
A COSTING FRAMEWORK FOR FUSION POWER PLANTS *

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ABSTRACT

This paper summarizes and consolidates fusion power-plant costing work performed in support of ARPA-E from 2017 through 2024, and documents the evolution of the associated analysis framework from early capital-cost-focused studies to a standards-aligned, auditable costing capability. Early efforts applied ARIES-style cost-scaling relations to generate Nth-of-a-kind (NOAK) estimates and were calibrated through a pilot study with Bechtel and Decisive Systems to benchmark balance-of-plant (BOP) costs and validate plant-level reasonableness from an engineering, procurement, and construction (EPC) perspective. Subsequent work, informed by Lucid Catalyst studies of nuclear cost drivers, expanded the methodology to treat indirect costs explicitly and to evaluate cost-reduction pathways for non-fusion-island systems through design-for-cost practices, modularization, centralized manufacturing, and learning. As ARPA-E's fusion portfolio expanded, these methods were applied across BETHE and GAMOW concepts (and select ALPHA revisits), including enhanced treatment of tritium handling and plant integration supported by Princeton/PPPL expertise. In 2023 the capability was refactored to align with the IAEA-GEN-IV EMWG-EPRI code-of-accounts lineage, while key ARIES-derived scaling relations were replaced by bottom-up subsystem models for dominant fusion cost drivers (e.g., magnets, lasers, power supplies, and power-core components) coupled to physics-informed power balances and engineering-constrained radial builds. These developments were implemented in the spreadsheet-based Fusion Economics code (FECONs) and released as an open-source Python framework (pyFECONs), providing a transparent mapping from subsystem estimates to standardized accounts and a consistent computation of LCOE.

1 Introduction

Economic credibility is now a central requirement for fusion energy: as concepts mature from physics demonstrations toward integrated pilot plants, developers, funders, and policymakers require cost estimates that are transparent, comparable across architectures, and traceable to underlying technical assumptions. The ARPA-E support work summarized here was motivated by precisely this need: to move beyond one-off, non-comparable fusion costing exercises toward a repeatable programmatic capability that can identify dominant cost drivers, test cost-reduction strategies, and enable like-for-like comparisons with advanced fission and other low-carbon generation options.

Foundation and guiding philosophy

The work builds on three complementary foundations: (i) the ARIES family of fusion power plant studies, which couple physics-informed power balances, engineering-constrained radial builds, conceptual plant layouts, and high-level cost scalings; (ii) ARPA-E's 2017 pilot study with Bechtel and Decisive Systems, which benchmarked and sanity-checked fusion plant capital costs from an EPC standpoint; and (iii) Lucid Catalyst analyses of nuclear cost drivers, which emphasize the importance of indirect costs, construction methodology, modularization, and learning in determining achievable \$/kW outcomes. Across these efforts, the guiding workflow remained consistent: begin with a physics-informed power balance, translate performance requirements into a feasible radial build subject to

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engineering constraints, size dominant driver systems (e.g., magnets, lasers, power supplies), and then translate thermal performance and layout into BOP equipment and buildings, with conventional plant subsystems anchored primarily to NETL baselines where appropriate.

Program evolution: from pilot studies to portfolio support

The program evolved through distinct stages. In 2017, the immediate objective was to establish an initial fusion costing workflow suitable for ARPA-E needs and to calibrate ARIES-derived outputs against EPC experience; this phase highlighted sensitivities to layout, buildings, and major equipment sizing and established a credible baseline for BOP-related costs. In 2019, the emphasis broadened to separate and scrutinize BOP and (especially) indirect costs, and to identify actionable pathways for reducing non-power-core costs via standardized layouts, modularization, centralized manufacturing, and learning effects—a key shift driven by the recognition that non-fusion-island costs often dominate total plant cost. During 2022–2023, the capability matured into a portfolio-scale support function for BETHE and GAMOW awardees (and selected ALPHA revisits), providing concept-consistent analyses across diverse private-sector architectures while improving realism in tritium handling and fuel-cycle assumptions through PPPL’s operational and safety expertise.

Standards alignment and tool release

By 2023, ARPA-E’s growing portfolio and the need for cross-concept comparability motivated a refactor toward a standardized, auditable, and extensible framework. This refactor aligned the costing structure with the IAEA (2001), GEN-IV EMWG (2007), and EPRI (2024) code-of-accounts lineage, and prioritized replacement of legacy ARIES scalings with bottom-up subsystem models for major fusion-unique drivers, coupled to explicit power-balance and radial-build calculations (including multi-fuel and blanket option coverage). The resulting capability was implemented in FECONs (spreadsheet) and released as pyFECONs (open-source Python), emphasizing transparency, traceability, and extensibility as a reference implementation for credible fusion costing and consistent LCOE evaluation.

Scope and contributions

Accordingly, this paper (i) documents the evolution of the ARPA-E fusion costing methodology from ARIES-derived scalings to bottom-up subsystem models, (ii) summarizes how portfolio-scale application sharpened identification of dominant cost drivers and improved tritium/fuel-cycle realism, and (iii) presents the standardized account structure and implementation philosophy embodied in the FECONs/pyFECONs tools, enabling auditable and like-for-like cost comparisons across fusion concepts and against other generation technologies.

2 Background

This work adopts a deliberately conservative and well-documented costing lineage, drawing on established power-plant cost-accounting methodologies that have been developed and refined within the nuclear sector. Specifically, the cost-category structure and economic accounting conventions used here are informed by (i) International Atomic Energy Agency (IAEA) guidance on economic evaluation of nuclear power plants, (ii) the Generation IV International Forum (GIF) Economics Modeling Working Group (G4EMWG) guidelines, and (iii) the synthesis and interpretation of these methods in Rothwell’s *Economics of Nuclear Power* framework [7, 6, 9]. The purposeful use of these contemporary, externally vetted methodologies improves transparency and facilitates reproducibility for researchers who wish to perform comparable analyses.

A key departure from many prior fusion costing studies is the explicit reorganization of the capital cost accounts. Direct costs are separated into Category 10 (pre-construction) and Category 20 (construction), while indirect and capitalized ancillary costs are grouped into Categories 30–60 (formerly Categories 91–98 in some legacy nuclear accounting structures). This structure retains substantial continuity with established practice—for example, the Category 20 construction accounts remain closely aligned with conventional plant breakdowns—while adding or clarifying elements that are particularly important for modern fusion development programs (e.g., explicit treatment of a digital twin and contingency). Additionally, the treatment of decommissioning is modified to improve accounting clarity: rather than embedding decommissioning in the LCOE in a manner that can be difficult to audit, decommissioning costs are represented as a capitalized indirect cost, enabling clearer attribution, sensitivity studies, and discussion of the drivers of end-of-life obligations.

Although the accounting structure is derived from fission-centered references, the cost drivers for fusion plants can differ substantially in the heat island, fuel cycle, remote handling, and replacement schedule of major components. Those

fusion-specific departures are therefore made explicit throughout the paper at the subsystem level. Where possible, we adopt the GEN-IV subcategory descriptions from the G4EMWG guidance, editing them to capture fusion-specific hardware and operational realities without losing the comparability benefits of a standardized taxonomy.

Our costing philosophy is to (i) provide recent cost-basis information for each cost category wherever possible, (ii) state the cost basis and its provenance directly in the text, and (iii) provide references that enable users of the accompanying models and code to trace assumptions back to primary sources. We are also judicious in terminology. In some contexts, the term “reactor” carries connotations that may hinder broader adoption of fusion energy systems; accordingly, we use the term “heat island” where it more precisely conveys function without unnecessary connotation. We recognize that terminology will evolve, and we aim for internal consistency and clarity in this edition.



Figure 1: Cost categories used in this work. The capital-cost taxonomy separates direct costs into Category 10 (pre-construction) and Category 20 (construction), and groups indirect and capitalized ancillary costs into Categories 30–60.

2.1 Foundational documents influencing the costing methodology

The GEN-IV Economics Modeling Working Group (G4EMWG) guidelines provide a comprehensive structure for economic modeling of advanced nuclear energy systems [6]. The guidance systematically defines cost categories spanning pre-construction activities through annualized financial costs, and it provides a granular breakdown of capitalized costs (direct costs, capitalized indirect service costs, owner’s costs, and supplementary costs), as well as recurring costs (operations and maintenance, fuel, and financing). In addition to defining the taxonomy, the guidelines emphasize disciplined cost accounting practices that support transparent budgeting, economic feasibility evaluation, and consistent comparisons across designs and deployment contexts.

Rothwell’s treatment of nuclear power economics provides an integrative foundation for interpreting these accounting conventions within the broader context of investment decision-making [9]. It emphasizes the relationship between capital cost determination, uncertainty and risk, and the financial structure of large-scale energy infrastructure. The framework is particularly relevant for fusion, where high capital intensity and technology novelty increase the importance of structured uncertainty treatment, clear cost boundaries, and auditable assumptions.

IAEA guidance (e.g., TRS/TECDOC methodology) provides a standardized approach to economic evaluation and to the calculation of leveled electricity metrics such as the Levelized Discounted Electricity Generation Cost [7]. The IAEA methodology highlights the role of financial parameters (discount rate, inflation, escalation, and plant lifetime), and it emphasizes sensitivity analysis as a necessary complement to point estimates, particularly for long-lived infrastructure projects where economic conditions and technology maturity can evolve over time.

2.2 Documents providing cost bases for key cost categories

To populate the cost accounts with defensible cost bases, we draw on fusion-specific cost documentation developed for the ARIES systems studies, alongside independent baselines for conventional power plants. The UCSD “ARIES Cost Account Documentation” report by Waganer provides historical and methodological context for fusion power plant costing and develops updated economic models suitable for forward-looking system studies [10]. It compiles and rationalizes costing information from earlier conceptual designs, documents escalation practices (e.g., use of macroeconomic deflators to translate historical estimates), and reviews the general cost-account structures originally

defined in DOE-era guidance. It also addresses recurring issues in fusion costing such as spare parts, contingency, and safety assurance level assumptions.

Complementing this, Waganer's ARIES project presentation on Cost Accounts 20 and 21 provides additional detail on the evolution of cost modeling for major plant structures and reactor/heat-island-adjacent equipment categories [11]. It motivates updates to legacy costing algorithms that were originally developed with limited documentation depth and highlights specific accounts that benefit from explicit definition and reporting (e.g., radioactive waste treatment, cryogenic systems, and plant maintenance equipment), which are also relevant to modern fusion facilities.

Finally, we use the National Energy Technology Laboratory (NETL) cost and performance baselines for fossil energy plants as an external reference for non-nuclear balance-of-plant components and for cross-technology benchmarking [12]. The NETL baseline reports employ a systematic and transparent technical-economic approach across multiple plant configurations (e.g., IGCC, PC, and NGCC, with and without CO₂ capture). These baselines provide independently assessed cost and performance anchors for conventional plant subsystems and serve as a useful comparator set when evaluating fusion plant cost allocations and performance assumptions in a broader power-market context.

3 Guiding philosophy

Across all studies, we followed the ARIES-style workflow: begin with a physics-informed power balance, translate this into a feasible radial build subject to engineering constraints (e.g., surface heat/power loading), then size the dominant driver systems (magnets, lasers, power supplies) and balance-of-plant (BOP). Assumptions and cost bases are stated explicitly in each generated report, with BOP costs primarily informed by NETL baselines and augmented by additional sources as available to each concept and partner.

4 Program Timeline and Study Objectives

4.1 Partners and stakeholders

Key collaborators across the period included:

- Bechtel (Desmond Chan, CTO)
- Decysive Systems (Ronald Miller)
- Lucid Catalyst (Eric Ingersoll)
- Princeton / PPPL (Mike Zarnstorff, lead POC) and PPPL domain experts (notably tritium handling and plant operations experience)

4.2 2017: Capital-cost-focused pilot with Bechtel + Decysive Systems

4.2.1 Goals

- Establish an initial fusion costing workflow suitable for ARPA-E program needs.
- Produce capital cost estimates for representative fusion systems.
- Calibrate ARIES-derived scaling outputs against an experienced EPC (engineering, procurement, construction) perspective.

4.2.2 Methodological basis

- Primary dependence on ARIES cost scaling relations (grounded in the UCSD-led body of work).
- Capital-cost scope only (no full indirect-cost model; limited treatment of O&M and lifecycle effects).

4.2.3 Role of Bechtel

- Provided calibration points and sanity checks using internal costing capability.
- Found rough agreement in BOP-related costs when compared to ARIES-derived scaling and internal benchmarks.

4.2.4 Key outcomes

- Initial validation that ARIES-derived plant-level scalings were directionally consistent for several BOP categories.
- Identification of cost elements most sensitive to plant layout, buildings, and major equipment sizing.

4.3 2019: BOP and indirect-cost deepening with Lucid Catalyst + Decisive Systems

4.3.1 Goals

- Separate and scrutinize BOP costs independent of EPC calibration.
- Expand emphasis on indirect costs and the costs outside the fusion power core.
- Identify actionable pathways to reduce dominant cost categories (buildings, turbine halls, heat exchangers, site works, construction management).

4.3.2 Focus areas

- Indirect cost structure: engineering, construction management, owner's costs, contingency framing, schedule/cost-of-money implications.
- Design-for-cost approaches: standardized layouts, simplified buildings where feasible, and disciplined accounting structures.
- Modularization and centralized manufacturing: quantify learning opportunities and repeatability benefits.

4.3.3 Key outcomes

- A comprehensive view of modularization feasibility and its potential impact on both direct and indirect costs.
- Clearer articulation that (for many concepts) non-power-core costs dominate total plant costs, motivating cost-out strategies beyond physics performance.

4.4 2022–2023: Program-support role for ARPA-E BETHE and GAMOW (and revisits to ALPHA concepts)

4.4.1 Goals

- Apply learnings from 2017 and 2019 across a growing portfolio of ARPA-E fusion concepts.
- Provide rapid, concept-consistent costing analyses as a supporting-team function.
- Engage directly with private fusion companies, often delivering their first structured costing assessment.

4.4.2 Activities

- Concept-by-concept cost driver identification for BETHE and GAMOW awardees.
- Revisit selected ALPHA concepts with updated assumptions and improved costing structure.
- Iterate power balance → radial build → driver system sizing → BOP translation for each architecture class:
 - MFE: magnets and power supplies frequently dominant
 - IFE: lasers and repetition-rate/target systems frequently dominant
 - MIFE: hybrid driver dominance depending on configuration

4.4.3 Princeton/PPPL contribution (2022–2023)

- Mike Zarnstorff served as the lead POC at PPPL for the collaboration.
- Deepened treatment of tritium handling, leveraging decades of operational and safety experience from PPPL.
- Improved realism in fuel-cycle assumptions, containment approaches, and implications for plant systems and facilities.

4.4.4 Key outcomes

- More accurate identification of cost drivers across diverse private-sector concepts.
- Better fidelity in tritium-related systems and associated facility/safety implications.
- More consistent cross-concept comparisons through harmonized assumptions and reporting.

4.5 2023: Refactor to International Cost Accounts and Transition to Bottom-Up Power-Core Costing

4.5.1 Motivation

By 2023, the program required a costing framework that was:

- standardized (comparable across concepts and institutions),
- auditable (transparent cost basis and assumptions),
- extensible (new blankets, fuels, and driver technologies),
- and less dependent on legacy ARIES scalings for novel architectures.

4.5.2 Cost-account standardization

- Refactored the cost code in accordance with the cost accounts originally proposed by the IAEA (2001),
- adopted by the GEN-IV Economics Modeling Working Group (EMWG) in 2007,
- and later adopted by EPRI (2024).

4.5.3 Replacement of ARIES-derived scalings with bottom-up subsystem models

Priority was given to bottom-up costing for major fusion-unique drivers and dominant plant cost contributors:

- Magnets (including supporting structures and cryogenic implications as required)
- Lasers (including scaling with energy, repetition rate, efficiency, and facility implications)
- Power supplies (sized to electrical demand profiles and driver requirements)
- Power core components and key materials/volumes driven by radial build

4.5.4 Physics-to-economics extensions

- Developed power balance and radial build capabilities for multiple fuel cycles:
 - D-D, D-T, D-³He, and p-¹¹B
- Incorporated published blanket configurations and broadened blanket option coverage.
- Maintained explicit constraint handling (e.g., surface heat/power loading limits) to ensure economic outputs remained tied to feasible engineering envelopes.

4.5.5 FECONs and pyFECONs: Tools, Releases, and Intended Use

4.6 FECONs (spreadsheet framework)

- Implemented the refactored accounts and bottom-up components in a spreadsheet tool named *FECONs* (Fusion Economics code).
- Designed to demonstrate the level of fidelity required for credible fusion costing and to provide an auditable pathway from assumptions to totals.

4.6.1 pyFECONs (open-source Python implementation)

- Converted FECONs to a Python script and released the open-source version as *pyFECONs*.
- Published on GitHub as a framework illustrating structure, data flow, and required fidelity for fusion cost analysis.
- The open-source release intentionally emphasized transparency and extensibility over proprietary calibration.

4.6.2 Clean Air Task Force supported extension (closed-source evolution)

- Subsequent development (post initial open-source release) was supported by the Clean Air Task Force.
- This branch is evolving into a closed-source version with a web interface and additional costing features, including expanded treatment of safety systems.

4.7 2025 Application Example (Contextual, Post-ARPA-E Window)

4.7.1 LANL Plasma Jet Magneto-Inertial Fusion concept

- Applied the matured costing framework to a small number of systems, including the LANL Plasma Jet Magneto-Inertial Fusion concept.
- Released under an LA-UR number and served as a consolidation of the analysis fidelity achieved to date.

4.8 Methodology (Common to All Studies)

4.8.1 Step 1: Physics-informed power balance

- Inputs range from analytic calculations to higher-fidelity modeling (including, where available, 3D MHD stability calculations).
- Outputs define required fusion power, driver power, recirculating power, and net electrical power targets.

4.8.2 Step 2: Radial build and engineering constraints

- Translate physics requirements into geometry: plasma/target region, first wall, blanket, shield, structural allowances, and maintenance space.
- Enforce constraints (notably surface power loading and material/thermal limits), which strongly shape plant size and cost.

4.8.3 Step 3: Driver system sizing (dominant cost drivers)

- MFE: magnets and associated systems (structure, cryogenics, power supplies).
- IFE: lasers, repetition-rate systems, and (where applicable) target-related handling/facilities.
- MIFE: hybrid dominance depending on architecture and operating point.

4.8.4 Step 4: Balance-of-plant translation

- Map thermal power, conversion efficiency, and plant layout into turbine hall, heat exchangers, cooling/heat rejection, electrical plant, and buildings.
- BOP cost basis primarily referenced to NETL reports, supplemented by other sources as needed for the specific concept and data availability.

4.8.5 Step 5: Indirect costs and total plant cost

- Evolve from early limited treatment (2017) to deeper, structured indirect cost consideration (2019 onward).
- Explicitly address the large influence of buildings, construction methodology, modularization, and learning on total plant cost.

4.8.6 Step 6: Reporting, assumptions, and traceability

- Each report states assumptions, the cost basis for major accounts, and the conceptual maturity level.
- Outputs emphasize identification of dominant cost drivers and sensitivity to key design parameters.

4.9 Evolution of the Costing Approach (Key Themes)

4.10 From scalings to bottoms-up

- 2017: ARIES-derived scalings used heavily for capital cost estimation with EPC calibration points.
- 2019: expanded indirect cost and modularization analysis; increased focus on non-power-core dominance.
- 2022–2023: portfolio-scale application with improved tritium realism and broader concept coverage.
- 2023: standards-aligned cost accounts; bottom-up costing for major drivers; multi-fuel and blanket option expansion.

4.10.1 From single-study outputs to program infrastructure

- Transitioned from one-off analyses to a repeatable framework supporting multiple ARPA-E programs and private-sector concepts.
- Emphasized auditable structure (accounts), reproducibility (code), and extensibility (multiple fuels/blankets/driver types).

4.11 Deliverables Summary

- 2017: Capital cost estimates with Bechtel calibration; ARIES-scaling-based foundation.
- 2019: BOP/indirect cost emphasis; modularization and centralized manufacturing implications.
- 2022–2023: BETHE/GAMOW support; ALPHA revisits; private-sector first-pass costing studies; tritium handling deepening with PPPL.
- 2023: Cost-account refactor (IAEA/EMWG/EPRI-aligned); bottom-up driver and power-core component models; multi-fuel and blanket coverage.
- FECONS: Spreadsheet-based framework capturing new fidelity requirements.
- pyFECONS: Open-source Python framework released on GitHub.
- CATF-supported branch: closed-source web-based evolution with added safety costing features.

5 Level-1 (“10-level”) cost accounts: IAEA, GEN-IV (GIF/EMWG), and ARPA-E fusion costing

In this work, “10-level” refers to the highest-level groupings in the cost code-of-accounts (COA)—the broad buckets that organize all lower-level accounts. The GEN-IV (GIF/EMWG) COA expresses these as {10, 20, 30, 40, 50, 60}; the IAEA TCIC COA uses closely corresponding groupings but (in the TRS-396 presentation) enumerates most capital accounts as 21–41, 50–54, 60–62, and 70–72 [6, 7].

5.0.1 IAEA NPP Total Capital Investment Cost (TCIC) account system (2001)

The IAEA TCIC COA organizes capital investment into four main groupings (plus supplementary items), with the structure explicitly listed in Table II of TRS-396. [7]

- **Base costs (Accounts 21–41).** The “overnight” plant construction cost before supplementary and financing.
 - **Direct plant costs (Accounts 21–28):** buildings/structures at site (21); plant equipment in major systems (22–27); plus simulators (28).
 - **Indirect services and site execution (Accounts 30–39):** supplier/A&E engineering, design, project management (home office and site), construction supervision, construction labor, commissioning, trial test run, and construction facilities/materials.
 - **Other base-cost services (Accounts 40–41):** staff training/technology transfer and related services (40), and housing/infrastructure (41).
- **Supplementary costs (Accounts 50–54).** Transportation/insurance (50), spare parts (51), contingencies (52), insurance (53), and decommissioning costs if not treated elsewhere (54).
- **Financial costs (Accounts 60–62).** Escalation (60), interest during construction (61), and fees (62), applied to the capitalized investment scope.
- **Owner’s costs (Accounts 70–72).** Owner’s capital investment and services (70), escalation of owner’s costs (71), and financing of owner’s costs (72).

5.0.2 GEN-IV (GIF/EMWG) COA (2007) for power generation plants

The GIF/EMWG guidelines provide a harmonized COA and reporting template (Table 1.2) that is widely used for advanced nuclear economic studies and implemented in the G4ECONS model. [6] At the “10-level” (highest level), the categories are:

- **Account 10:** Capitalized pre-construction costs.
- **Account 20:** Capitalized direct costs.

- **Account 30:** Capitalized indirect services costs.
- **Account 40:** Capitalized owner’s costs.
- **Account 50:** Capitalized supplementary costs.
- **Account 60:** Capitalized financial costs.

5.0.3 ARPA-E fusion costing (FECONs/pyFECONs) “10-level” accounts and how fusion maps into them

For the ARPA-E fusion costing refactor (FECONs/pyFECONs), we adopted the GEN-IV (GIF/EMWG) 10-level capital COA as the top-level reporting structure (for comparability with fission and other low-carbon technologies), while mapping fusion-unique subsystems into the appropriate direct-cost equipment/building accounts. [6]

Note on equivalence between IAEA and GIF “10-level” groupings. The GIF/EMWG 10-level accounts are a packaging of essentially the same scope elements represented in the IAEA TCIC COA, but expressed in a way that cleanly separates pre-construction, direct, indirect services, owner’s, supplementary, and financial adders at the top level. [6, 7]

Included in the Appendix is a complete chart of accounts that has been used for the ARPA-E work. Note that the chart of accounts given is for a MFE system. IFE and MIFE systems are almost identical, except for important ways such as the use lasers of pulsed power, and these major cost drivers are usually placed in 22.1.3. However, there are important differences between each fusion concept outside of 22.1.3, and so the accounts and methodology are provided only as guidance: each power plant will be highly customized.

6 Python fusion power plant costing code (pyFECONs example) overview

6.1 Implementation approach and cost-account realization

The pyFECONs example implements a sequential, physics-to-economics workflow in which each cost account is realized from explicit intermediate plant quantities rather than imposed as a single top-down scaling. The calculation begins by establishing a consistent *power balance*, which determines gross and net electric output and provides the capacity-normalization basis used throughout the costing (e.g., \$/kW_e factors, BOP sizing, and annual energy production for LCOE). With the net plant output fixed, the code proceeds to a *radial build* that defines the principal geometric dimensions of the fusion “heat island” (e.g., core, blanket/shield regions, coil envelope, and bioshield). These geometry and layout results then drive the sizing of the *containment / heat-island building* and associated plant structures.

Next, the implementation sizes the major *balance-of-plant (BOP)* systems—including turbines, generators, condensers, heat rejection, and supporting electrical and auxiliary plant equipment—using engineering rules and cost bases derived primarily from the NETL 2019 cost and performance baseline methodology. In practice, this means that once thermal power and conversion efficiency are specified, the steam cycle and heat rejection capacities are determined, turbine island equipment is scaled accordingly, and the remaining BOP subsystems are scaled consistently with power-plant practice. Buildings and site facilities are then placed around the major elements (heat island, turbine hall, electrical plant, cooling systems, service buildings), yielding an internally consistent plant layout and building program that is commensurate with the sized equipment.

Only after these plant-level physical quantities are established does the code assemble the *overnight construction cost (OCC)* by summing the relevant direct cost accounts (pre-construction and construction categories) and the explicitly sized structures and equipment. Finally, the code computes the remaining overhead and capitalized indirect accounts (indirect services, owner’s costs, supplementary costs, and financial costs) using predominantly bottom-up calculations and well-defined roll-ups, rather than embedding such items implicitly within LCOE. This sequencing enforces traceability: each cost account is linked to specific physical drivers (power, geometry, equipment size, and layout) and to documented cost bases, enabling auditable updates as subsystem assumptions evolve.

Interdependencies and coupled constraints in power-core costing. A recurring theme in fusion power-plant costing is that the dominant power-core subsystems are strongly coupled, so that a “local” design choice often propagates nonlinearly into several cost accounts. For example, magnet technology and operating temperature influence not only the direct magnet cost (e.g., conductor, structure, and manufacturing) but also the required power supplies, the cryogenic plant sizing and parasitic power, and the scope of safety and confinement systems needed to manage cryogens and quench events; these knock-on effects can shift both CAPEX and the recirculating power fraction that governs net output. Coolant selection is similarly interdependent with materials choices and safety: for instance, FLiBe (and

related molten salts) can be chemically aggressive and may require tighter materials constraints, corrosion allowances, chemistry control systems, and inspection/maintenance provisions, while helium or water choices shift heat-transfer equipment sizing, pumping power, and activation/contamination boundaries. Blanket thickness and composition are also coupled to magnet size and shielding: higher-field or larger-radius magnet sets can relax neutron shielding requirements but increase structural and cryogenic scope, whereas thinner blankets can reduce plant size while potentially increasing required lithium enrichment (or other breeding enhancements) to maintain target tritium breeding ratio (TBR), thereby coupling geometry to fuel-cycle and materials procurement assumptions. Beyond these subsystem interdependencies, the framework enforces basic engineering constraints that shape feasible operating points and costs, including surface power-loading limits on first-wall/structures, IFE chamber sizing to avoid first-wall melt limits, and IFE chamber clearing (pumping) requirements that couple repetition rate and debris/ash removal to vacuum system power and equipment size. Capturing these coupled dependencies is essential for credible TEA: it prevents double counting and ensures that cost and performance sensitivities reflect physically and operationally consistent plant designs rather than independent, unconstrained subsystem perturbations.

6.2 High-level workflow

At a high level, the script proceeds as follows:

1. Define blanket/material options and global economic assumptions (construction time, NOAK/FOAK toggle, plant life, availability).
2. Compute a plant power balance (fusion power, thermal power, gross and net electric power).
3. Compute capital cost accounts:
 - Account 10 (pre-construction),
 - Account 20 (direct costs) including 21 (buildings) and 22–28 plant equipment subaccounts,
 - Accounts 30/40/50/60 (indirect, owner, supplementary, financial).
4. Compute annualized costs (70 O&M, 80 fuel, 90 annualized capital/finance).
5. Compute LCOE and write results into LaTeX tables.

6.3 Power balance model

The script defines a steady-state power balance for a D-T-like energy partition, starting from a specified fusion power P_f (named PNRL in the code due to a legacy calculation of the fusion power using the NRL formulary [13]). Alpha power P_α is computed from the D-T energy split (3.52 MeV of 17.58 MeV), and neutron power is the remainder:

$$P_f \equiv P_{\text{NRL}}, \quad (1)$$

$$P_\alpha = P_f \left(\frac{3.52}{17.58} \right), \quad (2)$$

$$P_n = P_f - P_\alpha. \quad (3)$$

A neutron energy multiplier M_N (named MN) is applied to neutron heating. Several plant internal loads and fractions are defined, including:

$$P_{\text{aux}} = P_{\text{trit}} + P_{\text{house}}, \quad (4)$$

$$P_{\text{coil}} = P_{\text{TF}} + P_{\text{PF}}, \quad (5)$$

$$P_{\text{cool}} = P_{\text{TF,cool}} + P_{\text{PF,cool}}, \quad (6)$$

$$P_{\text{in}} \equiv P_{\text{INPUT1}} \quad (\text{auxiliary heating / driver input}). \quad (7)$$

The code forms a thermal power expression (named PTH) that includes: neutron-multiplied neutron power, alpha power, auxiliary heating input, and an additional term proportional to $(M_N P_n + P_\alpha)$ intended to represent heat associated with primary pumping and subsystems (implemented as a fraction times the thermal conversion efficiency):

$$P_{\text{th}} = M_N P_n + P_\alpha + P_{\text{in}} + \eta_{\text{th}} (f_{\text{PCPP}} \eta_p + f_{\text{sub}}) (M_N P_n + P_\alpha), \quad (8)$$

where η_{th} is the thermal-to-electric conversion efficiency, f_{PCPP} is the primary coolant pumping fraction, η_p is a pumping “capture efficiency” factor, and f_{sub} is a subsystem/control fraction.

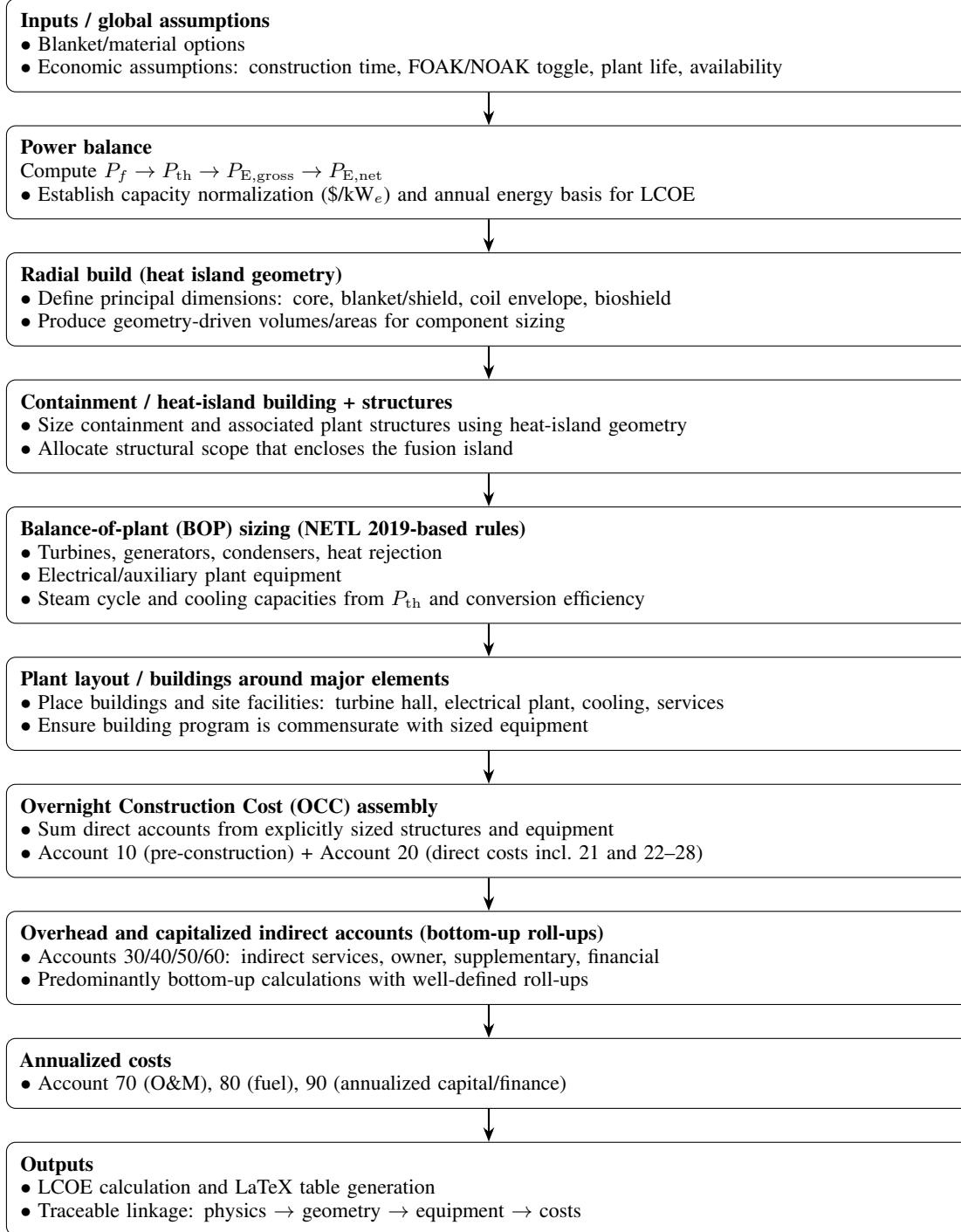


Figure 2: Sequential physics-to-economics workflow implemented in the pyFECOns example: power balance and net output establish the normalization basis; radial build and containment sizing determine heat-island geometry; NETL 2019-derived rules size the turbine island and BOP; plant buildings and layout are generated around major elements; direct costs are assembled into OCC; overhead and capitalized indirect accounts are rolled up bottom-up; annualized costs and LCOE are then computed and written to LaTeX tables.

Gross electric power is then:

$$P_{th,e} = \eta_{th} P_{th}, \quad (9)$$

$$P_{DE} = \eta_{DE} P_{\alpha}, \quad (10)$$

$$P_{E,gross} \equiv P_{ET} = P_{th,e} + P_{DE}, \quad (11)$$

with η_{DE} set to zero in the reviewed configuration.

The script defines a plant “engineering gain” Q_{eng} (named QENG) as a ratio of “useful” electric output to internal electric loads. With η_{wp} the wall-plug efficiency for auxiliary input power, the implemented form is:

$$Q_{eng} = \frac{\eta_{th} (M_N P_n + P_{pump} + P_{in} + P_\alpha)}{P_{coil} + P_{pump} + P_{sub} + P_{aux} + P_{cool} + P_{cryo} + P_{in}/\eta_{wp}}, \quad (12)$$

where the code sets

$$P_{pump} = f_{PCPP} P_{th,e}, \quad (13)$$

$$P_{sub} = f_{sub} P_{th,e}. \quad (14)$$

The recirculating fraction is $f_{rec} = 1/Q_{eng}$ (named REFRAC), and net electric power is:

$$P_{E,net} \equiv P_{NET} = \left(1 - \frac{1}{Q_{eng}}\right) P_{E,gross}. \quad (15)$$

Extension to alternative fuels and direct energy conversion. The foregoing partition is “D–T-like” in that it assumes a dominant neutron channel with a fixed alpha fraction. For alternative fuel cycles (e.g. D–D, D– 3 He, and p– 11 B), the power balance would require (i) replacing the fixed (3.52/17.58) alpha split with reaction-specific charged-particle and neutron energy fractions (including the appropriate branching ratios for D–D), (ii) updating the neutron multiplier term to reflect the substantially reduced (or, for some branches, redistributed) neutron heating, activation, and blanket multiplication pathways, and (iii) revising auxiliary loads that are tightly coupled to fuel choice (e.g. tritium-breeding and processing loads may decrease for D– 3 He and p– 11 B, while heating/driver requirements and wall-plug efficiency assumptions may shift due to different optimal operating temperatures and confinement requirements). These changes also interact with the balance-of-plant: a reduced neutron fraction can alter recoverable thermal power, blanket/coolant design choices, and heat-rejection requirements. Finally, if a significant portion of charged-particle power can be converted directly to electricity (non-thermal *direct energy conversion*), the term $P_{DE} = \eta_{DE} P_\alpha$ generalizes to the full charged-particle channel, and the gross electric output becomes a hybrid of thermal conversion and direct conversion. In that case, the recirculating-power accounting should avoid double-counting: parasitic electric loads should be subtracted from the combined $\eta_{th} P_{th} + P_{DE}$ gross output, while thermal-side loads should remain in the thermal balance.

Account 21 (Buildings) scaling. Buildings and site structures are largely scaled linearly with gross electric power $P_{E,gross}$ (PET in the code) using fixed coefficients (interpretable as \$/kW-type factors after escalation), summed as:

$$C_{21} = \sum_i k_{21,i} P_{E,gross} + C_{21,cont}, \quad (16)$$

with an optional contingency term that is suppressed in NOAK mode.

Account 22.1 (Fusion island / reactor equipment): bottom-up components. For several fusion-unique components, the script uses bottom-up volumetric/material models driven by a radial build (thicknesses for vacuum vessel, first wall, blanket, shields, coil region, bioshield, etc.). Volumes are computed from simplified torus/sphere geometry, and material costs are computed as:

$$C_{mat} \approx \frac{V \rho c_{raw} m}{10^6}, \quad (17)$$

where V is volume, ρ is density, c_{raw} is a raw material unit cost, m is a manufacturing multiplier, and the factor 10^6 converts to M\$ in the script. This structure is used, for example, for first wall + blanket materials and for portions of shielding and special materials.

Major cost driver: superconducting magnets (Account 22.1.3). A detailed magnet costing routine (`magnetsAll`) estimates REBCO tape length (or equivalent conductor usage), computes superconductor material cost using a \$/kA·m rate, adds copper/steel/insulation where applicable, and applies manufacturing and structural multipliers. In simplified form, the implemented magnet cost logic is:

$$C_{SC} \sim \frac{I_{tape}}{10^3} (L_{tape} \times 10^3) \frac{c_{YBCO}}{10^6}, \quad (18)$$

$$C_{Cu} \sim \frac{m_{Cu} c_{Cu}}{10^6}, \quad C_{SS} \sim \frac{m_{SS} c_{SS}}{10^6}, \quad (19)$$

$$C_{mag} = m_{mfr} (C_{SC} + C_{Cu} + C_{SS} + C_{ins}) + C_{struct}, \quad (20)$$

summed over coil sets (TF, CS, PF) and multiplied by coil counts. The code also includes an interpolation/extrapolation path (via `LinearNDInterpolator` and linear regression) to auto-generate CICC parameters from a reference dataset.

Treatment of IFE and MIF variants within Account 22.1.3 in the open-source code. While the MFE implementation treats superconducting magnets as the dominant 22.1.3 cost driver (as described above), the GitHub versions of the framework generalize Account 22.1.3 to represent the *primary driver technology* for the architecture class. For inertial fusion energy (IFE) cases, 22.1.3 is populated by a detailed laser cost breakdown that scales with delivered energy per pulse, repetition rate, wall-plug efficiency, optical train requirements, and associated facility interfaces; the implementation separates laser subsystem elements (e.g., gain media / pump sources, optics, power conditioning, thermal management, and integration allowances) to provide a transparent mapping from physics and driver requirements to capital cost within the standardized account structure. For magneto-inertial fusion (MIF) concepts, the same account is instead used to capture the pulsed-power driver train (and, where applicable, the associated magnet set), including stored-energy scaling, pulse-forming networks, switches, transmission lines, and capacitor banks, with explicit allowances for efficiency, repetition-rate constraints, and packaging into a plant-relevant driver module. In this way, the open-source code preserves a consistent COA across concept classes while ensuring that the dominant, concept-defining driver costs (lasers for IFE; pulsed power and often magnets for MIF; magnets for MFE) are represented at comparable granularity and roll up cleanly into the 22.1 account totals.

6.4 Cost-account structure implemented

The code computes a capital cost total (named C990000) from top-level accounts:

$$C_{99} = C_{10} + C_{20} + C_{30} + C_{40} + C_{50} + C_{60}, \quad (21)$$

corresponding (respectively) to pre-construction, direct costs, indirect services, owner costs, supplementary costs, and financial costs. Each account is computed as a sum of subaccounts with explicit variable names (e.g., C210000 for buildings, C220000 for reactor plant equipment, etc.).

Other notable direct-cost drivers. Additional drivers implemented with explicit scaling/estimation include:

- power supplies (scaled from an ITER-based reference, with a learning credit factor),
- vacuum vessel and vacuum pumping (geometry-based volume, manufacturing factor, and pump-count scaling),
- cryogenic cooling power requirement estimation (Carnot-based COP fraction) and cost scaling from an ITER reference,
- supplementary heating cost scaling from ARIES/ITER reference \$/W values,
- divertor cost from volumetric tungsten,
- installation labor estimated from construction time and a scaling with machine size.

All of these contribute into C_{22} and hence into C_{20} and C_{99} .

6.5 Annualized costs and LCOE calculation

The code forms three annualized cost terms:

- **Annual O&M cost (Account 70).** O&M is computed using a lookup-based factor of 60 USD/(kW_e-yr), applied to net electric power $P_E \equiv P_{E,\text{net}}$:

$$C_{\text{OM}} [\text{USD}/\text{yr}] = 60 P_E (1000), \quad (22)$$

$$C_{70} [\text{M\$}/\text{yr}] = \frac{C_{\text{OM}}}{10^6} = \frac{60 P_E (1000)}{10^6}. \quad (23)$$

- **Annual fuel cost (Account 80).** The fuel cost is computed from fusion energy production to deuterium mass consumption using the D-T energy release (17.58 MeV per reaction) and the Joule-per-eV conversion factor. In the implemented form:

$$m_D = 3.342 \times 10^{-27} \text{ kg}, \quad (24)$$

$$u_D = 2175 \text{ \$/kg}, \quad (25)$$

$$C_F [\text{USD}/\text{yr}] = \frac{N_{\text{mod}} P_f (10^6) (3600) (8760) u_D m_D p_a}{17.58 (1.6021 \times 10^{-13})}, \quad (26)$$

$$C_{80} [\text{M\$}/\text{yr}] = \frac{C_F}{10^6}. \quad (27)$$

Here P_f is the fusion power (MW), N_{mod} is the number of modules, and p_a is plant availability.

- **Annualized capital/financial cost (Account 90).** Annualized financial costs are computed as a fixed charge rate (capital return factor) multiplying the total capital cost:

$$C_{AC} [\text{USD}/\text{yr}] = f_{cr} (C_{99} \times 10^6), \quad (28)$$

$$C_{90} [\text{M\$}/\text{yr}] = \frac{C_{AC}}{10^6} = f_{cr} C_{99}, \quad (29)$$

where f_{cr} is calculated following NETL 2019 conventions (constant-dollar FCR in the report).

LCOE as implemented in the report text. Contributors to LCOE are expressed as

$$\text{LCOE} [\$/\text{MWh}] = \frac{C_{AC} + (C_{OM} + C_F) (1 + y)^Y}{8760 P_E p_a}, \quad (30)$$

where y is the annual fractional escalation factor applied to the recurring terms over a lifetime Y (years), P_E is net electric power (MWe), and p_a is plant availability.

Unit conversion.

$$\text{LCOE} [\text{cents}/\text{kWh}] = 0.1 \times \text{LCOE} [\$/\text{MWh}]. \quad (31)$$

6.6 Report generation and traceability

The script includes helper functions that copy LaTeX templates (“Originals”) into a “Modified” directory and overwrite placeholder strings with computed values. As a result, the cost breakdown, power balance tables, and LCOE outputs are written into a consistent report structure, and the mapping from computed quantities (e.g., $P_{E,\text{net}}$, $C_{22.1.3}$ magnets) into cost-account totals (C_{22} , C_{20} , C_{99}) is explicit.

7 Extended models and optional analysis modules

In the course of developing and applying the costing framework across multiple ARPA-E studies and subsequent customer engagements, we have created a set of appendices and “extra modules” that extend the standard costing workflow without requiring direct modification of the core code path. This architectural choice is intentional: maintaining a stable, standards-aligned “baseline” implementation supports reproducibility and like-for-like comparisons across concepts, while optional modules provide a controlled mechanism for exploring additional economic questions, deployment pathways, and design-for-cost opportunities. In practice, these modules consume the same intermediate plant quantities and account roll-ups produced by the standard workflow (power balance, plant sizing and layout, cost accounts, OCC/TCC, annualized costs), then apply additional transformations, scenario logic, or valuation methods.

7.1 Design-for-maintainability, reliability, and availability (RAM) cost-out modules

A first family of extensions examines cost reductions achievable through explicit design-for-maintenance and reliability engineering. These analyses explore how maintainability provisions, remote handling strategy, component segmentation, spares philosophy, and planned replacement schedules can reduce downtime, improve availability, reduce corrective maintenance burden, and shift lifecycle costs between capitalized scope (e.g., maintenance equipment, hot cells, shielding, and access provisions) and recurring O&M categories. The module framing supports trade studies in which increased upfront CAPEX can be evaluated against reduced forced outage rates, reduced replacement labor, shorter maintenance durations, and lower long-term operating costs.

7.2 Retrofitting and repowering of existing thermal plants

A second extension considers retrofitting (repowering) scenarios in which a fusion heat island replaces the combustion heat source at an existing coal (or other thermal) station. The key methodological feature is that a large fraction of the balance-of-plant (steam cycle, turbine island, electrical plant, cooling water/heat rejection infrastructure, and portions of the buildings and site utilities) may be treated as inherited assets rather than newly purchased scope. This provides a structured mechanism to evaluate FOAK deployment pathways that leverage existing infrastructure, potentially obviating much of the BOP cost and shortening schedule risk, while explicitly accounting for retrofit-specific costs such as integration engineering, demolition and site prep, new containment/heat-island building scope, and re-licensing or permitting requirements.

7.3 Materials scarcity, manufacturability, and supply-chain constraints

A third family of extensions examines the economic implications of material choice under scarcity and manufacturability constraints. Fusion concepts can be sensitive to the availability and processing routes of specialty materials, and some candidate materials (e.g., beryllium) are not currently produced or traded in the quantities implied by large-scale deployment. These modules are intended to (i) flag scarcity risk and potential price volatility, (ii) assess whether fabrication and joining routes are compatible with the required component sizes and tolerances, and (iii) explore substitutions or design adaptations that reduce reliance on constrained materials. The resulting outputs are expressed as scenario-dependent adjustments to raw material unit costs, manufacturing multipliers, yield/scrap assumptions, and availability of qualifying vendors, with transparent attribution to the affected cost accounts.

7.4 Extended financial and economic valuation metrics (open-source add-ons)

In addition to “engineering-to-cost” extensions, further modules have been developed in collaboration with customers and clients and released as open source to support a broader set of financial valuation and decision metrics for fusion energy projects. These add-ons allow users to compute, consistently and traceably from the standard costing outputs, a suite of project finance and economic measures commonly used in utility planning, investment decision-making, and policy analysis:

- Net Present Value (NPV), including explicit handling of discount rates and escalation assumptions;
- Total Life-Cycle Cost (TLCC);
- Revenue Requirements (e.g., required annual revenue stream to meet return and cost recovery targets);
- Levelized Cost of Energy (LCOE/LCOE variants) and related levelized-value concepts;
- Annualized Value (equivalent annual cost / equivalent annual value formulations);
- Internal Rate of Return (IRR) and Modified Internal Rate of Return (MIRR);
- Simple Payback Period and Discounted Payback Period;
- Benefit-to-Cost Ratios and Savings-to-Investment Ratios;
- Integrated Resource Planning / Demand-Side Management (IRP/DSM) ratio tests;
- Consumer and Producer Surplus metrics for welfare-oriented evaluations;
- Weighted Average Cost of Capital (WACC) calculation and its use within NPV and revenue-requirement analyses.

Rationale for modular extensions. These extended models are deliberately implemented as optional, composable modules rather than as edits to the baseline code. This preserves the integrity of the standardized costing workflow (and the comparability it enables) while allowing the framework to support diverse stakeholder questions: design-for-maintainability cost-out strategies, FOAK deployment via retrofit pathways, material and manufacturability risk, and project finance metrics that go beyond point LCOE. In this way, the methodology supports both a stable “standard” analysis mode and a growing ecosystem of targeted extensions that can be applied when the decision context requires additional fidelity.

8 Worked example: power balance, CAPEX, and LCOE

This section reproduces a compact worked example of the costing workflow, including (i) the steady-state power accounting, (ii) the resulting capital-cost roll-up by cost accounts, and (iii) the leveled cost of electricity (LCOE) variable set and calculation.

8.1 Power balance / power accounting

Table 1 summarizes the steady-state power accounting used to establish gross and net electric power, including auxiliary, compression/driver, and coolant-related recirculating loads.

8.2 CAPEX / cost-account roll-up

Table 2 reproduces the capital-cost account roll-up for this case, including direct costs and the capitalized indirect/owner/supplementary/financial accounts. The total is the Total Capital Cost (TCC), consistent with the costing structure used throughout the report.

Table 1: Worked example power accounting (all values in MW). This table fixes the thermal/electric normalization basis for subsequent cost scaling (e.g., BOP sizing, $\$/\text{kW}_e$ factors, and annual net generation).

Item	Description	Value [MW]
1.1	Fusion power P_f	1290
1.2	Neutron multiplier M_N	1.05
1.3	Driver power P_{in} (compressor)	30
1.4	House power P_{house}	5
1.5	Wall-plug efficiency η_{wp}	0.10
1.6	Coil power P_{coil}	10
1.7	Auxiliary cooling power P_{cool}	10
1.8	Cryogenic power P_{cryo}	5
1.9	Thermal efficiency η_{th}	0.35
1.10	Gross electric power $P_{E,\text{gross}}$	828.12
1.11	Q_{eng}	4.346
3.1	Pumping power P_{pump}	289.84
3.2	Subsystems power P_{sub}	31.99
3.3	Recirculating fraction f_{rec}	0.230
3.4	Net electric power $P_{E,\text{net}}$	636.75

Table 2: Worked example CAPEX by cost accounts (updated costs and codes). The table reports the account cost in MUSD and the percentage contribution to TCC. The rightmost columns provide the MARS comparison values shown in the source report.

Acct.	Cost account	Cost	%	MARS Cost	MARS %
20	Direct Costs	1538	71	7100.0	79.0
21	Structures/Site	258	12	1200.0	13.0
22	Reactor Plant Equip.	672	31	2700.0	29.0
22.1	Reactor Equip.	441	20		
22.1.1	First Wall & Blanket	150	7		
22.1.2	Shield	80	4		
22.1.3	Magnets	0	0	2200.0	24.0
22.1.4	Compression (Jets)	25	1		
22.1.5	Primary Structure	0	0		
22.1.6	Vacuum System	20	1		
22.1.7	Power Supplies	111	5		
22.1.8	Target Plasma	10	0		
22.1.9	Direct E. Conv.	0	0		
22.1.11	Assembly and installation	5	0		
22.2	Main Heat Transfer	106	5		
22.3	Auxiliary Cooling	3	0		
22.4	Rad. Waste Treat.	5	0	140.0	1.5
22.5	Fuel Processing	89	4	140.0	1.5
22.6	Other plant equipment	8	0		
22.7	Instrumentation and control	21	1	160.0	1.8
23	Turbine Plant Equip.	182	8	790.0	8.7
24	Electric Plant Equip.	45	2		
25	Misc. Plant Equip.	32	1		
26	Heat Rejection	78	4		
27	Special Materials	3	0		
28	Digital Twin	5	0		
29	Contingency	0	0		
30	Capitalized Indirect Service Costs (CISC)	16	1	51.0	0.56
40	Capitalized Owner's Cost (COC)	185	8	610.0	6.7
50	Capitalized Supplementary Costs (CSC)	213	10	700.0	7.7
60	Capitalized Financial Costs (CFC)	180	8	590.0	6.5
Total Capital Cost (TCC)		2173	100	9100.0	100.0

8.3 LCOE calculation

The report's LCOE definition is:

$$\text{LCOE} [\$/\text{MWh}] = \frac{\text{CAC} + (\text{COM} + \text{CF})(1 + y)^Y}{8760 P_E p_a}, \quad (32)$$

where CAC is the annual capital charge (TCC times fixed charge rate), COM is annual operations and maintenance, CF is annual fuel cost, y is the annual fractional increase applied over plant life Y , P_E is net electric power (MWe), and p_a is plant availability.

Table 3 lists the variable values used for the worked case, and the reported LCOE result.

Table 3: Variables used in the worked LCOE calculation. These inputs, together with Eq. (32), produce the reported LCOE of 55.1 \$/MWh (5.5 c/kWh).

Quantity	Description	Value
P_E	Net electric power (MW)	636.748
p_a	Plant availability (-)	0.9
y	Inflation / escalation (-)	0.025
Y	Plant lifetime (years)	30
CAC	Capital cost (M\$/annum)	195.6
COM	O&M cost (M\$/annum)	38.2
CF	Fuel cost (M\$/annum)	1.0
Reported LCOE		55.1 \$/MWh (5.5 c/kWh)

9 Discussion: Relationship to Prior Power-Plant and Fusion Costing Methodologies

The ARPA-E fusion costing capability developed from 2017–2024 can be understood as a deliberate synthesis of (i) the *standards-aligned* nuclear power-plant code-of-accounts tradition (IAEA / GIF-EMWG / EPRI), (ii) the *physics-to-plant* systems-study workflow pioneered in fusion by ARIES and related studies, and (iii) an *EPC- and manufacturability-aware* cost-reduction framing (layout, constructability, modularization, learning) motivated by both nuclear experience and ARPA-E program needs. In contrast to many earlier fusion costing studies that either (a) reported only a capital-cost point estimate or (b) embedded important cost categories implicitly within an LCOE formula, the ARPA-E workflow emphasized explicit account realization and traceability from physics assumptions to plant-level quantities, subsystem sizing, and rolled-up accounts, ultimately enabling auditable updates and portfolio-consistent comparisons.

9.1 Contrast with GEN-IV / IAEA-style economic methodologies

The GIF Economics Modeling Working Group (EMWG) guidelines were developed to support consistent economic evaluation across Generation IV nuclear systems, including a harmonized chart of accounts (COA), reporting conventions, and explicit attention to the distinction between top-down versus bottom-up cost estimating within an integrated economic modeling workflow [6, 7, 8]. In the GEN-IV context, the COA primarily serves as a standardized container for plant structures and systems, allowing results to be compared across designs, vendors, and national programs.

The ARPA-E methodology adopts this same *standards function* of the COA, but its main extension lies in how fusion-specific subsystems are *mapped into* and *realized within* those accounts. Rather than treating fusion as a small perturbation to a conventional nuclear plant, the ARPA-E implementation explicitly identifies the dominant fusion-unique drivers (e.g., magnets, lasers, pulsed power, power supplies, and power-core components) and replaces legacy single-factor scalings with bottom-up or semi-analytic subsystem models where those drivers dominate total cost. A second practical distinction is emphasis on conventional balance-of-plant (BOP) engineering translation: conventional subsystems (steam cycle, turbine island, heat rejection, electrical plant, and buildings) are sized consistently with power-plant practice and anchored to transparent external baselines, ensuring that non-fusion plant elements remain internally consistent as heat-island assumptions evolve.

Finally, GEN-IV/IAEA methodologies are typically deployed for concepts whose licensing basis, construction methods, and project execution pathways are relatively well understood. The ARPA-E program work therefore placed particular emphasis on indirect costs, construction methodology, and design-for-cost strategies, not merely as adders but as *controllable design outcomes*. This theme became central after early benchmarking exercises underscored that BOP, layout, and indirects can dominate plant cost even when the fusion island is aggressively optimized.

9.2 Contrast with ARIES and related fusion systems studies

ARIES established a durable methodological template for fusion power-plant studies: couple a physics-informed power balance to an engineering-constrained radial build, generate a conceptual plant configuration, and estimate costs using a mix of subsystem models and scaling relations. The ARPA-E support work explicitly follows this ARIES-style workflow as the guiding backbone across studies, while adapting it for broader portfolio use and for improved accounting traceability.

The ARPA-E methodology departs from classic ARIES practice in several important ways:

1. **Portfolio-consistent comparability across architectures.** ARIES studies typically optimize and report within a given magnetic-fusion class, whereas ARPA-E had to support a rapidly expanding portfolio spanning MFE, IFE, and MIF concepts with heterogeneous drivers, maturity levels, and plant integration assumptions. The costing workflow therefore evolved to preserve a common COA while allowing concept-defining drivers to be represented with comparable fidelity (e.g., magnets for MFE; lasers for IFE; pulsed power and sometimes magnets for MIF), enabling more uniform cross-concept comparisons.
2. **EPC calibration and constructability emphasis.** A distinguishing feature of the ARPA-E timeline is the explicit engagement of EPC-oriented validation and sanity checks, which highlighted sensitivities to layout, buildings, and major equipment sizing and materially influenced later emphasis on BOP, indirects, and design-for-cost.
3. **Explicit indirect-cost accounting and cost-reduction pathways.** The ARPA-E workflow elevated indirect costs and execution pathways (construction supervision, project management, owner's costs, schedule effects, and cost-of-money implications) as first-class objects for sensitivity studies and cost-out strategy. This emphasis reflects the recognition that non-power-core costs often dominate total plant cost for many fusion concepts.
4. **Standards-aligned refactor and bottom-up replacement of legacy scalings.** By 2023 the ARPA-E toolchain was refactored to align with the IAEA-GIF/EMWG-EPRI COA lineage, and key ARIES-derived scalings were replaced with bottom-up subsystem models for dominant fusion cost drivers, coupled explicitly to power balances and engineering-constrained radial builds. This shift moves the ARIES integrated workflow into a more auditable, standards-aligned accounting envelope while increasing granularity where fusion cost uncertainty is highest.

9.3 Relation to LIFE and other inertial-fusion costing studies

The LIFE program and related inertial-fusion energy studies provide an important comparison point because they developed integrated systems models that include cost and performance scaling relationships for major subsystems, including driver (laser), target systems, chamber, heat transfer, power conversion, and buildings [?]. The ARPA-E methodology is consistent with LIFE in treating the driver as a dominant, concept-defining cost element that must be modeled explicitly and traced to physics and operating requirements.

Where ARPA-E differs is principally structural and programmatic: (i) it enforces a standardized COA mapping across MFE/IFE/MIF so that the dominant driver appears in a consistent account context (e.g., as the main contributor to 22.1.3 for IFE or MIF variants), (ii) it integrates an EPC- and externally anchored BOP sizing step to maintain conventional-plant realism even as fusion island assumptions change, and (iii) it emphasizes explicit indirect-cost roll-ups and auditable cost bases rather than concept-specific adders that are difficult to compare across architectures.

9.4 Prior fusion costing analyses: Sheffield, Generomak, and the ESECOM-era tradition

A useful historical antecedent that merits explicit acknowledgement is the set of generic fusion physics/engineering/economic models developed in the 1980s, particularly the *Generomak* model associated with Sheffield and collaborators and later used in ESECOM-era analyses [14] (and updated considerably recently [15]). Generomak was explicitly designed as a consistent framework for evaluating the economic viability of alternative magnetic fusion reactors using a generic model of physics performance, engineering constraints, and plant economics. This tradition strongly parallels the modern “systems code” ethos: economic conclusions are only meaningful when the physics, engineering, and plant integration assumptions are internally consistent.

The ARPA-E methodology can be seen as a descendant of this systems-code lineage, but updated in three ways that reflect contemporary needs. First, it adopts a modern, internationally recognizable COA structure (IAEA/GIF/EPRI-aligned), which improves comparability with fission and with regulated power-plant accounting practices. Second, it reflects present-day understanding that indirect costs and construction execution can dominate outcomes; hence

modularization, centralized manufacturing, and learning are treated as explicit levers rather than qualitative commentary. Third, it explicitly targets auditable traceability from physics quantities to layout, BOP sizing, and account roll-ups, motivated by the needs of a portfolio program supporting diverse private-sector concepts.

9.5 Summary of distinguishing characteristics

In summary, the ARPA-E methodology is not a rejection of GEN-IV/IAEA economic guidance nor of ARIES-style fusion studies; rather, it is an operational synthesis tailored to portfolio decision-making and credibility requirements:

- It *inherits* the physics-to-plant integrated workflow of ARIES and earlier systems-code traditions (including Generomak/ESECOM), while increasing traceability and driver granularity.
- It *adopts* the GEN-IV/IAEA/EPRI COA lineage as a standards-aligned reporting and comparability layer, while mapping fusion-unique subsystems into accounts in a way that preserves cross-architecture consistency.
- It *extends* conventional practice by anchoring BOP and buildings to transparent external baselines and by treating indirect costs, execution pathways, and learning as central cost drivers that must be examined explicitly.

These choices reflect the central thesis that fusion economic credibility requires not only better physics and better components, but also better accounting: cost drivers must be explicit, comparable, and auditable as subsystem assumptions evolve and as concepts progress toward pilot-plant design.

9.6 Forward-looking: the next phase of fusion power-plant costing and analysis

Fusion power-plant costing is rapidly transitioning from document-centric, point-design reporting toward *data-rich, optimization-driven, and provenance-complete* digital workflows in which economics is evaluated concurrently with geometry and physics/engineering feasibility. A clear emerging pattern is the coupling of integrated multi-physics plant models to multi-objective optimization loops, with increasing reliance on machine-learning surrogates to make exploration of high-dimensional design spaces computationally tractable and to enable publication of Pareto trade spaces rather than single “best” designs. [16]

Recent work by nTtau Digital exemplifies this direction by embedding costing directly into an automated co-design loop: parametric CAD geometry generation (plasma boundary, coils, structures, and plant integration) feeds an automated multi-physics simulation stack (electromagnetics, structural mechanics, thermal analysis, and optional neutronics), and *as each component is instantiated*, its extracted quantities (e.g., mass, volume, surface area, power ratings, and complexity measures) are mapped into a standardized code-of-accounts. This produces an auditable “cost build file” per design point that aggregates component estimates into subsystem costs and plant-level totals, with complete provenance capture (inputs, code versions, solver settings, and outputs) and robust workflow orchestration across HPC resources. [17]

A second key development is the maturation of surrogate-assisted optimization as a practical mechanism for moving from hundreds of evaluations to tens of thousands (or more), including “surrogate-in-the-loop” strategies in which high-fidelity simulations are used selectively for verification and to resolve regions of high surrogate uncertainty. [17] This is particularly important for stellarator and other geometry-flexible concepts, where the dominant cost of evaluation often comes from repeated equilibrium/coil computations and downstream constraint checking, and where constraints are intrinsically geometric (coil curvature, clearances, maximum field, maintainability). [17] In parallel, broader private-sector practice is converging toward integrated whole-plant environments that evaluate plasma, magnets, structures, blankets, power conversion, and *cost* in a single workflow, then generate Pareto-optimal sets using evolutionary multi-objective optimizers. [16]

Looking forward, these developments suggest three concrete directions for fusion costing and analysis. First, *cost models will increasingly be treated as first-class citizens of the plant optimization loop*, rather than post-hoc adders: COA-aligned costing will be triggered by the same evolving CAD and systems models that enforce feasibility constraints, thereby making the cost model inherently geometry- and integration-aware (including building placement/layout effects and BOP routing penalties). [17] Second, the community is likely to shift from deterministic point estimates to *risk-informed and uncertainty-aware* economic results, where uncertainty propagation and probabilistic constraint violation (or robustness margins) are incorporated directly into the optimization objectives and the resulting Pareto fronts. [16] Third, as global surrogates mature, the field will move toward multi-fidelity ecosystems in which (i) standardized account-based costing and LCOE models remain the reporting backbone, but (ii) the dominant technical drivers (transport, exhaust, coil engineering, maintenance, and manufacturing complexity) are learned from increasingly large datasets generated by automated workflows, enabling faster design iteration and more transparent comparison across architectures. [17, 16]

In this framing, the long-term role of standards-aligned codes of accounts is strengthened rather than diminished: the COA provides the durable interface between evolving physics/engineering models and externally interpretable economic outputs. The main shift is operational: fusion costing becomes a continuously evaluated, dataset-producing element of an integrated digital design process, enabling both auditable “design → cost build” traceability and systematic exploration of cost/performance/risk trade spaces at scales that were previously impractical. [17]

10 Further work

The costing framework described here is intended to be extensible: its value increases as additional physics, engineering, safety, and supply-chain realism are incorporated in ways that preserve the same standards-aligned chart-of-accounts mapping and auditability. We highlight several high-leverage directions for further work.

10.1 Integrating fusion safety into plant-level costing and design iteration

A priority extension is a tighter integration of fusion safety analysis into the costing workflow, informed by the ongoing work of the CATF IWG on fusion safety. The central methodological opportunity is to treat safety not as a post-hoc checklist but as a *design-coupled cost driver*: confinement strategy, material selection, activation products, de-tritiation requirements, accident analysis assumptions, and regulatory posture each impose tangible implications for facility layout, ventilation and de-tritiation capacity, waste handling, remote maintenance provisions, and operational staffing. In practice, this suggests a future workflow in which the safety case and its key bounding assumptions (e.g., credible release fractions, confinement barriers, tritium inventory limits, waste classification approach, and emergency planning envelope) are captured as explicit model inputs that (i) drive additions or modifications to specific accounts (particularly buildings/structures, radioactive waste treatment, fuel handling, auxiliary systems, instrumentation and control, and owner’s costs), and (ii) propagate into indirect costs through construction complexity, QA/QC requirements, commissioning, and licensing scope. A structured integration of the CATF IWG fusion safety thinking would therefore enable consistent sensitivity studies on the cost impact of safety posture choices across concept classes, while improving the credibility and completeness of the plant-level cost basis.

10.2 Power-flow visualization and traceability via Sankey diagrams

A second tractable improvement is richer visualization of the internal power accounting and its relationship to cost drivers. The current workflow already computes the major terms in the plant power balance (fusion power partition, thermal conversion, recirculating loads, and net electric output), but the results are typically reported as tables. Sankey diagrams provide a natural complement by conveying the full *flow structure* of power: how fusion energy partitions into neutron and charged-particle channels; how recoverable heat moves through the primary heat-transfer system; how gross electrical output is reduced by auxiliary systems, coolant pumping, cryogenics, and driver wall-plug losses; and how these internal demands determine net delivery to the grid. Such diagrams are especially useful when comparing fuel cycles ($D-T$, $D-D$, $D-^3He$, $p-^{11}B$) and direct energy conversion options, where the qualitative flow structure changes. Embedding Sankey generation as a first-class output of the code would improve interpretability for non-specialists, strengthen internal consistency checks (e.g., preventing double counting between thermal and direct conversion channels), and provide a more transparent bridge between recirculating power fractions and the sizing/cost of the subsystems that create those loads.

10.3 Materials cost bases and the challenge of NOAK assumptions

A third major area for further work is the state of the art in materials costing for fusion-relevant materials and purity specifications. The present framework primarily reports Nth-of-a-kind (NOAK) costing, implicitly assuming that learning, supply-chain maturation, and industrialization have already reduced unit costs toward steady-state values. This assumption is appropriate for long-term economic comparisons but it creates a practical gap: for several fusion-relevant materials, *transparent NOAK cost bases are not readily available*, particularly at the purity levels required by some fuel-cycle, breeder, coolant, and materials-compatibility constraints. A concrete example is lithium: while commodity lithium pricing is widely reported, the marginal cost and market availability of $\geq 99.99\%$ purity lithium (and isotopically tailored lithium, where applicable) remain poorly documented in open sources, and similar gaps exist for beryllium, high-purity tungsten products, specialized steels, coatings, and certain ceramics. Addressing this gap will likely require a hybrid approach that combines (i) vendor engagement and anonymized price curve development, (ii) explicit specification of purity and form factor (ingots, granules, salts, alloys), (iii) treatment of yields and scrap/recycle assumptions, and (iv) explicit scenario analysis separating FOAK procurement from NOAK steady-state production. In the costing framework, such work would translate into improved raw-material unit cost inputs, manufacturing

multipliers that reflect realistic fabrication routes, and uncertainty bounds on materials-dominated accounts (notably first wall/blANKET and special materials) that can be propagated into LCOE and total capital cost uncertainty.

10.4 Summary

Together, these extensions—(i) safety-informed account realization aligned with CATF fusion safety thinking, (ii) Sankey-based power-flow visualization as a traceability tool, and (iii) improved materials cost bases consistent with NOAK assumptions but grounded in realistic purity and supply-chain constraints—represent a practical roadmap for increasing both the credibility and usefulness of fusion power-plant techno-economic analysis as the field progresses toward pilot-plant design and eventual commercial deployment.

11 Conclusion

Fusion is entering a phase in which economic credibility and comparability are as important as physics performance: as concepts mature from laboratory demonstrations toward integrated pilot plants, stakeholders require cost estimates that are transparent, traceable to technical assumptions, and comparable across architectures. The work summarized in this paper responds to that need by consolidating ARPA-E-supported costing development from 2017–2024 into a standards-aligned, auditable framework that evolved from early capital-cost-focused, ARIES-style scaling studies into a physics-to-economics workflow that emphasizes explicit power balance, engineering-constrained geometry and layout, and bottom-up subsystem models for dominant fusion cost drivers.

A central contribution is the explicit alignment of the account structure with the IAEA–GEN-IV EMWG–EPRI lineage, coupled to a computational implementation (FECONs and pyFECONs) that preserves traceability: each cost account is realized from intermediate physical plant quantities and documented cost bases, rather than being embedded implicitly in an LCOE result. This traceable mapping is what enables disciplined updating as subsystem assumptions evolve, and it supports like-for-like comparisons across fusion concepts and against other generation technologies.

Looking forward, the same forces that are driving maturation of fusion design practice—increasing integration across physics, engineering, and plant-level systems modeling—are likely to drive a corresponding maturation in fusion costing. The next phase of credible fusion TEA should increasingly (i) couple costing to integrated design workflows (power balance → engineering constraints → layout → cost accounts), (ii) quantify uncertainty and risk in ways that are explicitly attributable to model inputs and constraint margins, and (iii) support rapid iteration across architectures and operating points without sacrificing auditability. The evolution of this capability into open (pyFECONs) and closed-source, interface-driven implementations reflects that trajectory, as the tooling shifts from one-off study artifacts toward reusable infrastructure that can support broader stakeholder engagement and higher-frequency design iteration.

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A Chart of Accounts

Table 4: Chart of accounts (filtered to account labels / subsystem names, excluding cost-basis numeric rows).

Account	Description
8	Steam Turbine and Accessories (bare erected)
9	Cooling System (bare erected)
10	Pre-construction costs
11	Accessory Electric Plant (bare erected)
12	Site Permits
13	Plant Licensing
14	Plant Permits
15	Plant Studies
16	Plant Reports
17	Other Pre-Construction Costs
19	Contingency on Pre-Construction Costs
20	Capitalized Direct Costs (CDC)
21	Structures and Improvements
21.1	Site Preparation / Yard Work
21.2	Heat Island Building
21.3	Turbine Generator Building
22	Heat Island Plant Equipment
22.1	Heat Island Components
22.1.1	First Wall and Blanket
22.1.2	Shield
22.1.3	Coils
22.1.4	Supplementary Heating Systems
22.1.5	Primary Structure and Support
22.1.6	Vacuum System
22.1.7	Power Supplies
22.1.8	Electrodes or Plasma Guns
22.1.9	Direct Energy Convertor
22.01.11	Assembly and Installation Costs
22.01.11.01	First wall and blanket
22.01.11.02	Shield
22.01.11.03	Magnets
22.01.11.04	Auxiliary heating
22.01.11.05	Primary structure
22.01.11.06	Vacuum system
22.01.11.07	Power supplies
22.01.11.08	Divertor
22.01.11.09	Direct energy convertor
22.2	Main and Secondary Coolant
22.02.00.00	Main heat transfer and transport systems
22.02.01.00	Primary coolant system
22.02.01.01	Pumps and motor drives (modular & nonmodular)
22.02.01.02	Piping
22.02.01.03	Heat exchangers
22.02.01.04	Tanks (dump, make-up, clean-up, trit., hot storage)
22.02.01.05	Clean-up system
22.02.01.06	Thermal insulation, piping & equipment
22.02.01.07	Tritium extraction
22.02.01.08	Pressurizer
22.02.01.09	Other
22.02.03.00	Secondary coolant system
22.02.03.01	Pumps and motor drives (modular & non-modular)
22.02.03.02	Piping
22.02.03.03	Heat exchangers

Account	Description
22.02.03.04	Tanks (dump, make-up, clean-up, trit., hot storage)
22.02.03.05	Clean-up system
22.02.03.06	Thermal insulation, piping & equipment
22.02.03.07	Tritium extraction
22.02.03.08	Pressurizer
22.02.03.09	Other
22.02.04.00	Thermal storage system
22.03	Auxiliary Cooling Systems
22.03.04	Power Supply and Cooling System
22.03.04.01	Refrigeration
22.03.04.02	Piping
22.03.04.03	Fluid circulation driving system
22.03.04.04	Tanks
22.03.04.05	Purification
22.03.05	Other cooling systems
22.04	Radioactive Waste Treatment
22.04.01	Liquid waste processing and equipment
22.04.02	Gaseous wastes and off-gas processing system
22.04.03	Solid waste processing equipment
22.5	Fuel Handling and Storage
22.6	Other Reactor Plant Equipment
22.7	Instrumentation and Control
23	Turbine Plant Equipment
24	Electric Plant Equipment
25	Miscellaneous Plant Equipment
26	Heat Rejection
27	Special Materials
28	Digital Twin / Simulator
29	Contingency on Direct Capital Costs
30	Capitalized Indirect Service Costs (CISC)
31	Field Indirect Costs
32	Construction Supervision
33	Commissioning and Start-up Costs
34	Demonstration Test Run
35	Design Services (Offsite)
36	PM/CM Services (Offsite)
37	Design Services (Onsite)
38	PM/CM Services (Onsite)
39	Contingency on Support Services
40	Capitalized Owner's Cost (COC)
41	Staff Recruitment and Training
42	Staff Housing
43	Staff Salary-Related Costs
44	Other Owner's Costs
49	Contingency on Owner's Costs
50	Capitalized Supplementary Costs (CSC)
51	Shipping and Transportation Costs
52	Spare Parts
53	Taxes
54	Insurance
55	Initial Fuel Load
58	Decommissioning Costs
59	Contingency on Supplementary Costs
60	Capitalized Financial Costs (CFC)
61	Escalation
62	Fees
63	Interest During Construction (IDC)
69	Contingency on Capitalized Financial Costs

Account	Description
70	Annualized O&M Cost (AOC)
71	O&M Staff
72	Management Staff
73	Salary-Related Costs
74	Operations Chemicals and Lubricants
75	Spare Parts
76	Utilities, Supplies, and Consumables
77	Capital Plant Upgrades
78	Taxes and Insurance
79	Contingency on Annualized O&M Costs
80	Annualized Fuel Cost (AFC)
81	Refueling Operations
84	Fuel
86	Processing Charges
87	Special Nuclear Materials
89	Contingency on Annualized Fuel Costs
90	Annualized Financial Costs
92	Home Office Engineering Services

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