	2,644 $/kW
Annual Operation and Maintenance ($/MWh)	35 $/MWh	73 $/MWh
LCOE ($/MWh)	140 $/MWh	266 $/MWh
Capacity Factor	0.7	0.5

5.5 Summary

The findings of this cost driver analysis for ARAI-FPP's reactor plant equipment suggest that costs are inextricably linked to the fabrication processes of raw materials involved and regulatory factors. By examining the primary cost components—specifically the power core—innovative manufacturing techniques and learning curves present significant potential for cost reduction. Adopting advanced technologies and implementing mass manufacturing principles, as applied in other industries, can pave the way to substantially decrease fabrication costs.

The evolution of regulatory frameworks, particularly with recent NRC decisions, aligns with the industry's move towards more streamlined oversight, further enabling potential cost reductions without compromising safety. As we approach the projected deployment of FPPs, it becomes increasingly apparent that both technology advancements and regulatory adaptation will be pivotal in achieving the cost-effectiveness necessary for commercial viability. As illustrated in this chapter, the financial implications of such advancements confirm the potential for a marked reduction in capital expenditure, creating a path for a more economically feasible fusion energy future. This analysis, therefore, not only suggests the current cost dynamics but also provides a forward-looking perspective on how the industry might evolve financially as it matures and scales.

D. Conclusion

Fusion technology currently hosts uncertainties that cast a speculative shadow over the results of this analysis. Nevertheless, this thesis provides a unique capital cost methodology and comprehensive evaluation of NOAK technologies for an FPP while identifying the requisite fusion-specific FOAK technologies despite their inherent uncertainties.

The overnight capital cost and the annual operations and maintenance costs greatly impact the LCOE of an FPP. Within the overnight capital costs, it was found that the direct costs are the dominant cost of a NOAK FPP. While assumptions within the direct costs included both NOAK and fusion-specific ones, it was shown that the reactor plant equipment, which hosts the most fusion-specific technology, is the cost driver of the direct costs. A cost driver analysis of the reactor plant equipment revealed the significant impact of fabrication costs on power core components, thus suggesting that reducing costs by a factor of 10 could save at least ~1,200 $/kW (for the lower bound estimate) over the plant's lifetime.

Moreover, given the large cost increase in fission, driven by regulatory oversight, provided the fusion industry succeeds in maintaining a minimal radioactive footprint and gains social acceptance, it is reasonable to anticipate that future regulatory frameworks will not impose severe cost penalties in the U.S. This balanced approach to regulation, cost management, and societal engagement is essential for realizing the promise of fusion energy.

This analysis recognizes many sensitive parameters and acknowledges that the cost figures presented are the best estimates based on currently available information. The final outputs of this analysis are shown in Table 18. The most effective method for refining the overnight capital cost estimates for FPPs would be for companies to share their cost data transparently. Despite this, the true cost of building an FPP will remain uncertain until the FOAK plant is constructed. Nonetheless, this analysis is a vital reference in understanding the economic landscape of fusion technology, informing future R&D and regulatory decisions.

Table 18. Overnight Capital Cost, Annual Operations and Maintenance Cost and LCOE

	Lower Bound	Upper Bound
Overnight Capital Cost	8,831 $/kW	22,180 $/kW
Annual Operations and Maintenance Cost	35 $/MWh	182 $/MWh
LCOE	140 $/MWh	550 $/MWh

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