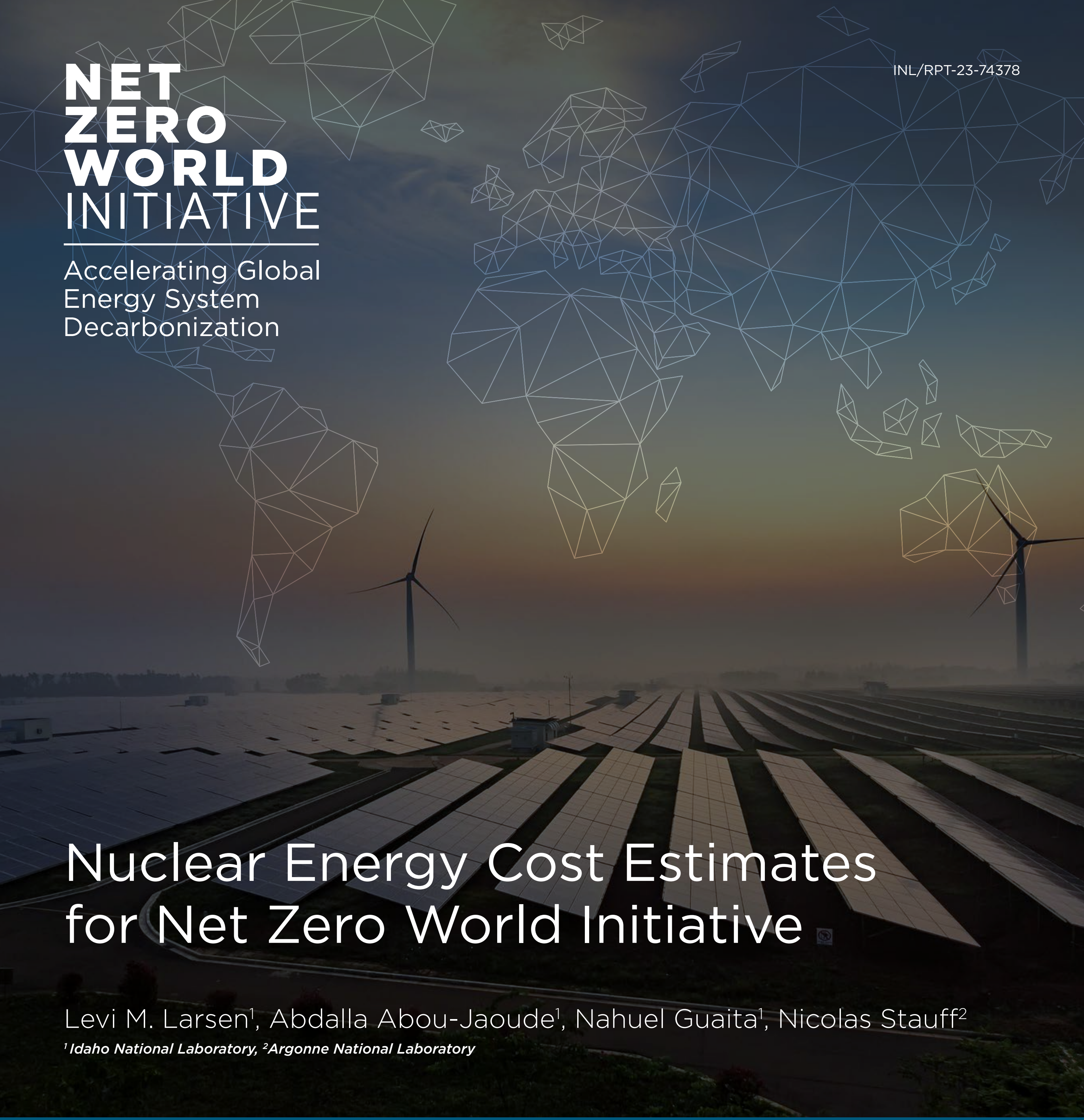

INL/RPT-23-74378

NET
ZERO
WORLD
INITIATIVE

Accelerating Global Energy System Decarbonization

Nuclear Energy Cost Estimates for Net Zero World Initiative

Levi M. Larsen[1], Abdalla Abou-Jaoude[1], Nahuel Guaita[1], Nicolas Stauff[2]

[1] Idaho National Laboratory, [2] Argonne National Laboratory

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Suggested Citation: Larsen, Levi M., Abdalla Abou-Jaoude, Nahuel Guaita, and Nicolas Stauff, 2024. Nuclear Energy Cost Estimates for Net Zero World Initiative. Idaho National Laboratory. INL/RPT-23-74378.

DISCLAIMER

Nuclear Energy Cost Estimates for Net Zero World Initiative

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Acknowledgements

This paper was authored by Battelle Energy Alliance LLC, operator of Idaho National Laboratory, under contract no. DE-AC07-05ID14517 with the DOE. It was also co-authored by UChicago Argonne, LLC, operator of Argonne National Laboratory (Argonne). Argonne, a DOE Office of Science laboratory, is operated under contract no. DE-AC02-06CH11357. The funding for this work was provided by the Net Zero World Initiative.

The authors would like to acknowledge Ed Hoffman for providing a content review of the report and Kelsey Gaston for technical editing.

EXECUTIVE SUMMARY

This report provides recommended parameters for incorporating nuclear energy systems into decarbonization modeling scenarios. The values are primarily intended for the Net Zero World (NZW) Initiative but are expected to prove useful to other related efforts. Both costs and operational metrics are provided in the study; they are summarized in Table ES-1. Several cost factors, namely overnight capital costs (OCC) and operational costs are taken to be country specific. OCC is defined as the value of building the reactor in one night considering all costs prior to the start of operations including fuel for the initial core load. The value assumes the build is neither a first nor a 'Nth' of a kind, but somewhere in between. All costs are escalated to 2022 USD values.

Table ES-1. Summary of Nuclear Energy Cost and Operational Parameters. All costs are in 2022 USD.

Parameter	Optimistic	Base	Conservative
Capital Costs			
OCC [$/kWe]	See Table 9	See Table 9	See Table 9
Fixed Operating Costs			
Operations [$/kWe-yr]	See Table 7	See Table 7	See Table 7
Variable Operating Costs			
Capital [$/MWh]	$3.25	$6.25	$9.50
Fuel reload [$/MWh]	$6.00	$6.75	$7.50
Spent fuel fee [$/MWh]	$1.00		
Retirement Costs			
Decommissioning costs [$/kWe]	$750	$1,000	$1,250
Adjustment Factors			
FOAK premium	1.5		
Learning rate [%]	15%	10%	5%
Construction & Operational Parameters			
Construction time [years]	4.5	5.5	8.0
Capacity factor [%]	95%	90%	80%
Reactor lifetime [years]	100	80	60
Maneuverability	See Table 12		
Non-Grid Energy Costs and Parameters			
HTSE OCC [$/kWe]	$900	$1,100	$1,500
HTSE fixed O&M [$/MWh]	$35	$35	$38
HTSE variable O&M [$/MWh]	$5.5	$7.0	$13.5
H_2 Output [Kg/kWe-yr]	196		
District Heating	See Table 14		

Taking the United States as a reference, these values were re-normalized for the nine additional countries. The new OCC values for NZW countries were found to range between $3,500–$6,500/kWe. Operating and maintenance costs (O&M) were separated between in fixed and variable costs. Fixed operation and maintenance costs were between $4 - $43/kWe per year (the large range shown is driven by labor cost differences). Variable operating costs for capital and fuel were between $9.25/MWh - $16.5/MWh. Recommended decommissioning costs ranges were between $750/kWe and $1,250/kWe. Finally, it is important to note that the learning rate is a percent reduction for each new unit built and not for each year.

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OCC	Overnight Capital Cost
CPI	Consumer Price Index
DOE	Department of Energy
EEDB	Energy Economic Data Base
EPR	European Pressurized Reactor
ETI	Energy Technology Institute
FOAK	First-of-a-kind
HTSE	High-temperature Steam Electrolysis
IAEA	International Atomic Energy Agency
ILOSTAT	International Labor Organization Statistics
INL	Idaho National Laboratory
ISIC	International Standard Industrial Classification
KEPCO	Korea Electric Power Corporation
LFR	Lead-cooled fast reactor
MIT	Massachusetts Institute of Technology
MITEI	MIT Energy Initiative
NEI	Nuclear Energy Institute
NOAK	Nth-of-a kind
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NZW	Net Zero World
O&M	Operation & Maintenance
PRIS	Power Reactor Information System
PWR	Pressurized Water Reactor
ROW	Rest of World
UAE	United Arab Emirates
WACC	Weighted Average Cost of Capital

1. INTRODUCTION

The Net Zero World Initiative aims to accelerate decarbonization of global energy system by enabling partner countries to harness the power and technical expertise of US and international industry, think tanks, and universities. Participant countries include Chile, Indonesia, Egypt, Nigeria, Argentina, and Ukraine. One of the key technical pillars of the initiative is an energy system-wide (ESW) decarbonization and investment analysis of climate-neutral pathways. These require key technology inputs (for variable renewable, battery storage, nuclear energy, etc.) to be used in the employed ESW models.

This report focuses on providing the basis for cost and operation specifications for nuclear energy. Due to the lack of nuclear energy adoption in certain participant states, modeling costs and operational inputs of nuclear reactors can prove difficult to quantify. Additionally, even in regions where nuclear has been deployed, data is limited, and exact estimates can be difficult to obtain. Effective modeling requires an understanding of costs associated with building, operating, and decommissioning the reactor. Beyond cost, capacity expansion models also must account for operational parameters such as construction time, reactor lifetime, and expected capacity factor.

ESW modeling performed under NZW will also account for the use of nuclear energy in non-grid energy applications. This will include the use of nuclear energy for applications such as district heating and hydrogen production. The inclusion of these two additional applications warrants the need for additional cost and operation data.

This report aims to provide ranges of ESW inputs for cost and performance for nuclear energy with corresponding justification for each of these variables. A combination of literature review and data processing is conducted on nuclear cost, operational parameters, and non-grid application factors. Where applicable, country-specific data is provided by leveraging a cost adjustment methodology that considers country-specific differences in larger cost areas such as labor and materials. This report also provides a range of potential outcomes for each variable in the form of optimistic, expected, and conservative values, as summarized in Table ES-1. All cost estimates in this report are provided in 2022 USD.

2. METHODOLOGY

2.1. Overnight Cost and Operation and Maintenance Cost Assumptions

Nuclear cost estimation is an inherently challenging task. Even in countries where multiple reactors have been built, cost estimation can be relative imprecise. This is partly because nuclear costs depend on a myriad of factors from regulatory process, commodity inputs, contractor experience, and construction technologies. In the United States various efforts have attempted to produce cost range targets [1–4, 9]. One of the more recent efforts was undertaken by researchers at the Idaho National Laboratory (INL) [5]. This study consisted of a comprehensive literature survey coupled with specific recommendations for a reactor build ‘between a first- and Nth-of-a-kind’ (BOAK). Because grid modelers can safely assume that a first of a kind demonstration has already occurred elsewhere, BOAK values are directly applicable as they would correspond to near-term follow-on units (not the ultimate ‘Nth’ cost after dozens of units are built). The recommended BOAK values will be used as the foundation of this paper for overnight nuclear costs. Operational cost estimates rely on recent Nuclear Energy Institute (NEI) estimates for the existing US nuclear fleet [6]. Table 1 provides the estimated nuclear cost ranges for both overnight costs (OCC) and operation and maintenance (O&M) costs from said reports. Note that values from the original reports have been escalated (and rounded) to reflect 2022 USD values.

Table 1. Recommended estimated nuclear cost ranges for advanced reactors in the United States. Values escalated to 2022 USD. Taken from [5] and [6].

Large Reactors and Small-Modular Reactors	Optimistic	Base	Conservative
BOAK Overnight Capital Costs (USD/kWe)	$5,250	$8,000	$9,250
Total O&M (USD/MWh)	$29	$34	$45

It is important to note that [5] recommends the range above irrespective of the reactor type or size (excluding microreactors) and is intended to represent costs of baseload reactors in commercial electricity markets including reactors with hydrogen production capacity. Reactors (especially microreactors) deployed specifically for other applications would need to be considered separately as higher costs are expected and likely acceptable for those types of applications. In essence, the compiled data from the study did not reflect statistically significant differences in normalized costs between reactor types (water, sodium, gas, or salt cooled) nor between the sizes of the reactors (MW or GW range) and if there were, the lower cost alternatives would expect to be deployed in commercial markets. As a result of this uncertainty, the recommendation for the costs is assumed to be reactor agnostic at this time. Additionally, these values consider single nuclear power plant (NPP) unit sites and do not account for multi-unit adjustments where costs may be lower because multiple reactors are sited together and reap OCC and O&M cost synergies. Discussion of NPP siting strategy is typically beyond the scope of ESW models. Lastly, as previously highlighted, these overnight costs are for a non-first-of-a-kind reactor, referred to in [5] as 'BOAK'. They assume a demonstration has already been built somewhere in the globe and correspond to the expected price for near-term following units. The costs are also distinct from a NOAK estimate which assumes a long-term plateauing of costs after dozens of units have been built (in that sense the BOAK costs may still observe cost reductions from the effects of learning). The O&M costs on the other hand are all based on existing data for the light-water reactor fleet in the United States. This is assumed to be representative of future builds regardless of reactor type.

The high-level methodology used in the modeling behind this report allows for leveraging United States nuclear cost ranges and adjusting them on a country-by-country basis to provide local cost estimates for each NZW participant. To do so for OCC, values from Table 1 were escalated to 2022, and OCC was divided into three primary cost categories—labor, materials, and equipment—and country-specific adjustment factors were defined for each category. Said adjustment factors were then used to produce new cost ranges for each country.

For operational costs, the same approach was used where values from Table 1 were first escalated to 2022, and operational costs were divided in to three primary cost categories. These categories included fuel, capital, and labor, and country-specific adjustment factors were defined. Again, the results produced a new, country-specific cost range. It should be noted that all values discussed throughout this paper are given in USD and not in country-specific currencies.

To validate the results, the method was benchmarked against both overnight and operational costs in China and compared against observed costs. This is then repeated for United Arab Emirates to further validate the approach for OCC estimates.

The cost adjustment approach used for a given OCC level (split between optimistic, base, and conservative) is represented in more detail in Equation 1 below.

$$OCC_x = OCC_{US}(\gamma LF_x + \alpha MF_x + \sigma EF_x)$$

Equation 1. OCC adjustment equation.

Where,

- X represents a given country
- OCC represents total nuclear overnight costs, represented in USD/kWe
- γ represents the percentage of labor costs of total OCC
- α represents the percentage of material costs of total OCC
- σ represents the percentage of equipment cost of total OCC
- $\gamma + \alpha + \sigma = 1$
- LF represents the labor adjustment factor for a given country
- MF represents the material adjustment factor for a given country
- EF represents the equipment adjustment factor for a given country

The same method was used to adjust O&M costs and is shown in Equation 2 below.

$$O\&M_x = O\&M_{US}(\gamma LF_x + \lambda CF_x + \phi FF_x)$$

Equation 2. Operational cost adjustment equation.

Where,

- X represents a given country
- O&M represents nuclear operational costs, represented in USD/MWh
- γ represents the percentage of labor costs of total O&M
- λ represents the percentage of capital costs of total O&M
- ϕ represents the percentage of fuel cost of total O&M
- $\gamma + \lambda + \phi = 1$
- LF represents the labor adjustment factor for a given country
- CF represents the capital adjustment factor for a given country
- FF represents the fuel adjustment factor for a given country.

For both OCC and O&M costs, this process was repeated for optimistic, base, and conservative costs in order to produce an expected range for each country.

2.2. Country-Specific Cost Adjustments

To make country-specific adjustments, several key assumptions were made to determine which costs will vary on a country basis. The primary assumptions for OCC adjustments being that labor and material costs vary, but equipment costs remain constant across all countries. In essence, it is assumed that labor and material are predominantly locally sourced, while equipment is externally provided (hence not country-specific). This assumption is supported by the comparative analysis produced by The Energy Technology Institute (ETI) Nuclear Cost Drivers Project [3], which compares the EU/US light-water reactor genre (conventional in Europe and North America) and the Rest of World (ROW). In Figure 1 the proportions of different components of cost from the research can be observed.

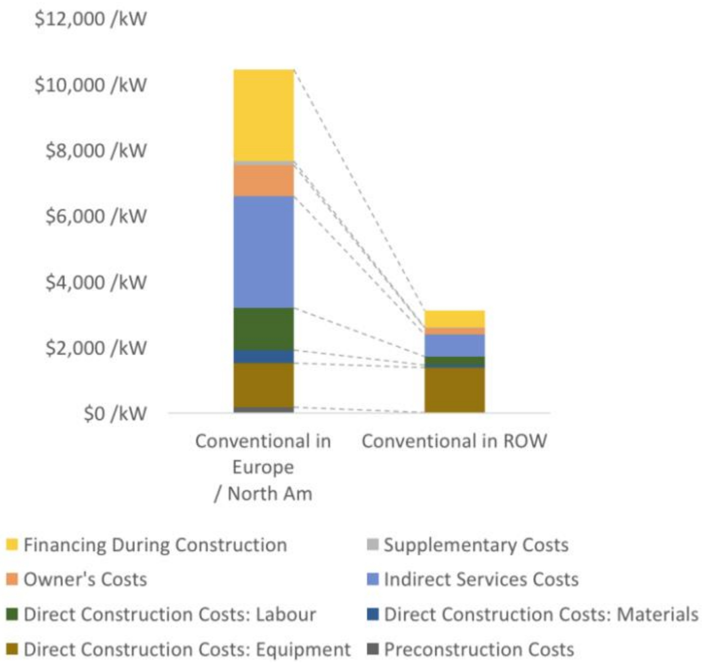

Figure 1. Cost Comparison: Europe/North America and ROW Costs. Taken from [3].

In their report, equipment is almost identical in both regions (shown in a brownish color), and the primary sources of variation are due to labor direct construction, financing during construction, materials, and indirect services (which is predominantly labor-based) costs. For O&M cost adjustments similar type of assumption is made. It was assumed that fixed costs change by country, but that variable costs (which are split into capital and fuel costs later in this report) do not.

To make accurate adjustments to both OCC and O&M, costs needed to be split into the respective categories described previously. To determine correct percentages of labor, material, and equipment, costs included in OCC data from the Energy Economic Data Base (EEDB) was leveraged [7]. The data, which is representative of a generic pressurized water reactor (PWR), points to a total cost split of labor at 28.71%, material at 12.57% and equipment at 58.72%. The adjustment methodology used in this report breaks material into the two primary categories of steel and concrete with given weights of 24% and 76% of total material cost using rough approximations from the Massachusetts Institute of Technology (MIT) study [9].

Literature around the percentages of overnight costs for nuclear reactors is relatively inconsistent. The four sources considered for OCC breakout were from MIT, ETI, NREL, and EEDB [3–10]. MIT, ETI, and NREL weighted labor costs more significantly than was observed in EEDB—in some instances more than double the value EEDB reported. Subsequently, these same sources also appeared to weight equipment costs at half the value of EEDB. A possible explanation for this variation could be how select sources differentiate between, overnight capital costs and total cost. The labor portion in the other references range from 47–61% of total costs. It is often unclear how this is estimated, and a detailed breakdown is not always provided. On the other hand, EEDB data (and the updated numbers provided by Stewart & Shirvan in [32]) clearly delineate their methodology and provide detailed breakdowns. EEDB differentiates between median case and better experience basis for a PWR. Total on-site labor cost as a proportion of total base cost ranges between 25.9%–27.57% in 1987 USD. Based on these numbers, [32] escalated the cost to 2018 USD and reached a proportion of labor cost on total base cost of 27.8%. Costs have been prepared for the EEDB as “overnight” base construction costs, which are the sum of the direct and indirect costs given in constant (not adjusted by inflation) dollars. Direct costs are the costs of commodities, equipment, and their installation labor. Indirect costs are the costs of construction services, engineering, construction management, field supervision and testing. Contingency, owners, and inflation related costs are not included [7]. The EEDB-based proportion was selected due to this higher level of transparency provided for the estimate.

With the OCC cost factor proportions established, the next step is to generate country-specific weights. For labor-based cost adjustments, earnings of employees by economic activity from the International Labor Organization Statistics (ILOSTAT) data set was used—specifically, data from the manufacturing, energy, and construction sectors. The monthly earnings relate to the gross remuneration in cash and in kind paid to employees, at regular intervals, for time worked or work done together with remuneration for time not worked, such as annual vacation, other type of paid leave, or holidays. Earnings exclude employers’ contributions in respect of their employees paid to social security, pension schemes, the benefits received by employees under these schemes, severance, and termination pay [11].

According to the methodology described by ILOSTAT, the time series are harmonized. The data reported as weekly, monthly, and yearly was converted to hourly using data on average weekly hours when available. The data was converted to US dollars as the common currency, using exchange rates or using purchasing power parity rates for private consumption expenditures. This methodology allows for international comparisons by taking account of the differences in relative prices between countries. Data disaggregated by economic activity are provided according to the latest version of the International Standard Industrial Classification (ISIC) of all economic activities available for that year [11].

As MIT points out in [9], this approach is relatively limited. Ideally, all construction tasks would be broken down within their respective labor categories and multipliers would be sought for each specific bracket. However, due to the unavailability of data (both in the breakdown of labor tasks for nuclear construction and country-specific ratios), this was considered outside of the current scope. However, the approach outlined above was still deemed to be representative of potential cost variations across countries. Since an energy construction-specific ratio of average labor rates is expected to be relatively representative for nuclear energy and incorporate, to some extent, the impact of productivity. This is discussed further in Appendix B – Labor Productivity Differences.

Finally, the ratio of material costs against the United States was considered. It was assumed that the material cost category of overnight costs was divided into two sub-categories, steel and concrete. It was also assumed that concrete costs correspond to 24% of total material costs and steel to 76% [9]. The cost of both concrete and steel was then adjusted on a country basis by identifying the export price of concrete and steel commodities (Using 2021 USD estimates which were then escalated to 2022 values) [12].

To project and adjust the O&M costs on a country basis NEI estimates for US costs were used, which breaks operational costs into three categories (fuel, capital, and operations) and provides low, medium, and high projections for each category [6]. Table 2 shows the reported cost ranges from NEI broken out into categories. Note that these are the same costs shown in Table 1 except in this instance, they are broken out further and represented in fixed (USD/kWe) and variable (USD/MWh) amounts depending on the cost category. Note that the fixed operating costs were adjusted from the normalized NEI values to ensure they do not account for the impact of capacity factors.

Table 2. NEI report US fixed (operations) and variable (capital and fuel) nuclear O&M cost breakout.

United States O&M	Optimistic	Base	Conservative
Operations [USD/kWe-yr]	$154	$179	$223
Capital [USD/MWh]	$3.25	$6.25	$9.50
Fuel [USD/MWh]	$6.00	$6.75	$7.50

Here another assumption is made that some costs will remain consistent across countries while others will not. It was assumed that fuel and capital costs would not change and therefore be static across countries, but that operations costs (which are almost entirely labor driven) would vary from country to country. Subsequently, to adjust labor costs for O&M the same labor adjustment factor was leveraged that was used to adjust the labor portion of OCC.

2.3. Cost Escalation Methodology

The cost escalation method used in this research matches that in [5]. While that study reported costs in 2019 USD, the indices used were extended into 2022 to further adjusted costs. The method uses the United States' new industrial building construction cost index [13]. It was applied to adjust overnight costs from 2019 USD values to 2022 USD values and operational costs from 2021 USD values to 2022 USD values.

For validation of the methodology, the results obtained in this report were compared against recent international builds from China and United Arab Emirates. Baseline costs from builds in both countries required escalation to adequately compare the proposed method and actual outcomes for said builds. In this instance an alternative escalation method was leveraged which adjusted costs by country-specific consumer price index (CPI) plus an additional amount. The additional amount, which varied by case, was defined by measuring the gap between the United States CPI and the new industrial building construction cost index in year the foreign build took place. This gap was assumed to be constant over time and applied to the CPI in target year. Equation 3 below shows how this might be applied.

$$Escalation_x^t = CPI_x^{2022} + (IBC^t - CPI_{us}^t)$$

Equation 3. Escalation equation for cost adjustment to 2022 USD values.

Where,

- Escalation represents the escalation factor used to adjust prices from a given year to 2022 USD values
- X represents a given country
- t represents the base year from which the costs need to be adjusted to 2022 values
- CPI represents the consumer price index
- IBC represents the industrial building construction cost index (note this is an index exclusive to the US).

It is worth reiterating here that all costs shown in this report are shown in 2022 USD values and have been escalated where necessary using the above methods unless otherwise indicated.

2.4. Non-Cost Parameterization Methodology

Beyond costs, this report also provides guidance on other expected operational parameters. These additional parameters include, construction time, reactor lifetime, capacity factor, load-following capability, and retirement costs. For each of the construction and operational parameter recommendations, a combination of US-centric data and global data were leveraged. Where enough data was available, it was evaluated in detail to show trends in distribution. First, second, and third quartiles were highlighted as the basis for the expected range of values for a given parameter. It should be noted that while this method is an effective means of producing statistically sound ranges, in some instances observed commercial values may be more tightly grouped than is reported by the quartile method. For select categories, expected performance ranges are discussed and recommendations made based on existing research and operational experience.

Given the NZW focus on leveraging nuclear for more than just electricity production, two non-electrical applications are briefly outlined in this research. Recommendations for modeling values were provided. The two applications discussed are nuclear-powered hydrogen production and district heating. In both instances, performance of said systems is discussed including input requirements. In the case of nuclear-powered hydrogen production, a range of costs is presented from existing research.

3. REFERENCE DATA ON NUCLEAR COSTS

3.1. Between of a kind (BOAK) Overnight Capital Costs

3.1.1. Adjustment of Overnight Capital Costs in the US to the country of interest

The overnight capital cost was disaggregated on labor, material concrete, material steel, and equipment with the United States taken as the reference point. In the first step, export prices for concrete and steel of NZW countries were taken from Reference [12]. In a second step, the prices were normalized to the United States' costs. The results are shown in Table 3. Argentina has the lowest normalized steel cost but the highest normalized concrete cost amongst the countries selected. Indonesia has the lowest concrete cost and Egypt the highest steel cost.

The labor costs by country were taken from the International Labor Organization and were escalated to 2022 prices only when data from previous years was available. All the labor costs were then normalized to the United States' costs. It is important to note that Nigeria, India, and Egypt have the lowest normalized labor cost and the highest labor normalized labor corresponds to Chile, South Africa, and Argentina.

Finally, equipment costs are assumed to be near identical to the United States' costs. As a result, their country-specific multipliers are all set to 1.0.

Table 3. Capital cost adjustment factors by category, normalized to United States costs.

Country	Labor	Material Concrete	Material Steel	Equipment
United States	1.00	1.00	1.00	1.00
Chile	0.28	0.63	0.52	1.00
Indonesia	0.04	0.29	0.43	1.00
Egypt	0.07	0.59	0.57	1.00
Nigeria	0.03	0.57	0.50	1.00
Argentina	0.18	0.78	0.33	1.00
Thailand	0.11	0.36	0.44	1.00
India	0.05	0.30	0.51	1.00
Ukraine	0.12	0.30	0.43	1.00
South Africa	0.19	0.59	0.48	1.00

3.1.2. Country-Specific Nuclear Overnight Capital Costs

The results of the overnight cost modeling are shown in Figure 2. Generally, all NZW countries will likely incur relatively similar nuclear costs with small amounts of variation. Differences between labor and material costs appear to cancel each other out. The base costs for most countries appear close to the optimistic level for the United States. This highlights the particular impact of labor rates on nuclear costs.

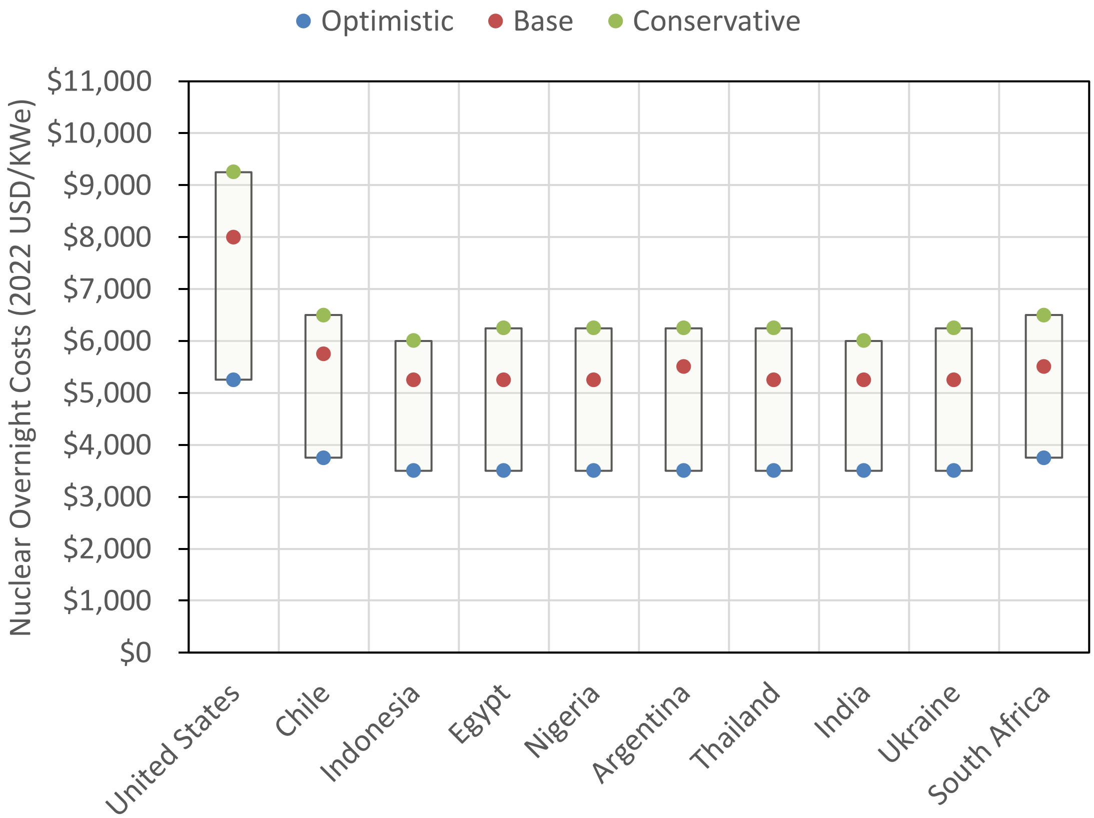

Figure 2. Country-specific nuclear overnight cost ranges, shown as 2022 USD values.

Corresponding values from Figure 2 are shown in Table 4. In both Figure 2 and Table 4 all nuclear OCC outputs from the model were rounded to the nearest multiple of 250. These estimates are recommended to be used in the modeling activities for NZW.

Table 4. Country-specific nuclear overnight cost ranges, shown as 2022 USD values.

Country	Optimistic	Base	Conservative
United States	$5,250	$8,000	$9,250
Chile	$3,750	$5,750	$6,500
Indonesia	$3,500	$5,250	$6,000
Egypt	$3,500	$5,250	$6,250
Nigeria	$3,500	$5,250	$6,250
Argentina	$3,500	$5,500	$6,250
Thailand	$3,500	$5,250	$6,250
India	$3,500	$5,250	$6,000
Ukraine	$3,500	$5,250	$6,250
South Africa	$3,750	$5,500	$6,500

3.1.3. Comparison Against Observed Costs

To validate the cost adjustment approach, the same methodology was followed and applied to China and the United Arab Emirates, where actual costs for nuclear builds were available. In China these two builds were the Sanmen and Taishan reactors. The Sanmen 1 and 2 builds were AP1000 PWR reactors developed by Westinghouse Electric Company that came on line one after during 2018. Combined the two Sanmen reactors have a nameplate capacity of 2,314 MWe. The Taishan 1 and 2 builds were Generation III European Pressurized Reactors (ERP) developed by Framatome that came online in 2018 and 2019. Combined the two Taishan reactors have a nameplate capacity of 3,320 MWe. In the United Arab Emirates (UAE) the build used for comparison was the Barakah reactor. The plant consists of 4 units, only 3 of which have been completed with a nameplate capacity of 5,380 (once all 4 reactors have entered commercial service). The Barakah builds are APR-1400 PWR reactors developed by the Korea Electric Power Corporation (KEPCO) and units 1, 2 and 3 entered commercial operation in the years 2020, 2021, and 2022 respectively.

Figure 3 shows the projected nuclear overnight cost ranges in China and Figure 4 for United Arab Emirates. Each uses local labor and material multipliers as highlighted in Section 2.2. The builds are then baselined against these ranges. The solid black and dashed black lines show the actual costs incurred for reactors. United States cost ranges were included for reference as well.

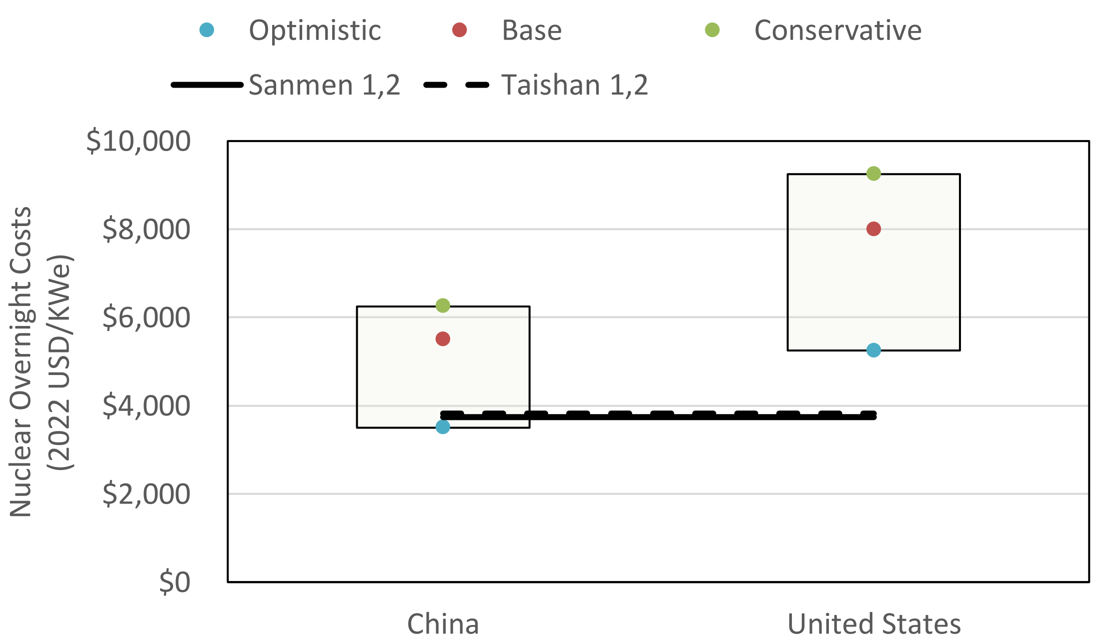

Figure 3. Estimated China nuclear overnight costs compared to actuals.

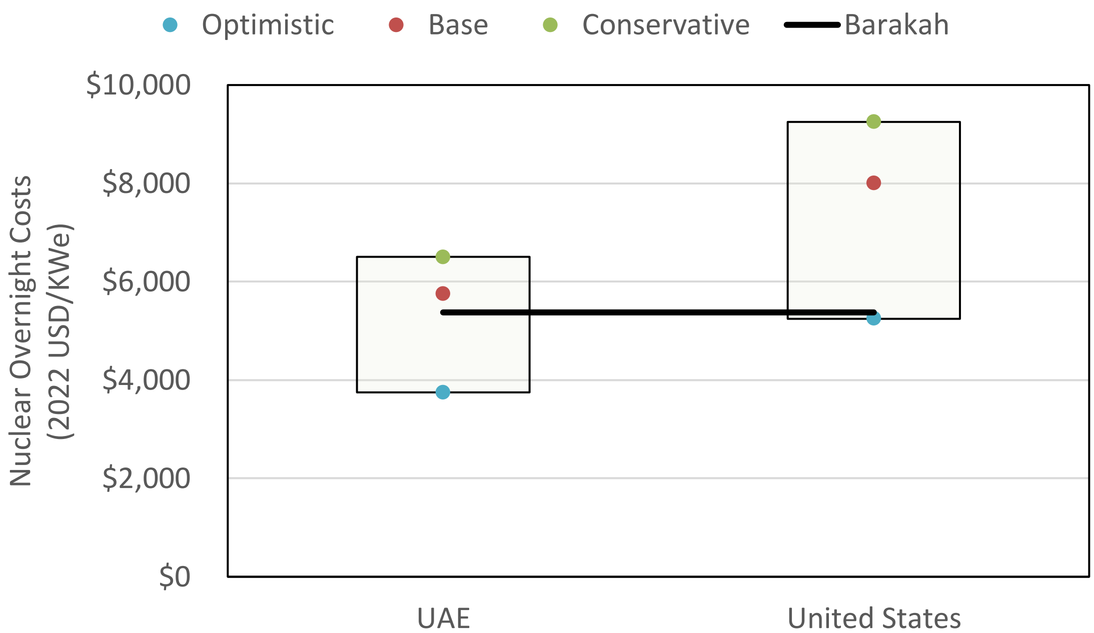

Figure 4 Estimated United Arab Emirates nuclear overnight costs compared to actuals.

The figures above show that the cost adjustment method produces a range that captures actual nuclear costs from recent builds. In the case of builds in China, the cost range produces a more conservative estimate. The observed costs land near the lower end of the cost range; this suggests the estimates using this method may be more conservative (meaning the method produces higher cost estimates than might be observed). This is despite the fact that both countries experienced cost overruns and delays [14,16]. In the case of the build in the UAE the observed data falls much closer to the base case of the model. The Barakah plant did have some minor cost overruns but was considered to be close to the estimated cost range. Given the observed cost was just below the base costs point, this suggests the method produces semi-conservative estimates. Overall, these benchmark exercises show the relative suitability of the high-level methodology despite its limitations. The country-specific nuclear overnight cost ranges produced using this methodology may in fact err more on the conservative side.

3.2. Operating and Maintenance Costs

3.2.1. Adjustment of Operating and Maintenance Costs in the US to the country of interest

For the adjustment of O&M costs in each country, it is assumed that the operating costs are mainly driven by labor related expenses. Given this, the fuel and capital expenditures are assumed to be the same as US costs and are set to 1.0. The variable that is specific to each country is “operations,” which represent the average monthly earning (from the sectors energy, manufacturing, and construction) per worker for each country normalized by the average monthly earning per worker in the United States. In Table 5, the lowest operations costs correspond to Nigeria, Indonesia, and India, while the highest costs (excluding the United States) are in Chile, Argentina, and South Africa.

Table 5. O&M cost adjustment factors by category, normalized to United States costs.

Country	Operations	Fuel	Capital
United States	1.00	1.00	1.00
Chile	0.28	1.00	1.00
Indonesia	0.04	1.00	1.00
Egypt	0.07	1.00	1.00
Nigeria	0.03	1.00	1.00
Argentina	0.18	1.00	1.00
Thailand	0.11	1.00	1.00
India	0.05	1.00	1.00
Ukraine	0.12	1.00	1.00
South Africa	0.19	1.00	1.00

3.2.2. Country-Specific Nuclear O&M Costs

The results of the operational cost modeling are shown in Figure 5. The plot aggregates all the various O&M costs into one total for each country represented in USD/MWh. Note that values are rounded to the nearest multiple of 0.25. These results also show that NZW countries tend to cluster around the same range with limited variance between each country. For O&M expenses, even low United States operational costs are above the highest projected estimate of all NZW countries. Again, this showcases the significant impact of the cost of labor (the only cost factor that is country-specific here) on overall operating costs.

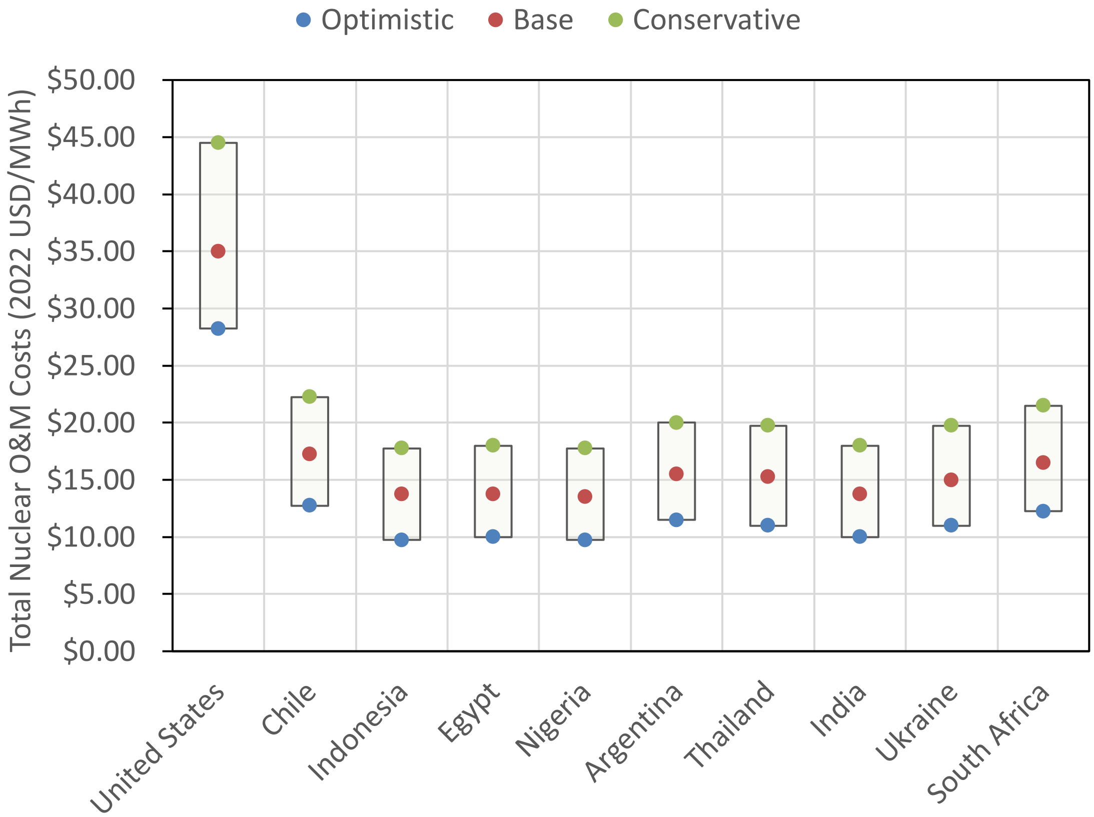

Figure 5. Country-specific nuclear operating cost ranges.

Values from Figure 5 are also divided into fixed (on a USD/kWe basis, while also removing the impacts of capacity factor from the normalized NEI values) and variable (on a USD/MWh basis) portions in Table 6 and Table 7. Recall from Section 2.2 that fixed O&M consisted of labor driven operation costs and subsequently vary from country to country, but that variable O&M consisted of capital and fuel costs which were considered to be constant irrespective of location and therefore are shown as identical across all countries. Also note that the decision to use O&M costs from NEI was predicated upon the data being recently reported O&M costs from existing US reactors [6]. The values are close to but do not line up exactly with reported O&M costs from other references such as the Cost Basis Report [1] and the 2018 MIT study [9]. However, the NEI values were preferred as they are the most recent and consist of real, observed reactor O&M costs in the US.

Table 6. Country-specific nuclear variable O&M cost ranges (USD/MWh).

Country	Optimistic	Base	Conservative
United States	$9.25	$13.00	$17.00
Chile	$9.25	$13.00	$17.00
Indonesia	$9.25	$13.00	$17.00
Egypt	$9.25	$13.00	$17.00
Nigeria	$9.25	$13.00	$17.00

Country	Optimistic	Base	Conservative
Argentina	$9.25	$13.00	$17.00
Thailand	$9.25	$13.00	$17.00
India	$9.25	$13.00	$17.00
Ukraine	$9.25	$13.00	$17.00
South Africa	$9.25	$13.00	$17.00

Table 7. Country-specific nuclear fixed O&M cost ranges (USD/kWe-year).

Country	Optimistic	Base	Conservative
United States	$154	$179	$223
Chile	$28	$35	$43
Indonesia	$4	$6	$6
Egypt	$6	$6	$8
Nigeria	$4	$4	$6
Argentina	$18	$20	$24
Thailand	$14	$18	$22
India	$6	$6	$8
Ukraine	$14	$16	$22
South Africa	$24	$28	$37

An additional factor to consider outside of standard operational costs is the spent fuel tax. For the case of the United States, in 1982 the country enacted a spent fuel tax on nuclear utilities of 1.0 mil per kilowatt-hour, which translates into $0.001/kWh or $1.00/MWh as shown in Table ES-1 [22]. Given the low relative size of this value, a flat amount of $1.00/MWh is assumed across the scenarios.

3.2.3. Comparison Against Observed Operating Costs

To validate the cost adjustment approach for O&M, the methodology was compared against the case of reported O&M costs in China. Local country-specific labor adjustments were applied as done above, and Figure 6 shows the projected total nuclear O&M ranges in China. The solid black lines show the values for China O&M costs, taken from the MIT 2018 report [9]. The United States total O&M cost ranges from the NEI report are included for reference as well.

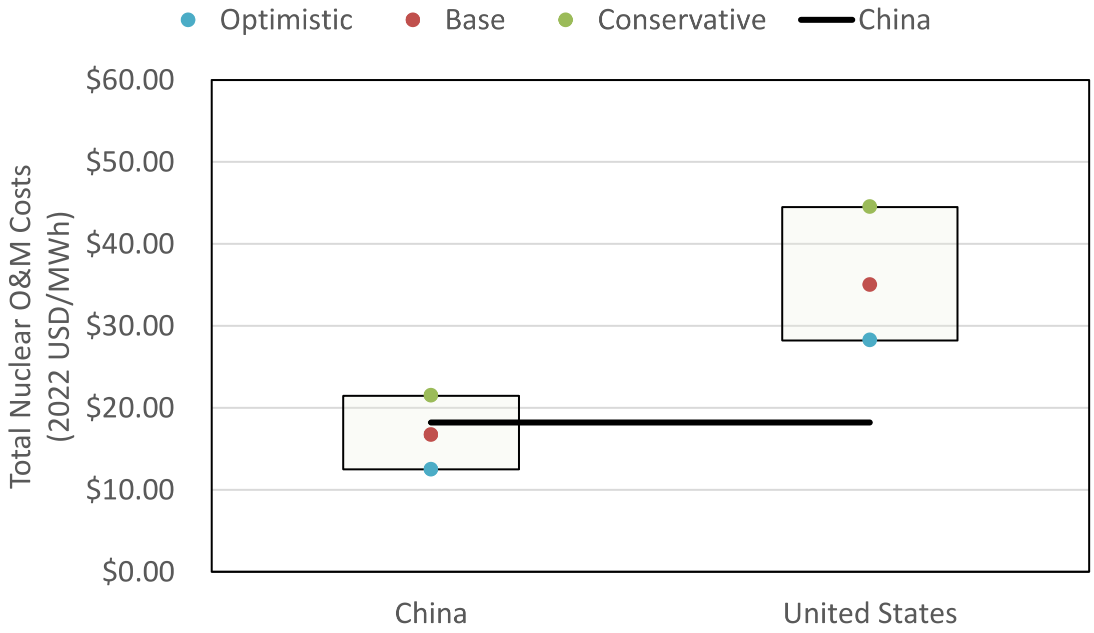

Figure 6. Estimated China nuclear O&M compared to MIT 2018 reported.

The figure above shows that the cost adjustment method produces a range that captures reported actual nuclear O&M. In this instance, the projected range for O&M in China indicates that observed costs are close to the base costs from the methodology. Generally, this helps to validate that the approach used produces accurate estimates that can be used in modeling efforts.

However, it should be noted that only when the total O&M costs are aggregated to a single USD per MWh are they consistent with those found in the MIT report. When the data is disaggregated between fixed O&M and variable O&M, the breakout values deviate from those in MIT. This may be due to differences in operational costs between 2018 (when the MIT study was conducted) and 2021 (date of the reported NEI costs used in this study). Additionally, the categorization of what is considered fixed versus variable between the NEI data and MIT data could be different. This could produce values that aggregated to similar totals but differ when broken out. It is also possible that the methodology used in this report is overestimating the cost reductions in labor rates (producing a fixed cost value that is lower than MIT reports) but underestimating the change in variable costs (capital and fuel) (producing a variable cost value that is higher than observed by MIT). This combination of over and under estimation may have resulted in an error cancelation when aggregated to a single USD per MWh value. Further work is needed to identify the exact cause of the discrepancies in the disaggregated costs [23].

3.3. Retirement (Decommissioning Costs)

Retirement costs, also referred to as decommissioning costs, are incurred at the end of a reactor's lifetime. In the United States, these costs are often placed into a trust that is formed during the construction of the plant and collected over the lifetime of the plant [19]. Costs are incurred by the utility at the end of the reactor lifetime when decommissioning is carried out. Alternatively, the trust can be sold to a third party that performs the decommissioning using the accrued funds. It is important to note that the time at which these costs are incurred can change the impact in present dollar terms. Discount factors must be applied to decommissioning costs to produce accurate estimates when modeling. To better understand the range of costs that could be incurred, retirement costs of United States reactors were collected from the Nuclear Regulatory Commission (NRC) and a United States utility [20]. Costs were escalated to 2022 USD values using the overnight cost escalation methodology discussed in the previous sections.

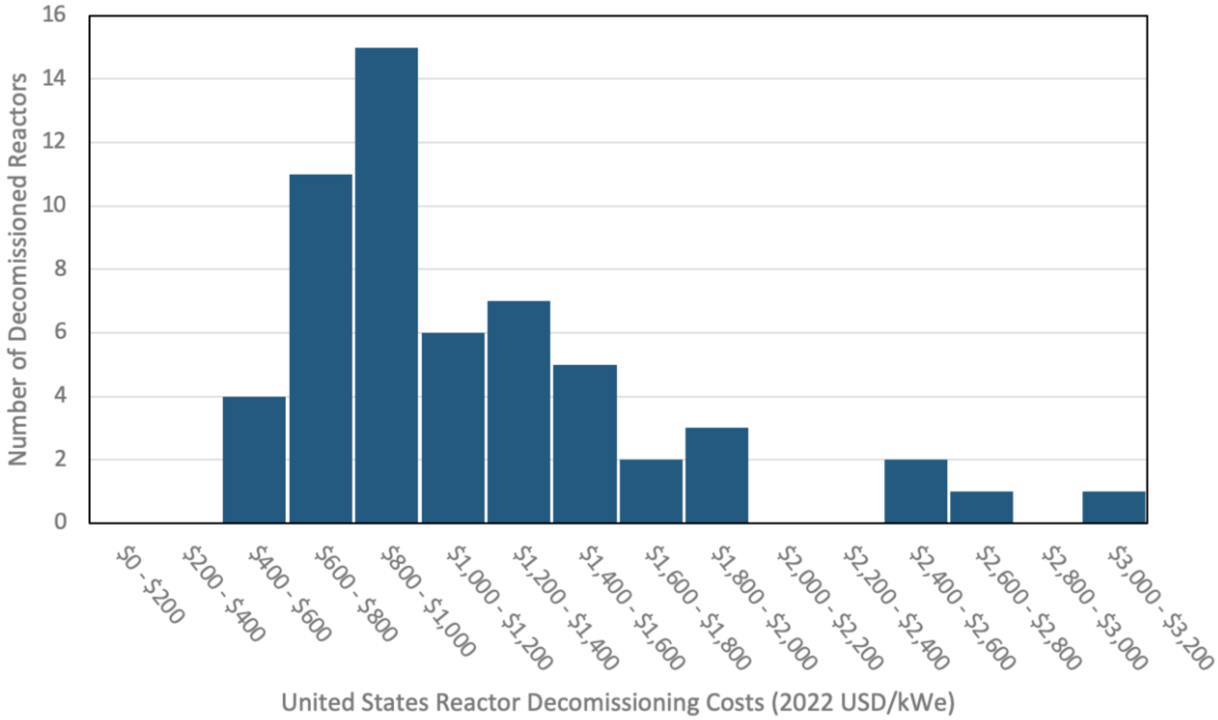

Figure 7. U.S. Decommissioning cost ranges.

Figure 7 shows the distribution of historical United States nuclear reactor decommissioning costs [21]. The distribution is right-tailed with a small number of reactors showing substantial decommissioning cost overruns. Nevertheless, Table 8 shows that data is grouped between $750 to $1,250 2022 USD per kWe with a median decommissioning cost of $1,000 per kWe. Again, it is important to note that these costs should not be conflated with OCC and are typically accounted for at the end of a project, as an annual fee accumulated throughout operations, or as a smaller initial downpayment that earns interest up till the point of retirement.

Table 8. Decommissioning cost ranges.

US Decommissioning Costs [2022 USD/kWe]		
Low – 1st Quartile	**Medium – 2nd Quartile**	**High – 3rd Quartile**
$750	$1,000	$1,250

3.4. Adjustment Factors

Adjustment factors for first-of-a-kind (FOAK) builds and the impact of learning rates on subsequent builds were also based on recommendations from [5]. Recall that estimates for OCC numbers are not considered to be FOAK demonstrations nor nth-of-a kind (NOAK). To adjust numbers downward for NOAK builds or upwards for FOAK builds, the adjustment factors shown in Table 9 should be used. For countries without existing nuclear programs the FOAK adjustment factors would not include the cost for starting a nuclear program in that country. In these instances, models would only represent FOAK OCCs and additional costs would need to be accounted for to represent the formation of a national nuclear program to accompany the adoption of the technology. Only a single value is recommended from FOAK premium. This is because typically conservative FOAK adjustment factors are likely correlated with optimistic BOAK costs and vice versa. For simplicity, and to provide a more consistent analysis, a single reference premium multiplier is recommended for any of the three scenarios.

Table 9. First-of-a-kind capitals cost adjustment factor ranges and learn rate capital cost reduction ranges.

Country	Optimistic	Base	Conservative
FOAK premium		1.5	
Learning rate [%]	15%	10%	5%

For additional context, the recommended value in Table 9 was obtained from reference [5] by estimating the median value of FOAK-to-BOAK ratios across different reactor cost estimates. The learning rate in this instance is defined as a percentage reduction in cost when a doubling in number of deployments is achieved. For example, a learning rate of 5% implies that the cost of the second plant will be 95% that of the FOAK, and the 4th plant will be 90.25% (95% of 95%) and so on. Mathematically this can be expressed as shown in Equation 4.

$$Cost_n = FOAK(1 - LR)^{log_2 n}$$

Equation 4. Learning rate adjustment equation.

Where,

- Cost represents the learning rate adjusted cost of the nth reactor
- n represents the number of reactor deployments
- FOAK represents the OCC costs of the FOAK deployment
- LR represents the desired learning rate from Table 9.

In the case of calculating FOAK build costs, the value shown in Table 9 is used as a direct multiplier. Meaning, the OCC cost should just be multiplied by the FOAK premium to get an expected FOAK cost. Again, a mathematical representation is shown in Equation 5.

$$FOAK = BOAK \times FP$$

Equation 5. FOAK cost adjustment equation.

Where,

- FOAK represents First-of-a-kind OCC
- BOAK represents a given OCC value from Table 4
- FP represents FOAK premiums Table 9.

4. REFERENCE DATA ON NUCLEAR CONSTUCTION AND OPERATION

While considering construction and operational parameters within this section one should recall that for construction time and capacity factor the methodology leverages the use of quartiles from observed data to produce a suggested range of values for modeling. This approach was also leveraged for estimating decommissioning cost ranges. It should be noted that while this method is an effective mean of producing statistically sound ranges, in some instances, observed commercial values may be more tightly grouped. This differentiation likely stems from the use of globally data overtime where differences in parameters may produce minor skewing. Where this may be a factor in the reported ranges it is discussed with more detail.

4.1. Construction Time

Time to complete a nuclear reactor can vary based on several factors. This includes regulatory approval timelines, issues with material sourcing, project management issues, etc. To better understand the expected range data from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database was leveraged [17]. Table 4 shows the distribution of construction time, in years, of all nuclear reactors built in the world. Construction time in this instance is defined as construction start - breaking ground, to first criticality. Note that this time excludes the time needed to obtain regulatory approval for siting the reactor at a given location.

Global median construction time for all nuclear reactor builds, from breaking ground to first criticality is 5.5 years. High, medium, and low estimates for construction times can be found in Table 10.

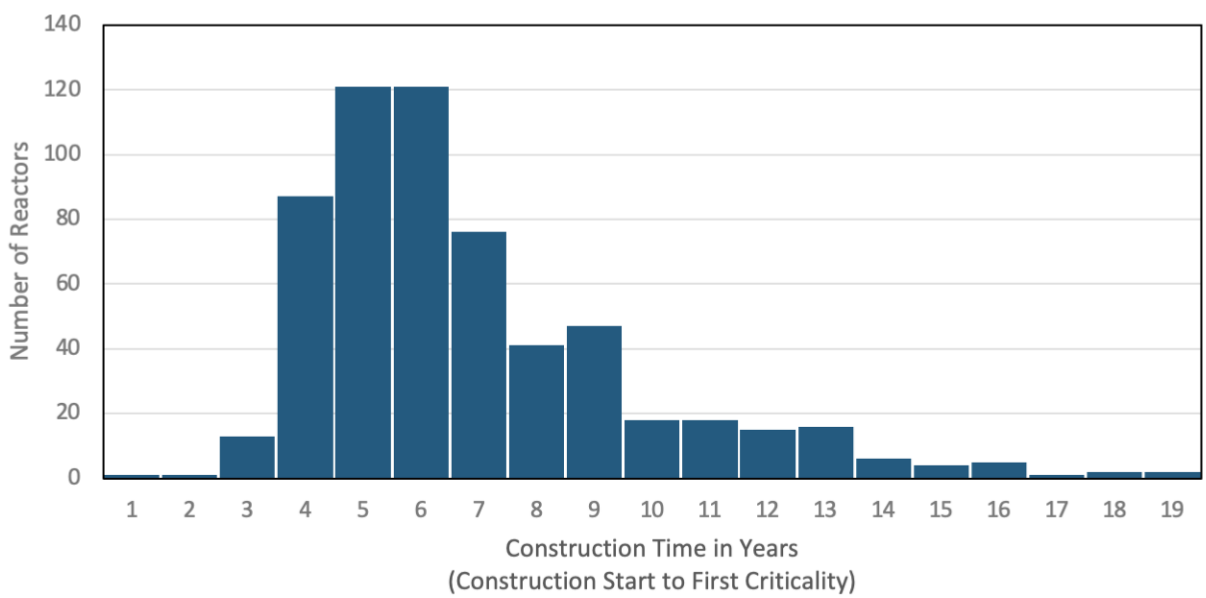

Figure 8. Global nuclear reactor construction time distribution from breaking ground to first criticality.

Figure 8 shows that global construction time data is right skewed with a long right tail. This behavior is expected given that some projects that experience long delays will push the distribution right. However, Table 10 shows that the middle 50% of projects from the PRIS dataset needed between 4.5 years and 8.0 years in total construction time. The median construction time reported was 5.5 years. Note that this value could be sensitive to several factors including reactor type, reactor size, country of build, and construction firm executing on the build.

Table 10. Global nuclear reactor construction time statistics, breaking ground to first criticality.

Global Construction Times [Years]: Breaking Ground to First Criticality		
Low – 1st Quartile	Medium – 2nd Quartile	High – 3rd Quartile
4.5	5.5	8.0

4.2. Capacity Factor

Capacity factor is an important aspect of nuclear modeling that can have a substantial impact on total energy production. As nuclear power plants are able to operate for a larger percent of the year, the more value is drawn from the asset. Capacity factors vary around the globe with the highest coming from United States reactors. PRIS data was leveraged again to understand the distribution of capacity factors across the globe [17].

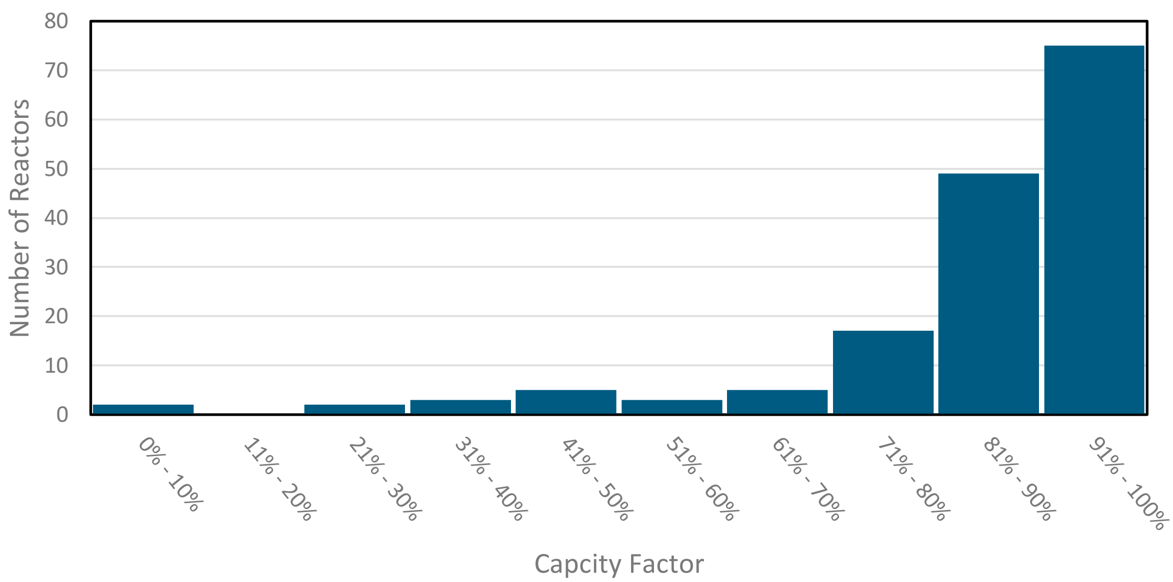

Figure 9. Global nuclear capacity factor distribution, site specific reporting.

Figure 9 shows that nuclear capacity factors are grouped around 80%–100% with a long -left tail. Reactors with a 0% capacity factor were removed from the dataset (as they were assumed to be non-operational) but some reactors in the dataset still showed extremely low-capacity factors. It is likely that some of the low-capacity data points are from test reactors or reactors with low utilization due to abnormal operational circumstances. In commercial applications operators are incentivized to keep capacity has high as possible to maximize profitability. Despite the presence of outliers in the dataset, Table 11 indicates that the first and third quartiles are 80% and 95% with a global median capacity factor of 90%. A lower end capacity factor of 80% is considered very unlikely for normal commercial operation (the data my be skewed by non-commercial or non-traditional operations). On the other hand, the upper bound of 95% may be considered overoptimistic, but the range obtained is essentially a function of the methodology. Note that this data group reports site specific data and not reactor specific data (i.e., reactor site with four reactors counts as a single data point instead of four).

Table 11. Global nuclear capacity factor statistics, site specific reporting.

Global Nuclear Capacity Factors		
Low – 1st Quartile	**Medium – 2nd Quartile**	**High – 3rd Quartile**
80%	90%	95%

4.3. Reactor Lifetime

The average age of American reactors approaches 40 years, and there are no technical limits to these units operating beyond that point. To date, 20 reactors in the United States are planning or intending to operate up to 80 years [8]. Though nuclear plants are originally intended to operate safely for 40 years, experts agree that older reactors could last another 50 years [15]. The lifetime of a reactor is assumed to be at least 60 years according to Dominion Energy research [18]. This is taken to correspond to the “conservative” case. The base case recommendation is 80 years, and the optimistic is taken to be 100 years [18].

4.4. Nuclear Plant Load-Following Capability

Nuclear power plants were designed for load-following operation, and the nuclear industry in various countries accrued decades of experience successfully ramping up/down operations of their nuclear fleet. Below is a summary of European’s utilities requirements for nuclear power plant maneuvering capabilities: where “conservative” refer to minimum requirements, and “optimistic” refer to capability currently achieved by some NPP concepts [25].

Table 12. Maneuverability and other performance metrics for nuclear.

	Min	**Max**
Load-following operation available during cycle length	90%	100%
Ramp rate of load-following operation	3%Pr/min	5%Pr/min
Daily maneuverability	2 daily cycles/day 5 cycles per week 200 cycles per year	No limit
Lower range of power operation	50%Pr	20%Pr
Primary frequency control (available at all time)	+/- 2%Pr	+/- 5%Pr
Secondary frequency control	(optional)	+/- 10%Pr with ramps of 5%Pr/min

Additional features include the possibility of nuclear plants participating in emergency load variation with ramp rate of 20%Pr/min down to minimum load of the unit, and grid restauration with ramp-up of 10%Pr/min[a].

It should be noted that many recent designs (including the AP1000) are certified to comply with these requirements. Similar utility requirements were defined in the United States [26].

Added costs to load-following operation are not included here since those are expected to be mostly accounted for by the reduced reactor utilization while still incurring fixed operating costs. Reduced fuel utilization and maintenance costs due to load-following operations can be estimated via variable O&M costs [27].

These maneuvering capabilities are based on large advanced light-water reactors technologies, while some advanced SMRs may provide improved maneuvering performance. For instance, the TerraPower Natrium, Westinghouse LFR, and Moltex concepts are designed to couple with thermal energy storage (several hours of storage are being considered), which enables ramping up/down the plant electrical output without varying nuclear plant output.

5. NON-GRID NUCLEAR ENERGY APPLICATIONS

5.1. Hydrogen Production

For non-grid applications, nuclear-powered hydrogen production has gained increased global interest. Specifically, high-temperature steam electrolysis (HTSE) is being considered as a prime candidate for nuclear-based hydrogen production. To better understand the cost and technical implications of coupling HTSE plants with nuclear reactors, a range of expected costs and parameters were produced using existing research from [24]. Table 13 shows technical and cost requirements for HTSE plants ranging from systems with a 10 MWe to 500 MWe requirement.

HTSE processes require both heat and electricity from a nuclear plant to produce hydrogen. For example, an HTSE plant with a 500 MWe requirement will need an even larger power output from a nuclear plant to account for the thermal energy, powering of HTSE components (e.g., pumps, heaters), and losses in the system. To account for the power and heat requirement from the nuclear power plant, the additional MWth requirements were re-converted back to MWe (assuming a 33% thermal efficiency) to produce the total power and heat requirements in MWe. In this example, a 500MWe HTSE plant would require an equivalent 569 MWe nuclear power plant to fulfill all heat and power requirements. Table 13 provides key inputs such as power and heat requirements, capital expenditures, fixed and variable operation and maintenance costs, and hydrogen output. Estimates are shown in $/MWh and $/kWe units. Note that these cost numbers are MWh and kWe of the total power required which accounts for the cost of both heat and electricity and accounts for losses during the generation and transfer process of heat and electricity from the NPP to the HTSE plant.

[a] %Pr/Min is defined as the measure of change per minute in percent of power rated.

Table 13. High-temperature steam electrolysis key production variables by plant size.

HTSE Plant Size [MWe]	10 MWe	20 MWe	100 MWe	500 MWe
Nuclear Power and Heat Requirement [MWe]	12	23	115	569
OCC [USD/kWe]	$1,900	$1,500	$1,100	$900
Fixed O&M [USD/MWh]	$38	$38	$35	$35
Variable O&M [USD/MWh]	$18.5	$13.5	$7.0	$5.5
Hydrogen Output [Kg/kWe-Year]	196	196	196	196

Modeling nuclear-powered hydrogen production should account for differences in scale. It is worth noting that across all HTSE plant sizes, the output is identical, but the systems benefit from economies of scale in both OCC and O&M categories (most notable in OCC where a reduction in USD/kWe of more than 50% is observed). This range in values was then used to infer recommended optimistic/base/conservative values for hydrogen production costs.

5.2. Nuclear Power Plant Performance for District Heating

Steam from light-water reactors can also be extracted for district heating at various temperatures. This can range from ~43°C at the waste heat level (past the turbine) to ~273°C of high-temperature steam (prior to the turbine). The following estimates are based on AP1000 balance of plant model, as documented in [28]. Figure 10 and Table 14. indicate the quantity of process heat that can be extracted (as a fraction of the total thermal power of the plant) at various temperatures, along with the associated reduction on the plant electrical output. Depending on the district heat temperature requirements, one can easily estimate how much thermal power is available and the penalty on electricity production.

For instance, considering a 1,000 MWe plant with 35% thermal efficiency, a thermal output of 2845 MWth is generated. Around 77% of this heat (2,190 MWth) can be extracted at 167°C, resulting in reduction of electrical power to 562 MWe. All the waste heat (around 1845 MWth) can be extracted at 43°C, without penalty to the electrical power.

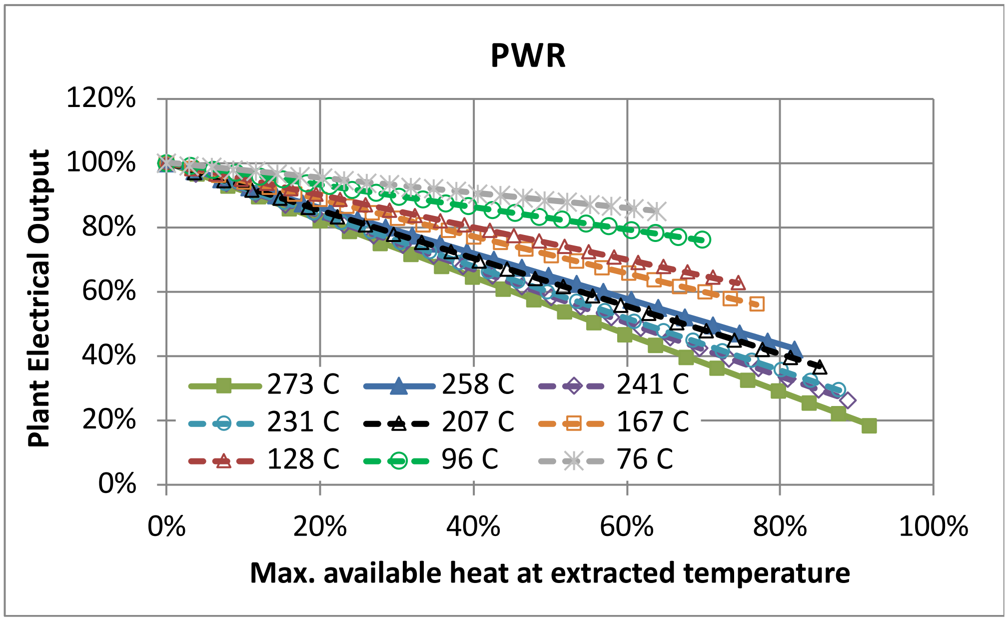

Figure 10. Available process heat for a PWR and impact on plant electrical output [28].

Table 14. Maximum process heat available for each temperature line, in a PWR and impact on plant electrical output [28].

Temperature [ºC]	Max. available heat at extracted temperature [% Plant thermal power]	Resulting electrical power [% Plant electrical power]
43	64.8%	100.0%
76	66.7%	84.5%
96	69.8%	76.1%
128	74.5%	62.9%
167	76.9%	56.2%
207	85.1%	36.8%
231	87.7%	29.6%
241	88.8%	26.6%
258	81.9%	42.3%
273	91.7%	18.5%

6. LIMITATIONS AND FUTURE WORK

The modeling recommendations provided in this report are not without weaknesses and can be improved further as part of future work. Several key aspects to consider further are highlighted below:

1. More representative costs for nuclear overnight costs. An alternative approach could be to focus on observed costs throughout the world and provide a baseline for the NZW participating countries.
2. A more granular and robust methodology for accounting for local cost multipliers. In an ideal case, all labor-based expenses would be broken into hours spent, type of laborer, and rates. These would then be adjusted on a country-by-country basis, accounting for changes in rates and productivity. Furthermore, a more detailed methodology may be able to account for non-local labor factions that should be held constant across all nations.
3. Additional work is also needed to improve the methodology for O&M cost estimation across countries. Notably the discrepancy between variable and fixed costs should be investigated further to improve accuracy when costs are disaggregated from a total O&M cost number to fixed and variable costs.
4. The impact of cost reductions at multi-unit sites (both on OCC and O&M) could be investigated in further details if models can capture these nuances.

In addition to improvements of the methodology highlighted above, the study could be expanded to account for additional considerations. For instance, microreactors are expected to be of interest to remote communities. Microreactor costs are expected to vary substantially from those observed for the larger reactors emphasized in this study. In addition to hydrogen, synthetic fuels (both ammonia or carbon based) could be considered as part of the model. Similarly, thermal energy storage (and other forms of storage) could be considered when accounting for maneuverability of reactors and load -following. Coupling a nuclear reactor to CO_2 direct air capture systems could be of particular interest as well when exploring aggressive net zero targets. Lastly, siting constraints are also important considerations for large scale deployment of nuclear technology.

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8. APPENDIX

8.1. Appendix A - Cost of Capital

While not a primary focus of this report some research was done into the expected cost of capital for nuclear projects and how this may vary between NZW countries. The cost of capital was taken considering the ownership class (public or private) of the energy companies/utilities in each country. When the ownership is public, data from the short-term interest rate from each central bank was taken from [29]. For those countries with private utilities the data was taken from [31–31].

Between countries it is necessary to take into account inflation and exchange rate variations to explain the different rates. They are not independent from the weighted average cost of capital (WACC). Also, it is vital to note that the WACC is expressed in the currency of each country. So, a higher WACC does not mean a higher internal rate of return in dollars. When the WACC is transformed from the country currency to dollars using the exchange rate, it will result in a lower WACC in dollars closer to the United States and the difference will be the risk premium.

The interest rate from the central bank (in this case for Ukraine) is the nominal short-term interest rate not adjusted by inflation and controlled by the central bank authority representing the opportunity cost of the economy (i.e., it is the minimum rate that another investment should pay if they want to be competitive against the central bank by putting money in the bank instead of in any investment). The short-term rate is the only variable the central bank controls (as is the case in most countries in the world). Furthermore, the concatenation of the short-term interest rate will be the long-term rate. In summary, the short-term rate can be used for long-term modeling and recovery and post-recovery investments. In the long run, it is assumed that the variables tend to return to their steady state (long term equilibrium) position and furthermore, there should not be a difference between the interest rate of the central bank and any other interest rate of the economy.

Table A-1. Country-specific weighted average cost of capital by ownership type [29–31].

Country	Owner	WACC
United States	Public/Private	[5%;10.8%]
Chile	Private	11.30%
Indonesia	Public	5.75%
Egypt	Public	18.25%
Nigeria	Private	8.88%
Argentina	Public	91%
Thailand	Public	2%
India	Public/Private	[4.54%;6.5%]
Ukraine	Public	25%
South Africa	Public	8.25%

8.2. Appendix B – Labor Productivity Differences

As discussed in the main body, one limitation of the high-level translation of costs from the United States to NZW participants was that this did not account for granularity in the wages, and hour spent in construction. While changes in productivity will also have an impact on labor costs (countries with less productive construction labor will require more hours incurring more cost to complete the project) this is not entirely captured by the high-level cost estimation used here. However, productivity changes are partly captured in the index selected to normalize energy-specific construction between countries. Starting from the assumption that the price of a given good is the sum of the inputs used directly and indirectly in its production. The cost of commodities in each country (steel, cement, etc.) results from the capital productivity level in each industry, the cost of inputs for production plus the cost of workers' hours (wages). If cement is cheaper in country A, this would also indicate that the capital could be more productive, but it could also be because the wage paid there is lower, or the minimum wage is lower, or some other production input is cheaper, etc. In this sense, it becomes relevant to understand what could happen to the workers' wages.

It is possible to write the wage in one country as a function of four variables as follows:

$$Wage = f(labor\ skill, min\ wage\ policy, labor\ bargaining\ power, labor\ productivity)$$

Furthermore, it is not easy to differentiate and measure the effect of each of these variables on the final cost of a commodity. Based on the minimum wage, bargaining power and worker skills are relatively fixed in the short and medium run. For instance, governments are not changing minimum wage from year-to-year, they are not enacting laws giving more bargaining power to workers, and workers are not obtaining new qualification each year. It can be assumed that the change in cost year-to-year is due to productivity changes or because costs of a critical input used in the production process went down (for example, as a result of subsidized electricity or the use of strategic oil reserves that decrease oil price).

Differentiating the effects of variables on cost levels is only important when working with time series rather than a specific point in time. Higher productivity should be reflected in the lower production costs and lower market prices of the corresponding prices of inputs or final goods. Even when the hours worked are not considered, as this study is using monetary values (physical quantity times a price) and not only physical quantities, but the effect of productivity is also implicitly included. For instance, higher productivity (from labor and capital) relates to lower production costs of the commodities used directly and indirectly in the reactor's construction project. Furthermore, higher productivity could be reflected in lower monetary values. If a productivity effect is added, it will essentially be counted twice because the prices already reflect the productivity effect.

NET ZERO WORLD INITIATIVE

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This paper was authored at Idaho National Laboratory by Battelle Energy Alliance LLC under contract no. DE-AC07-05ID14517 with the US Department of Energy.

INL/RPT-23-74378 • January 2024