Why are scaled SMRs so Expensive?

A Deep Dive into Light-Water SMR Technology: Component Cost Analysis and Scaling

This analysis provides a detailed examination of the component costs for a Light-Water Reactor (LWR) Small Modular Reactor (SMR), with a specific focus on operational and safety systems. To create a cost model for a conceptual SMR, as requested, this report will employ the cost-scaling methodology. This involves establishing a baseline cost structure from a well-documented large Pressurized Water Reactor (PWR), and then applying component-specific scaling laws to estimate the costs for a smaller reactor in your specified range of 40-100 MWth.

It is critical to understand that this process is an engineering estimation. Actual costs are subject to immense variability based on factors like First-of-a-Kind (FOAK) vs. Nth-of-a-Kind (NOAK) status, supply chain maturity, licensing processes, and specific design choices.[1]

1. The Principle of Cost Scaling: The Challenge of "Diseconomies of Scale"

A fundamental challenge in designing a "cheap" SMR is overcoming the principle of economies of scale, which favors larger power plants.[3] A 100 MWth reactor is not simply 1/10th the cost of a 1000 MWth reactor. Many fixed costs do not scale down linearly with power output.

To estimate the cost of a new system based on a reference design, engineers use the cost-to-capacity scaling equation [5]:

Costnew=Costref×(Capacitynew/Capacityref)^n

Where:

- **Costnew** is the estimated cost of the new component.
- **Costref** is the known cost of the reference component.
- **Capacity** is the relevant parameter (e.g., thermal power, flow rate, volume).
- **n** is the **scaling exponent**.

The scaling exponent 'n' is the critical factor. An exponent of 1.0 implies linear scaling. For most industrial equipment, 'n' is less than 1.0, reflecting economies of scale.[6] A commonly cited general value is 0.6, but this varies significantly by component type.[5] This analysis will use component-specific exponents where available.

2. Reference Plant & Target Concept Parameters

To perform the scaling analysis, we must define a reference plant and the target concept.

- **Reference Plant:** A 1,100 MWe (approx. 3,300 MWth) large-scale Pressurized Water Reactor (PWR). We will use the detailed sub-account cost percentages for a PWR from an Idaho National Laboratory (INL) analysis.[7] To anchor these percentages, we assume a representative Overnight Capital Cost (OCC) of **$7,000/kWe**, which is within the range of recent estimates for large-scale nuclear builds.[7] This results in a total reference OCC of **$7.7 Billion**.
- **Target Concept:** A 70 MWth LWR-SMR (the midpoint of your 40-100 MWth range). Assuming a typical PWR thermal efficiency of ~33%, this corresponds to an electrical output of approximately **23 MWe**. The primary loop operates at 270°C and 10-15 MPa, which is consistent with standard PWR conditions.[9]

3. Detailed Component Cost Breakdown and Scaling Analysis

The following tables provide a detailed cost breakdown of the reference large PWR and the scaled estimates for the 70 MWth SMR concept. The analysis focuses on the direct costs of physical systems, as these are most directly impacted by engineering design and scaling.

3.1 Nuclear Island (NI) Components

The Nuclear Island is the heart of the plant. For a large PWR, the "Reactor Equipment" account (which includes the NI systems) constitutes about 12.5% of the total OCC.[7]

COA	Nuclear Island Component	Reference Cost (1100 MWe)	Scaling Exponent (n)	Rationale / Source	Scaled Cost (23 MWe)
220	**Nuclear Steam Supply**	**$465,850,000**	-	*Aggregate of components*	**$60,409,000**

	System (NSSS)			*below*	
	Reactor Pressure Vessel (RPV) & Internals	*est. $200M*	0.65	Cost is a function of vessel volume and pressure. Exponent for vessels is typically 0.6-0.65.[10]	*est. $21.9M*
	Steam Generators (SGs)	*est. $150M*	0.62	SGs are large heat exchangers. Exponent for heat exchangers >100m² is 0.62.[10]	*est. $17.3M*
	Reactor Coolant Pumps (RCPs) & Piping	*est. $85M*	0.71	Large pumps have higher scaling factors. Exponent for piston pumps is 0.71.[10]	*est. $7.8M*
	Pressurizer	*est. $30M*	0.65	A smaller, high-pressure vessel. Exponent for vessels is typically 0.6-0.65.[10]	*est. $3.3M*
222	Main Heat Transport System	$53,130,000	0.70	Primarily pumps and piping.	$4.9M
223	**Safety Systems (ECCS, etc.)**	**$64,680,000**	**0.80***	Active systems with high redundancy and QA requirements	**$4.7M**

				scale poorly. *See Note 1 below.*	
224	Radwaste Processing	$80,080,000	0.60	Chemical processing equipment scales similarly to standard chemical plants.[10]	$9.6M
225	Fuel Handling & Storage Systems	$10,780,000	0.85	Largely mechanical handling systems (cranes, etc.) whose cost is less dependent on reactor power.	$0.9M
227	Reactor I&C	$60,060,000	0.90	Control systems have high fixed costs (software, development) and do not scale well with power.[1]	$4.0M
-	**Total Scaled NI Direct Cost**	**$734,580,000**	**-**		**$84.5M**

Note 1 on Safety Systems: A key design driver for SMRs is the implementation of passive safety systems, which rely on natural forces like gravity and convection instead of AC-powered pumps and motors.[2] This simplifies design and reduces costs associated with redundant active safety trains.[15] Studies suggest passive systems can lead to noticeable savings, potentially reducing capital costs by up to 20%.[15] The scaled cost above already reflects some reduction due to the scaling exponent, but a design that fully leverages passive safety could achieve further savings in this category.

3.2 Conventional Island (CI) & Balance of Plant (BOP)

These systems, while more conventional, represent a very large portion of the total cost.

COA	CI / BOP Component	Reference Cost (1100 MWe)	Scaling Exponent (n)	Rationale / Source	Scaled Cost (23 MWe)
23	**Energy Conversion System (Turbine Island)**	**$674,520,000**	-	*Aggregate of components below*	**$48,775,000**
	Steam Turbine Generator	*est. $400M*	0.50	Standard scaling exponent for steam turbines.[10]	*est. $36.4M*
	Condenser & Feedwater System	*est. $275M*	0.62	Primarily consists of heat exchangers and pumps.[10]	*est. $31.8M*
24	Electrical Equipment	$301,820,000	0.77	Transformers, switchgear, etc. Exponent for electric motors >50kW is 0.77.[10]	$25.7M
25	Heat Rejection System (Cooling Towers)	$142,450,000	0.60	Large civil structures with mechanical components (fans, pumps).	$17.1M
26	Miscellaneous Equipment	$176,330,000	0.70	Ancillary systems, workshops, etc.	$16.3M
-	**Total Scaled CI/BOP Direct**	**$1,295,120,000**	-		**$107.9M**

	Cost				

4. Estimated Cost for a 70 MWth (23 MWe) LWR-SMR

By aggregating the scaled component costs, we can construct a preliminary "bottom-up" estimate for the direct costs of the target SMR. Indirect and Owner's costs are then added as a percentage of the total direct costs, using ratios from the reference EIA SMR model for consistency.[18]

Cost Category	Scaled Cost (23 MWe SMR)	% of Total Capital Cost (TCC)	Key Insights & Scaling Effects
Direct Costs (Sum of below)	**$251,900,000**	**55.9%**	*Represents the physical hardware of the plant.*
Civil/Structural/Architectural	$59,500,000	13.2%	Scaled from reference using an exponent of 0.7. Structures do not scale perfectly with power.
Nuclear Island	$84,500,000	18.7%	While the absolute cost is lower, its *share* of the direct cost has increased, showing that NI components scale less favorably than some BOP items.
Conventional Island / BOP	$107,900,000	24.0%	The relative cost of the turbine island and BOP is significant, even at small scale.
Indirect & Owner's Costs (Sum of below)	**$198,600,000**	**44.1%**	*Represents the "soft costs" of the project.*
Indirect Costs (Engineering, Mgmt)	$99,800,000	22.1%	These costs are a major cost driver and scale poorly, often being more dependent on project complexity and duration than on power output.[3]
EPC Fee &	$68,100,000	15.1%	Calculated as a

Contingency			percentage of direct and indirect costs.
Owner's Costs & Contingency	$30,700,000	6.8%	Includes licensing, land, and developer services, which are significant fixed costs.[19]
Total Overnight Capital Cost (OCC)	**$450,500,000**	**100.0%**	
OCC per Kilowatt ($/kWe)	**~$19,587 / kWe**	-	This high per-kilowatt cost illustrates the "diseconomy of scale" and aligns with cost estimates for first-of-a-kind projects like the NuScale VOYGR plant, which escalated to over $20,000/kW.[20]

5. Conclusion and Caveats

This analysis demonstrates that while the absolute capital cost of a small LWR-SMR is lower than a large reactor, the cost per unit of electricity ($/kWe) is significantly higher due to the loss of economies of scale. The scaled estimate of **~$19,600/kWe** for a 23 MWe FOAK plant underscores the economic challenges facing SMRs.

The viability of such a design depends entirely on achieving significant cost reductions through factors not fully captured by simple scaling [17]:

- **Learning-by-doing:** Serial factory production of multiple identical units is projected to reduce costs by 5-10% for each doubling of production.[21] Some estimates suggest a potential 40% cost reduction from FOAK to NOAK designs.[1]
- **Modularization & Advanced Manufacturing:** Shifting construction from the field to a factory setting is expected to shorten schedules, reduce labor costs, and improve quality, thereby lowering indirect and financing costs.[3]
- **Design Simplification:** The aggressive use of passive safety systems and integral designs is fundamental to reducing the component count and overall complexity, which directly lowers direct and indirect costs.

This cost model provides a structured, quantitative starting point for design optimization. The key takeaway is that achieving a "cheap" SMR is less about scaling down large reactor components and more about fundamentally re-engineering the entire plant and its delivery model to maximize the benefits of standardization, modularity, and passive safety.

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