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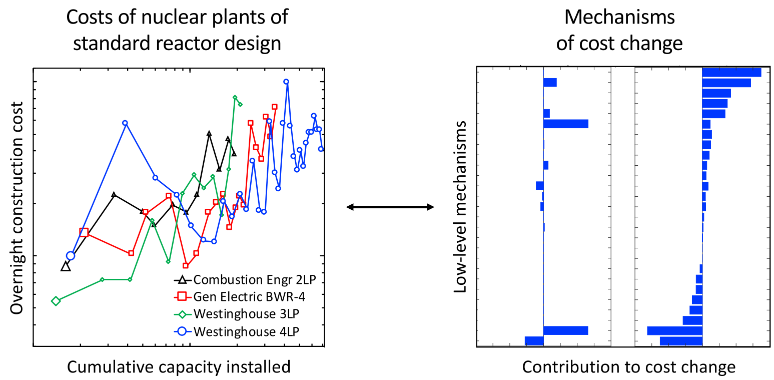

We study nuclear plant costs in the US over the past 5 decades to understand the mechanisms that contributed to cost escalation and the repeated underestimation of construction cost. We show that declining labor productivity and "soft" costs were leading contributors. Counter to expectation, nth-of-a-kind plants have been more expensive than first-of-a-kind plants. Our prospective analysis of the containment building suggests that the cost resilience of nuclear construction could be increased through improved materials and automation.

Philip Eash-Gates, Magdalena M. Klemun, Goksin Kavlak, James McNerney, Jacopo Buongiorno, Jessika E. Trancik

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HIGHLIGHTS

US nuclear plant cost estimation does not align with observed experience

"Indirect" expenses, largely soft costs, contributed a majority of the cost rise

Safety-related factors were important but not the only driver of cost increases

Mechanistic models inform innovation by relating engineering design to cost change

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Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design

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SUMMARY

Nuclear plant costs in the US have repeatedly exceeded projections. Here, we use data covering 5 decades and bottom-up cost modeling to identify the mechanisms behind this divergence. We observe that nth-of-a-kind plants have been more, not less, expensive than first-of-a-kind plants. "Soft" factors external to standardized reactor hardware, such as labor supervision, contributed over half of the cost rise from 1976 to 1987. Relatedly, containment building costs more than doubled from 1976 to 2017, due only in part to safety regulations. Labor productivity in recent plants is up to 13 times lower than industry expectations. Our results point to a gap between expected and realized costs stemming from low resilience to time- and site-dependent construction conditions. Prospective models suggest reducing commodity usage and automating construction to increase resilience. More generally, rethinking engineering design to relate design variables to cost change mechanisms could help deliver real-world cost reductions for technologies with demanding construction requirements.

Context & Scale

Nuclear power plants provide roughly half of the low-carbon electricity in the US. However, projections of nuclear plant costs have repeatedly failed to predict the cost overruns observed since the 1960s. We study the mechanisms that have contributed to the rise in nuclear construction costs over the past 5 decades to understand the divergence between expected and realized costs.

We find that nth-of-a-kind plants in the US have been more expensive than first-of-a-kind plants, with "soft" factors external to reactor hardware contributing over half of the cost increase between 1976 and 1987. Costs of the reactor containment building more than doubled, primarily due to declining on-site labor productivity. Productivity in recent US plants is up to 13 times lower than industry expectations. A prospective analysis of the containment building suggests that improved materials and automation could increase the resilience of nuclear construction costs to variable conditions.

INTRODUCTION

Nuclear power is often referenced as a potential solution for helping to reduce greenhouse gas emissions from electricity generation and industrial process heating, as required to achieve net zero emissions (e.g., Davis et al.,[1] Buongiorno et al.,[2] Energy Advisory Board,[3] and Deutch et al.[4]). Although concerns about safety and waste management can affect the public acceptance of nuclear power plants,[5,6] and long-term waste management solutions are still in development,[7,8] nuclear power's life-cycle emissions are comparable to other low-carbon options such as solar and wind energy,[9] and nuclear power has the ability to supply base-load and load-following electricity, relies on significant uranium resources, and shows low fuel price volatility and operating costs compared to fossil fuel-fired power plants.[10,11]

The US plays an important role in the global nuclear industry in several ways. The US pioneered the technology in the 1950s for naval submarine use and to this day generates more electricity in nuclear plants than the three next leading countries combined: France, China, and Russia.[12] US federal investment in nuclear research and development is the second highest among International Energy Agency member countries,[13] and international cost estimating guidelines are based heavily upon US reactor design and construction practices (e.g., the work of the Economic Modeling Working Group of the Generation IV International Forum[14]).

However, the history of nuclear energy in the US is one of mixed results. Rapid capacity growth in the 1960s was accompanied by significant unit upscaling, followed by operational improvements and rising capacity factors.[15] But in the 1970s, rising project durations and costs, alongside studies on thermal pollution and low-level radiation, became a source of public controversy.[16] Following the 1979 Three Mile Island accident, a long hiatus of nuclear construction began. Rising construction costs and project delays have continued to affect efforts to expand nuclear capacity in the US since the 1970s.[17–19] A survey of plants begun after 1970 shows an average overnight cost overrun of 241%.[19] Since the 1990s, two nuclear projects have begun construction, both two-reactor expansions of existing generating stations. The VC Summer project in South Carolina was abandoned in 2017 with sunk costs of $9B, and the Vogtle project in Georgia is severely delayed. Current estimates place the total price of the Vogtle expansion at $25B ($11,000/kW), almost twice as high as the initial estimate of $14B, and costs are anticipated to rise further.[20,21]

Challenges in nuclear construction are not unique to the US. Recent projects in Finland (Olkiluoto 3) and France (Flamanville 3) have also experienced cost escalation, cost overrun, and schedule delays.[22] Cost estimates for a plant under construction in the United Kingdom (Hinkley Point C) have been revised upward.[23] In contrast to the experience in Western Europe and the US, however, China, Japan, and South Korea have achieved construction durations shorter than the global median since 1990.[2,24,25] Cost and construction duration tend to correlate (e.g., Lovering et al.[26]), but it should be noted that cost data from these countries are largely missing or are not independently verified.[27,28] (Cost data should be provided and audited by entities not actively involved in plant procurement and construction, including data from international organizations or government agencies as opposed to data from utilities and reactor equipment providers.)

Despite historical precedence for rising costs, nuclear industry, government, and research agencies continue to forecast cost reductions in nuclear construction.[14,29–33] These entities make significant investments in the development and commercialization of next-generation reactor designs based on the expectation that successive plants of standard design will cost less than first-of-a-kind plants.[2,14,34–36] This notion is applied to all commercial reactors, though the anticipated cost reductions are greatest for small modular reactors (SMRs) due to expected learning effects in factory settings.[32,37,38] The first SMR has yet to be built.

The projected role of nuclear power in many decarbonization scenarios (e.g., Iyer et al.[39] and the Intergovernmental Panel on Climate Change[40]) also stands in contrast to recent trends. In the US, nuclear power plants provided roughly 20% of the electricity supply in 2019, down from a reported peak of 23% in 1995, and roughly 50% of low-carbon electricity,[41,42] though the exact reported values show a small amount of variation.[43] Low-cost domestic natural gas supply and declining costs of renewable power have put several plants at risk of premature retirement, and equipment replacements to extend plant lifetimes have proven challenging.[44] Four US plants have shut down despite possible license extensions, and closure of 15–20 more plants is expected by 2030.[45] Other countries with aging nuclear infrastructure (e.g., Spain and the UK) are facing similar challenges.[25]

Previous literature has presented various hypotheses on the causes of nuclear construction cost increases. These studies fall into two groups: (1) studies of nuclear technology cost trends over time; (2) engineering cost models of nuclear power

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plants for a given design, at a given point in time. By studying time series of overnight capital costs, studies in the first group have shown that nuclear costs in the US have increased before and after Three Mile Island,[15] cost trends differ across countries,[26,46] and construction costs have increased even in countries with comparatively short construction times.[47] Previous work has reported cost reductions when the same firm built multiple plants of the same model in France,[48] and stable costs in Japan between 1980 and 2011, owing among other factors to supportive national policies.[46] Overall, the majority of studies document construction cost increases and conclude that the nuclear experience has been one of limited or even negative cost-related learning.[15,47,49–51]

Cost increases have been associated with reactor upscaling, a lack of technology standardization, fragmented industry structure and plant ownership, and increasing plant complexity including increases in the number of plant components, new control systems, redundancy in equipment, and added safety features.[17,47,52,53] Studies of cost escalation in mega-projects more broadly have found that nuclear power plant projects exhibit greater and more frequent cost overruns and delays compared to other electricity generation infrastructure, which has been linked to reduced modularity and more complex project governance compared to other technologies.[54,55]

By developing engineering cost models of nuclear reactors and plants, studies have provided cost benchmarks for plant construction in the US[56–63] and other countries (e.g., Harris et al.[64]). Other, forward-looking studies have outlined strategies for cost reduction, such as modularization, off-site manufacturing, passive cooling, and advanced construction materials.[2,33,35,65] However, the focus of these studies has been on aggregated cost measures such as total construction costs, which are important for comparing technologies but can mask the contribution of specific technological developments, such as changes in engineering design or labor productivity, to cost change over time. Studies estimating these contributions based on empirical data are currently absent from the literature.

Both bottom-up engineering and top down models are also used to develop standards for estimating individual nuclear plant costs[36,66] or forecasting costs of specific reactor technologies.[14,31,32,35] In response to cost uncertainty, such guidelines have been developed to minimize financial risk and provide consistent comparison among available technologies. Similarly, cost estimating guidelines are used in models for projecting industry-wide growth and cost change at a national or global scale across nuclear and non-nuclear energy technologies,[67,68] and in global planning for climate change mitigation.[40,69] Although cost estimating guidelines used in these studies generally assume that costs will decline with experience, empirical trends of nuclear construction indicate that costs have escalated as industry experience has grown.[15,47,49–51] Studies that test the validity of modeling assumptions against empirical evidence are currently largely missing.

In this paper we begin to address these gaps by examining US construction cost data from five decades and modeling the cost evolution of entire plants and of one major plant component, the reactor containment building. We present a collection of insights on cost trends and the sources of these trends. Contrary to standard engineering estimates for expected cost declines, we find that costs have instead risen in the US, even for plants of the same design class. This specific finding is missing in previous literature. Next, we examine what types of costs contributed most to cost increases, using cost accounting data on individual plant components and mechanistic models of cost change determinants. We find that declining labor productivity and increasing commodity use were major contributors to cost increases. Overall, a common theme emerging from this analysis is the lack of anticipation in engineering models of the cost-increasing contributions of soft technology external to standard reactor hardware, in response to changing regulations and other factors such as variable project-specific conditions. Prospective modeling shows the potentially transformative effect of rethinking engineering design to adapt to these factors, for example through reduced commodity usage and the automation of some construction processes.

RESULTS

Rising Costs of Standard Plant Designs

Many nuclear power plant cost projections and estimating guidelines assume that costs will decline as more plants are built. Such projections are frequently stated in terms of the costs of an nth-of-a-kind (NOAK) plant relative to a first-of-a-kind (FOAK) plant. That NOAK plants will be less expensive than FOAK plants is often posed as a "well-known fact" (e.g., Buongiorno et al.[2] and Carelli et al.[35]), and this assumption is reflected in a large number of projections and estimating guidelines. Cost reductions are typically expressed in terms of technology learning rates, in which technology costs are fit to a power law $C \sim x^{-b}$, where x is the cumulative production of the technology. The learning rate LR is given by LR = $100(1 - 2^{-b})$, and represents the percent cost reduction associated with a doubling of cumulative production under this model. A positive learning rate corresponds to cost reduction. Due to their wide use, learning rates provide a convenient benchmark to compare estimated rates of cost reduction across studies. In its cost guidelines for advanced reactors, for example, Oak Ridge National Laboratory[36,66] recommends that labor costs be projected with a learning rate of 2% and equipment costs with a learning rate of 6% for NOAK reactors of any standard design with more than 4.5 GW_e of cumulative capacity installed. The Economics Modeling Working Group (EMWG) of the Generation IV International Forum[14] establish a guideline of 6% total cost reduction with every doubling of cumulative capacity after 8 GW_e. The academic and scientific communities often use similar learning rates to assess the role of nuclear power in future energy strategies and greenhouse gas mitigation scenarios (e.g., Sepulveda et al.[70]). Published estimates range from 1% to 10%, with SMRs at the upper end (e.g., Abdulla et al.[32]) due to expected cost benefits of factory fabrication. The emissions scenarios behind IPCC climate modeling have relied on nuclear learning rates between 1% and 7%, while global scenarios of the International Atomic Energy Agency (IAEA) have assumed higher learning rates.[31,40,69]

The prevalence and specificity of such projections may be a reason why nuclear plants are commonly assumed to fall in cost as more are built. Another possible reason, however, is that historical studies have typically aggregated across different plant types, while engineering projections focus on the cost trajectories of individual plant technologies. In principle, some plant designs could have realized declining costs, which are obscured by averages across designs. If so, such cases could provide a historical basis for the widespread projections of declining costs. We target this issue here, examining the cost trajectories of individual standard plant designs using historical data from the US (Figure 1).

We first examine the overnight cost of construction of 107 nuclear plants from across the US nuclear experience (Figure 1A). Similar curves are shown in Grubler,[47] Koomey and Hultman,[15] Cooper,[50] and Lang.[71] Echoing previous findings,[15,47,49–51] we see that costs rose rapidly. We estimate a learning rate of −115% for the industry, implying that plant costs more than doubled with each doubling of cumulative US

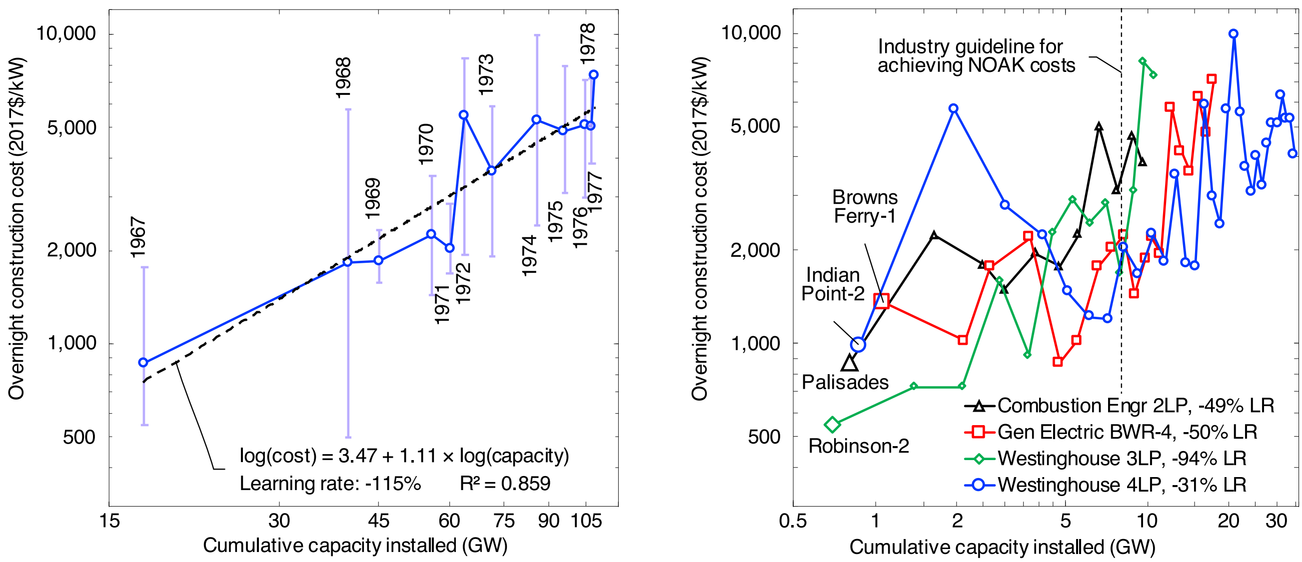

Figure 1. US Nuclear Construction Costs

(A) Average overnight cost of plants with construction beginning in each year from 1967 to 1978. Vertical bars give the minimum and maximum construction cost in each year. The dashed line is an OLS regression fit and its slope corresponds to a learning rate of −115%.

(B) Overnight cost of individual plants for all four standard plant designs that reached a cumulative built capacity of 8GWe (indicated by the dashed vertical line), a threshold at which cost guidelines expect plants to realize NOAK cost reductions.[14] Each marker represents one plant of a particular design, and the first marker of each series shows the FOAK plant of a given design. OLS fits were made to the data for each plant design, from which the learning rates shown were computed.

capacity. Nevertheless, the costs in Figure 1A are averages across plants of all reactor designs. It is possible that the rise in the average cost hides trends of decreasing costs in particular reactor designs. To see whether this is the case, we split out the cost trajectories of several reactor designs. We examine the cost trajectories of all four standard reactor designs that exceeded 8GW$_e$ of installed capacity in the US, corresponding to the conditions under which the EMWG guidelines project cost reductions. However, even after disaggregating, construction costs rose across all four designs as more plants were built. In fact, the FOAK plant was the least expensive in three of the four cases and was among the least expensive plants in the fourth.

Next, we examine the assumption of model-specific cost reduction, plotting experience curves separately for each prominent technology class in Figure 1B. Although the rapid rise in costs across all nuclear plants is well known, the assumption that cost reductions may still have occurred for particular classes of plants persists. The practice of including cost data from all reactor types may contribute to this, as historical reports of construction costs (e.g., analysis of nuclear power plant construction costs[19] and nuclear power plant construction activity[72]) and previous publications[15,26,47,50,67,68] lack information on reactor type. The study of Berthelemy and Rangel[48] is the only one we find that quantifies the cost effect of model standardization. Their results show that standardization decreased cost in the US and France, while design innovation increased construction costs.

Thus, NOAK cost reductions are far from being a certain consequence of repeatedly building a given design. In the analyses that follow we further examine the reasons why. We note that plants of a given design are subject to the same idiosyncratic effects affecting other plants. Although these plants are based on the same reactor

Table 1. Nuclear Learning Rates

Approach	Study	Reactor Models[a]	Market	Time Period[b]	Learning Rate	Data Source
Empirical	this work	various	US	1971–1996	−115%	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	this work	standard	US	1971–1996	−56%[c]	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	this work	standard, CE 2LP	US	1971–1985	−49%	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	this work	standard, GE BWR-4	US	1972–1990	−50%	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	this work	standard, WH 3LP	US	1971–1987	−94%	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	this work	standard, WH 4LP	US	1973–1996	−31%	Koomey and Hultman,[15] EIA1985,[72] EIA1986,[19] PRIS Plants (2018)[24]
Empirical	Cooper, 2010[50]	various	US	1971–1996	Negative	[d]
Empirical	Rubin et al., 2015[51]	various	US, France	1971–1996	−38%	Grubler, 2010[47]
Empirical	Lang, 2017[71]	various	US	1970–1996[e]	−102%	Lovering et al., 2016[26]
Empirical	Lang, 2017[71]	various	world	1970–2015[e]	−23%	Lovering et al., 2016[26]
Cost guideline	ORNL[36,66]	standard, advanced	US	1989–	6%/2%[f]	[d]
Cost guideline	EMWG[14]	standard, advanced	US→world[g]	2007–	6%	[d]
Future growth[h]	McDonald and Schrattenholzer[68]	various	world	1975–1993	6%	Kouvaritakis et al., 2000[67,i]
Future growth	Abdulla et al.[32]	standard, SMR	US→world[g]	2012–	10%[i]	expert elicitation
Future growth	IPCC[69]	various, advanced	world	2000–2100	4%–7%[j]	[d]
Future growth	IPCC[40]	various, conventional	world	1990–2100	1%–5%[k]	[d]
Future growth	IAEA[31]	various, advanced	world	2000–2100	7%–10%[k]	[d]

[a]CE, combustion engineering; GE, General Electric; WH, Westinghouse; BWR, boiling water reactor; LP, loop; SMR, small modular reactor.
[b]Based upon first year of commercial operation.
[c]Mean value of four US standard designs. Median value is –50%.
[d]Does not disclose a data source.
[e]We omit the result for an earlier period, which includes turnkey project prices that do not reflect actual costs.
[f]Equipment and labor, respectively.
[g]The US industry is the basis for this study, but findings are applied globally.
[h]Often cited as empirical, this study instead reports assumed learning rates.[73–75]
[i]Expert responses ranged from 0%–1% to 15%–20%, with 10% as the median.
[j]Based upon climate stabilization scenarios of the IPCC Climate Change Synthesis Report[69] as studied by Azevedo et al.[76]
[k]Based upon scenario A1T of the IPCC Special Report on Emission Scenarios[40] as studied by IAEA.[31]

model, they are not identical, and design differences in other aspects of plant design or construction may have mattered more than expected, contributing to unexpected cost increases. We return to this possibility in the analyses that follow. A summary of the various learning rates in historical and prospective studies is given in Table 1, and it shows the disparity between empirical estimates and projections.

Sources of Cost Change in Nuclear Plant Construction

To shed light on the causes of cost escalation, we decompose overnight construction into its cost components, beginning with the period 1976–1987, for which we have reliable cost data on all components of a Westinghouse four-loop plant.[56,57,59,60,63] We examine the contributions of 61 different cost accounts from the Department of Energy's Energy Economic Data Base (EEDB) to cost increases. These accounts, shown as c_i in Equation 1 below, represent individual plant components and services needed to install these components. Q_E is the electrical output capacity of the plant.

$$C_{total}\left(\frac{\$}{W_e}\right) = \frac{1}{Q_E}\sum_{i=1}^{61} c_i \quad \text{(Equation 1)}$$

The contribution of an individual account, c_i, to total plant cost change is calculated in Equation 2 below:

$$\Delta c_i = \frac{c_{i,2} - c_{i,1}}{\sum_{i=1}^{61} c_{i,2} - \sum_{i=1}^{61} c_{i,1}} \quad \text{(Equation 2)}$$

where $c_{i,1}$ and $c_{i,2}$ represent the cost of account i in periods 1 and 2, respectively.

Figure 2 depicts the effects of the most important accounts, and Supplemental Information Section S2 provides a full listing of the 61 cost accounts. The overall trend is cost increase, with few accounts experiencing minor cost decline, suggesting that any positive learning effects are outweighed by other factors. Further, a diversity of accounts contributes to the total cost escalation, indicating that the cause cannot be easily attributed to any one source. However, grouping accounts into direct and indirect categories, we identify that changes in indirect expenses were the greatest. Indirect costs consist of construction support activities such as engineering, administration, construction services, construction management, field supervision, startup, and testing.[77] Direct costs are the costs of materials, labor, and equipment needed for physical components like the plant reactor, structures, control and monitoring systems, and assemblies.[77]

Indirect costs caused most (72%) of the cost increase during period 1 (1976–1987), in particular the indirect expenses incurred by home office engineering services (engineering design, purchasing and expediting, estimating and cost control, planning, and scheduling), field job supervision (salaries and relocation expenses), temporary construction facilities (materials and labor to construct and manage temporary buildings needed during construction), and payroll insurance and taxes. A majority of these costs are not hardware related and are rather ‘‘soft’’ costs.

But why did indirect costs rise so dramatically, while the modeled reactor design (Westinghouse 4-loop) remained the same? The literature presents many hypotheses, but little quantitative evidence. The account from EEDB[63] in 1988, the last year the database was updated, suggests a multitude of causes: proliferation of safety regulations, codes, and standards; owner/designer reaction to the rapid appearance of these regulations, codes, and standards; rework caused by field interferences, constantly changing designs in response to new requirements, and inadequate engineering-to-construction lead times; extreme precision required in analyses, coupled with inflexible design and construction quality assurance requirements; management preoccupation with regulatory inspection, enforcement personnel site visits, and prudency reviews; and low worker morale, caused by all of the above.

To quantify which aspects of the technology were most responsible for the rise in indirect expenses, we delve further into the EEDB model and attribute indirect costs to plant components. We estimate the amount of indirect costs incurred by each direct cost component by aggregating the indirect expenses into cost ‘‘bases,’’ B_ω, according to the construction inputs that incur them: site labor, materials, factory equipment, and safety-related components. We assume each direct account is responsible for a share of the indirect costs base that is the proportion of its construction inputs to the total construction inputs for each input category, ω. For instance, indirect costs incurred by the fuel storage building are proportional to the ratio of fuel storage labor, material,

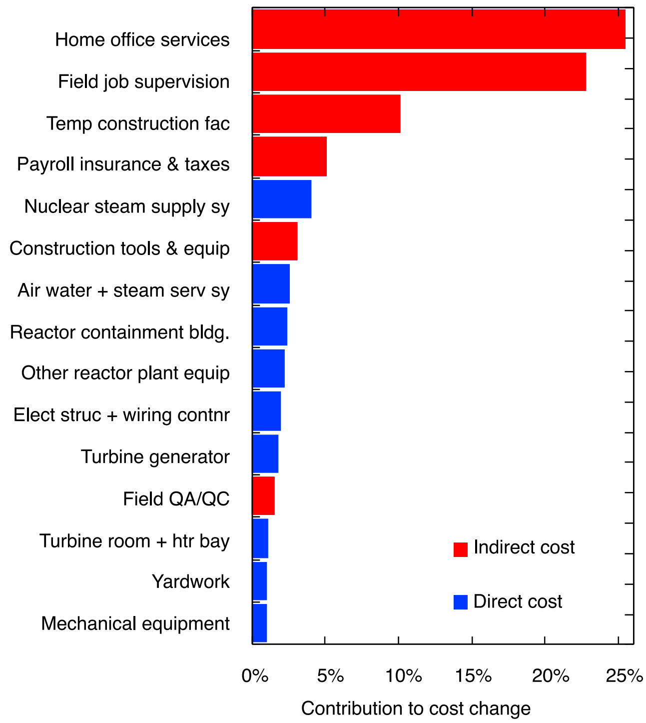

Figure 2. Nuclear Plant Cost Change, 1976–1987

Indirect cost accounts comprise 72% of the total cost change. The four largest contributors to cost increase are indirect accounts, many of which are "soft" costs: home office engineering services (engineering design, purchasing and expediting, cost control, and planning and scheduling), field job supervision (salaries and relocation expenses), temporary construction facilities (materials and labor to construct and manage buildings needed during construction), and payroll insurance and taxes. Only accounts with a cost change contribution exceeding 1% are included (see Figure S1 in the Supplemental Information for a full list of accounts). Interest during construction is excluded. Direct costs are the costs of materials, labor, and equipment. Indirect costs include construction support activities. Abbreviations: Bldg, building; Contnr, container; Htr, heater; Fac, facilities; QA/QC, quality assurance and control; Struc, structure; Serv, service; Equip, equipment; Sy, system; Temp, temporary.

equipment, and safety-related costs to total plant costs in these four categories. The total indirect cost incurred by an account, Z_i, then, is the sum of the products of each account's share and the indirect cost base for each cost category:

$$Z_i = \sum_{\omega} \frac{C_{i\omega}}{\sum_i C_{i\omega}} B_{\omega} \quad \text{(Equation 3)}$$

We assume that the ratio of indirect to direct costs is constant within each of the four input categories across all accounts, mimicking the methods used in EEDB. A complete description of the method and our assumptions is provided in Supplemental Information, Section S3.

Figure 3 shows the results of redistributing indirect costs to individual plant components. These are rough estimates based on the assumptions outlined above, in line with an expectation that components with more and longer installation steps are more labor intensive and also require more engineering and construction supervision to ensure compliance with standards, including safety standards. Using this estimation method, the three plant components most influential in causing indirect cost change—the nuclear steam supply system (NSSS), the turbine generator, and the containment building—also contributed heavily to direct cost increase.

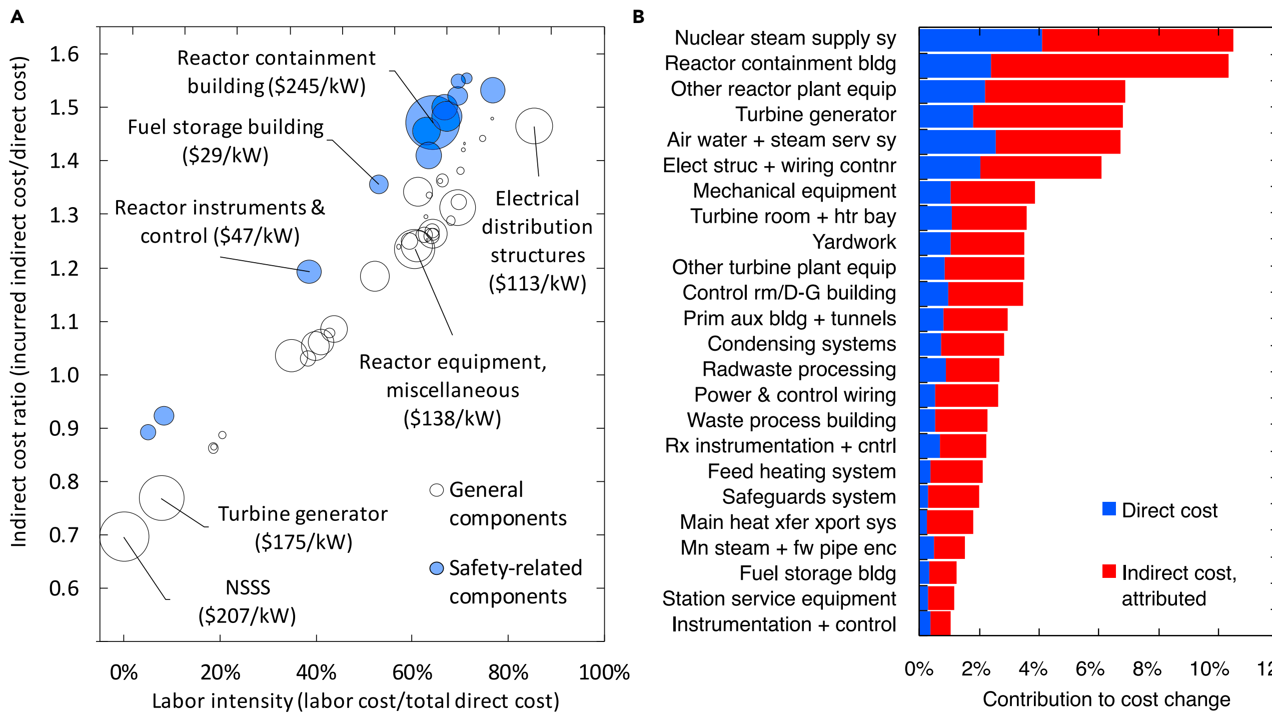

Figure 3. Nuclear Plant Indirect Costs, 1987, and Cost Change, 1976–1987

(A) Attribution of indirect expenses to the direct cost accounts that incur them reveals that labor-intensive components and safety-related components represent a disproportionately large share of indirect expenses relative to their cost. The containment building incurs more indirect expenses than any other component. Results are shown for year 1987, though are similar in 1976.

(B) Indirect cost accounts comprise 72% of the total cost change between 1976 and 1987. The containment building is responsible for the largest share of cost change due to indirect expenses. Only accounts with a cost change contribution exceeding 1% are included. Interest during construction is excluded.

Abbreviations: Sy, system; Bldg, building; Equip, equipment; Serv, service; Rm, room; Prim, primary; Aux, auxiliary; Xfer, transfer; Xport, export; Rx, reactor; D-G, diesel generator; Mn, main; Fw, feedwater; Enc, enclosure; Contnr, container; Htr, heater; Fac, facilities; Struc, structure; Temp, temporary.

Recognition of the cost interdependence of direct and indirect accounts motivates going beyond these simplified assumptions in our subsequent analysis of the technical and economic mechanisms of cost change. In Sources of Cost Change in Nuclear Plant Construction, we focus on direct containment building costs in further decomposing cost changes into underlying engineering choices and productivity trends because we can model these costs using historical and recent design drawings. Further, the containment building is one of the most expensive components and a component with significant safety requirements. The use of design drawings enables us to extend our analysis from the historical period 1 (1976–1987) to the year 2017. We also discuss why the main conclusions we draw hold for total containment costs, not just indirect costs, using the indirect cost data currently available, while acknowledging uncertainties.

Sources of Cost Change in Containment Buildings

In this section, we further examine mechanisms that led to increases in cost components discussed in Sources of Cost Change in Nuclear Plant Construction, using a case study of the containment building. Containment buildings are airtight steel and concrete structures that form the outermost layer of a nuclear reactor. They are designed to prevent the escape of radioactive gases or materials during accidents, to protect the reactor against missile and aircraft impacts, and to provide structural support for the nuclear steam supply system. We focus on the containment building for two reasons: (1) as the largest safety-grade structure of a nuclear power plant, the containment building constitutes a useful lens to study field construction challenges and changing safety paradigms that also affect other plant components; (2) as a symmetric structure with comparatively simple geometry, design parameters can be more easily extracted from publicly available design drawings than for other components.

Our cost model separately accounts for material and labor costs to construct the foundation, shell, and dome of the containment. We write total containment construction costs as

$$C_{containment}\left(\frac{\$}{W_e}\right) = C_{foundation} + C_{shell} + C_{dome}. \qquad \text{(Equation 4)}$$

We focus on steel, rebar, and concrete and omit other, less costly materials used for formwork (see Section S4 for model details).

To study the effects of labor productivity trends on costs, we develop a model with deployment rates of construction materials as variables. For structures made of materials i, this deployment rate is the ratio of material volumes V_i to the quantity of labor (in person-hours) needed to deploy these volumes, τ_i: $v_i = \frac{V_i}{\tau_i}$. This choice results in an equation for direct construction costs of the form shown in Equation 5, where costs are a sum of products of structure volumes V_i, material prices p_i, volumetric material fractions f_i, and per-volume labor costs $(\frac{w_i}{v_i})$:

$$C_{containment}\left(\frac{\$}{W_e}\right) = \sum_{i=1}^{3} \frac{V_i}{Q_E}\left(f_i p_i + \frac{w_i}{v_i}\right). \qquad \text{(Equation 5)}$$

In Section S5, we use a simple expansion of this model to estimate indirect containment costs and to draw conclusions about overall plant construction costs.

We select two periods of study to align with major shifts in US nuclear construction. 1976 to 1987 (period 1) was a period characterized by changing public opinion, rising nuclear regulations, and the events surrounding the Three Mile Island accident. The period from 1987 to 2017 (period 2) has been one of protracted construction periods, the development of new generations of reactor design, a long hiatus in nuclear project development, and an attempt to revive the nuclear industry.

Populating our cost model with values from these periods, we can ask how much each variable contributed to the cost increase of the containment building. Even with a cost model in hand, attributing cost increases to particular variables is non-trivial. Drawing on a recently developed method,[78] we model the cost of a technology as a sum over a set of cost components, $C(\vec{r}) = \sum_i C_i(\vec{r})$, each of which is a multiplicatively separable function $C_i(\vec{r}) = \prod_y g_{iy}(r_y)$ of cost-determining variables $\vec{r}$. The elements of the vector $\vec{r}$ can include prices, design parameters, and other characteristics that affect the cost of a technology. This method results in estimates of the contributions ΔC_y of each variable to cost change between two periods t_1 and t_2, given by

$$\Delta C_y \approx \sum_i \tilde{C}_i ln\left(\frac{g_{iy}\left(r_y^2\right)}{g_{iy}\left(r_y^1\right)}\right), \qquad \text{(Equation 6)}$$

where r_y^1 and r_y^2 are the values of the yth variable in periods t_1 and t_2, and $\tilde{C}_i$ is the logarithmic mean of the ith cost component over the two periods. We refer to changes in the variables $\vec{r}$ as low-level mechanisms of cost change.

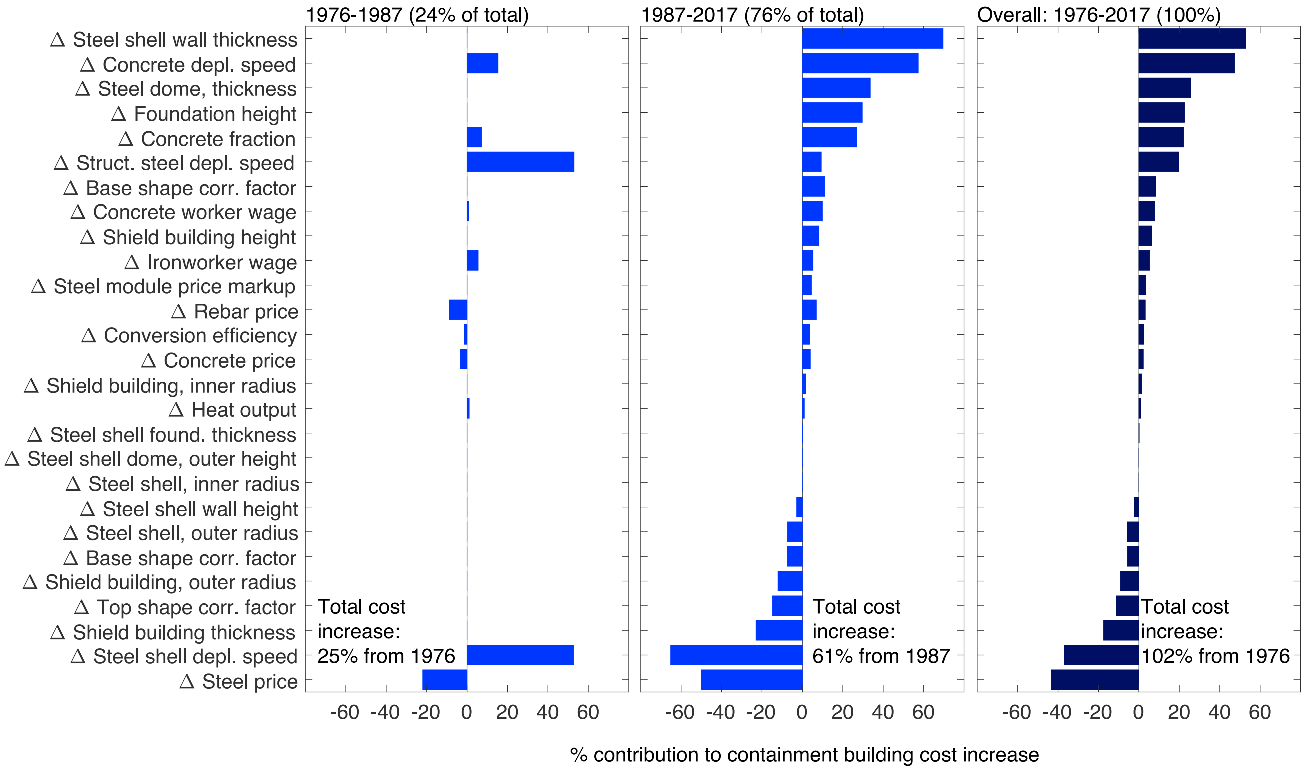

Figure 4. Percentage Contributions of Containment Building Low-Level Mechanisms

Contributions to the increase in direct containment costs during period 1 (1976–1987, left), during period 2 (1987–2017, middle), and during both time periods (1976–2017, right) are listed in the order of their contributions to total cost increase during the 1976–2017 period. Period 1 caused 24% of total containment cost increase over the 1976–2017 period, while period 2 caused 76% (total refers to the sum of all mechanisms shown as bars above). Shape correction factors ("corr. factors") account for the change in containment design and geometry in time period 2. The full set of variable names is given in Supplemental Information Table S1. Shape correction factors are explained in Supplemental section S4.

As shown in Figures 4 and 5, some low-level mechanisms were significantly more influential for cost increase than others. These mechanisms include changes in material deployment rates, structure thicknesses, and steel prices. However, the importance of these mechanisms changed over time. During period 1 (1976–1987), the design of the containment structure stayed the same, and cost increase was caused primarily by declining deployment rates. Although concrete and steel worker productivity declined by comparable amounts (−40% for steel, −50% for concrete during the 1976–1987 period), steel worker productivity made a larger contribution to cost increase due to the higher wage paid to steel workers. We study nuclear productivity decline in more detail in Further Evaluation of Construction Productivity Changes.

During period 2 (1987–2017), a new containment design was adopted by Westinghouse (the AP-1000), and the resulting changes to dimensions, material usage, and labor needs drove cost increase. The switch from active to passive cooling, a design that reduces the need for operator intervention during emergencies by taking advantage of natural forces, required the separation of the steel liner from the concrete shield building. This change enabled natural air convection between the two layers but also required thicker structures since layers previously acting together to resist external and internal forces now needed to hold up independently.[79–81] The thickness of the steel shell, which was five times greater in 2017 as it was in 1987, made the single largest contribution to cost increase (70%). Period 2 caused the majority of cost increase (80%) during the 1976–2017 period.

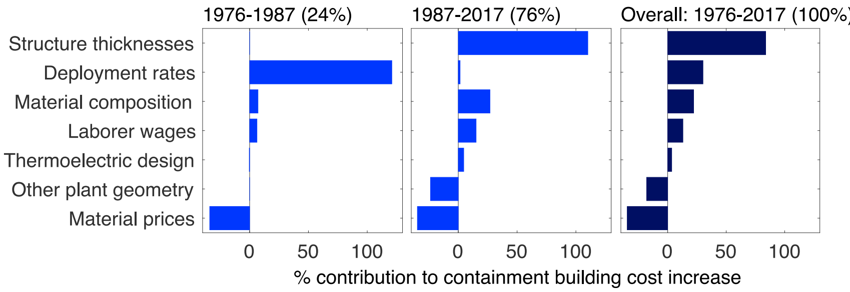

Figure 5. Aggregations of the Percentage Contributions Shown in Figure 4 according to Variable Types

"Structure thicknesses" account for the contributions of changing thicknesses of steel and concrete layers, "deployment rates" account for changing steel and concrete deployment rates, "material composition" represents the changing concrete fraction in reinforced concrete, "wages" include changing labor rates for steel and concrete workers. "Thermoelectric design" accounts for changes in the thermal power output and the efficiency of the plant, "other plant geometry" accounts for the changing geometry of the containment building (see shape correction factors in Figure 4), and "material prices" account for changing concrete and steel prices. Variable types are listed in the order of their contributions to total cost change over the 1976–2017 period.

Our results illustrate trade-offs that can result from innovations that affect many variables simultaneously. Switching to a free-standing containment steel vessel in period 2 allowed the use of cheaper steel, as well as more rapid steel shell deployment, but the cost-reducing effect of these changes was offset by increasing structure thicknesses and the resulting higher material and labor costs. Avoiding a cost increase over the 1987–2017 period despite increased commodity use would have required massive improvements in labor productivity (a 10-fold increase in steel and rebar deployment rates, over the 1987–2017 period). While our analysis of direct cost change in containment buildings covers only 3%–4% of total plant costs in 1976 and 1987, the costs of civil works in sum account for 30%–50% of total nuclear power plant costs.[2] The conclusions drawn from this case study—e.g., on the effects of increased commodity usage—can, therefore, add insight on drivers of cost change in other field-constructed plant components such as spent fuel handling buildings, turbine generator buildings, and cooling towers.

Contrary to the years 1976 and 1987 we do not have information on total indirect costs in 2017 because the Vogtle plant is still under construction. We exclude indirect containment costs in Figure 4 but examine the effects of currently available indirect cost data on total containment cost change in Section S5. Although total containment costs depend sensitively on assumptions regarding indirect costs, mechanisms that are influential for direct containment cost change also tend to be influential for total containment cost change. Deployment rates are slightly more important because they affect a larger fraction of total costs. Commodity prices become less influential. We explore the effects of data uncertainties using a sensitivity analysis (see Section S6). Cost change results are most sensitive to uncertainties in variables related to the use of steel, but our major conclusions are unaffected by these uncertainties.

Further Evaluation of Construction Productivity Changes

In Sources of Cost Change in Containment Buildings, we find that declining construction productivity was a major source of containment building cost increase in period 1 (1976–1987). Here, we further analyze the factors leading to this decline. Previous work points to a general decrease in US construction productivity during the period[2,19] but has not looked at the nuclear industry specifically.

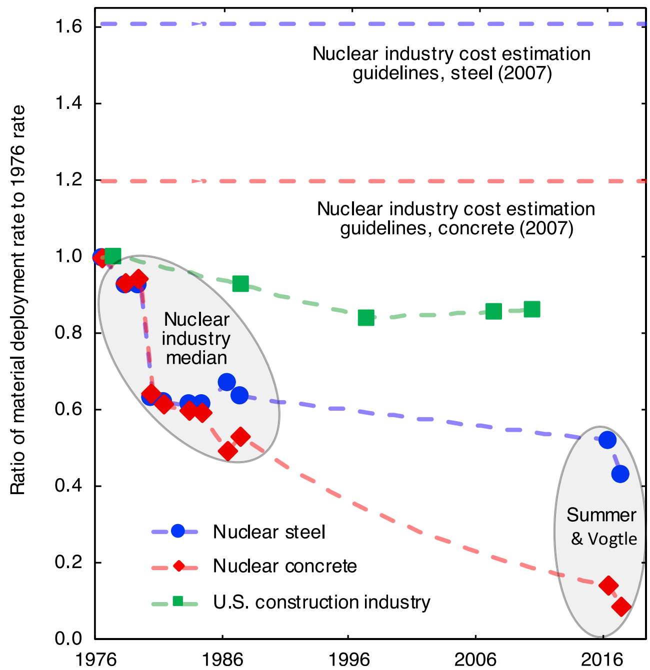

Figure 6. Historical Construction Productivity Change in the Nuclear Industry and at Large

Material deployment rates are normalized to their distinct 1976 values (and nuclear and non-nuclear productivity are not equal in 1976). Nuclear productivity declined sharply in association with the Three Mile Island accident and has decreased further in the decades following. Deployment rates used in cost estimating[14] are disjoint from the last five decades of experience. Data are derived from EEDB,[56–63] recent engineering reports from the VC Summer and Vogtle projects,[82,83] and the U.S. Bureau of Labor Statistics.[106]

To study this, we look at the evolution of material deployment rates in nuclear construction, a measure of labor productivity in terms of material installed per unit of labor (e.g., m^3/person-hour). Using data from EEDB reports[56–63] and recent AP1000 engineering construction reports,[82,83] we compute the ratio of the volume of materials (steel or concrete) installed to the total hours of labor needed for installation. We compare these deployment rates with two benchmarks: an index of material deployment rates in the construction industry as a whole and deployment rates assumed in nuclear industry cost estimation guidelines.

Material deployment rates in the construction industry decreased over the period of study, falling about 14%, as shown in Figure 6. Nevertheless, deployment rates in nuclear construction declined more dramatically, with a precipitous drop between 1979 and 1980 following the Three Mile Island accident. Compared with the construction industry at large, nuclear deployment rates declined five to six times more quickly. This productivity decline was a primary cause of nuclear cost increase. Labor interviews provide insight into some of the causes of declining productivity,[84] pointing to problems experienced in the field. Craft laborers, for example, were unproductive during 75% of scheduled working hours, primarily due to construction management and workflow issues, including lack of material and tool availability, overcrowded work areas, and scheduling conflicts between crews of different trades.

Material deployment rates in the US nuclear industry have been considerably lower than those assumed by the industry for cost estimation purposes (e.g., EMWG[14]). Industry average rates in the post-Three Mile Island period were two to three times

Table 2. High-Level Mechanisms and Abbreviations

High-Level Mechanisms	Abbreviation
Research and development	R&D
Process interference, safety	PIS
Worsening despite doing	WDD
Other	Other

slower for steel and concrete. More recently, rates at the Vogtle and VC Summer project sites have been three to four times slower for steel, and eight to thirteen times slower for concrete. This disparity between projections of productivity and actual experience has contributed significantly to cost overruns.

These trends are observed despite recent efforts to improve productivity through modular design. Instead of using standard reinforced concrete, which is constructed on-site using elaborate formwork, the shield building in the AP-1000 is comprised prefabricated steel-plate composite (SC) modules. SC modules have two steel layers and tie bars that act as concrete reinforcement, reducing the time needed for formwork and rebar placement.[85] Smaller modules are assembled into larger modules on-site and then lifted into place. However, placement is only one of many steps needed to install a module, which also involves welding, piping, cabling, and other tasks.

Although SC modules were used in two major structures on the AP-1000 nuclear island (the containment and auxiliary buildings), the effect of modular construction on the average steel deployment rate across the nuclear island was not enough to raise productivity over previous years. Skills and training gaps, and the extra steps needed for quality control of the modules, are among the possible causes of low productivity.

High-Level Mechanisms of Containment Building Cost Change

What were the higher-level human activities and strategies behind the low-level mechanisms of cost change discussed in Sources of Cost Change in Containment Buildings and Further Evaluation of Construction Productivity Changes? A common view is that safety regulations have increased the costs of nuclear power plant construction.[2,4,49,86,87] Here, we consider this view alongside other drivers by estimating the role of different activities in changing costs. To do this we attribute changes in the variables in our cost model (low-level mechanisms) to higher-order processes that likely caused these changes (high-level mechanisms, see Table 2).[78]

We assign changes that require significant modifications of the containment building design and construction process to the mechanism "research and development (R&D)." While construction projects are inherently site specific, and on-site adjustments are common, the mechanism R&D accounts for more fundamental changes that require longer-term, off-site activities. For example, changing the design by separating the steel liner and concrete shield building required years of R&D by Westinghouse, as indicated by patents and journal papers from the 1970–2017 period (Table S3).

We define three additional high-level mechanisms to account for changes driven by non-R&D-related processes. The first mechanism, "Process interference, safety (PIS)," represents the effects of on-site NRC and other safety-related personnel on the construction process. Construction supervision, quality assurance and control by NRC regulators can interfere with construction workflows and slow productivity (see Table S6).

The second additional high-level mechanism represents decreases in the performance of construction workers. We refer to this mechanism as "worsening despite doing (WDD)" instead of "negative learning"[47] to distinguish between WDD and learning by doing as a concept in economic theory. Learning by doing refers to improvement as a result of an activity, such as working.[88] WDD, in contrast, attributes performance decreases to parasitic processes (e.g., decreasing morale) that did not originate in construction activities but were also not counteracted by them. These processes may have diminished productivity gains from problem-solving during routine, sequential work steps, which is often seen as the source of learning by doing.[88,89] Note that these processes may have been indirectly linked to safety regulations through complex, project-specific interactions but were not directly mandated by regulations, and we therefore distinguish between PIS and WDD. Finally, we use the mechanism "other" to refer to changes originating predominantly outside of the nuclear industry (e.g., wage or commodity price changes).

We relate cost changes to high-level mechanisms by using engineering and construction knowledge to identify relationships between these mechanisms and the variables in our cost model, and then check this initial assignment with information from patents and journal papers describing the motivations for innovations and the drivers of productivity changes (see Section S7). A complete list of assignments for the low-level mechanisms shown in Figure 4 is given in Table S5. In time period 1 (1976–1987), we assign material deployment rates to R&D, WDD, and PIS to account for several parallel developments that affected labor productivity. Following the Three Mile Island accident, NRC regulations required increased documentation of safety-compliant construction practices, prompting companies to develop quality assurance programs to manage the correct use and testing of safety-related equipment and nuclear construction materials. In contrast to the more informal practices used in the 1960s, NRC quality assurance standards became increasingly specific in the 1970s, regulating construction steps such as concrete placement and rebar testing.[86] We therefore categorize slowdowns in productivity as R&D. Time period 1 also saw the inception of the NRC's resident inspector program, putting NRC directly on site to monitor construction activities.[90] Since these interferences directly affected construction practices,[90,91] we categorize material deployment rates as PIS. Finally, we account for non-safety-related productivity changes by assigning deployment rates to the mechanism WDD. A worker survey from six nuclear power plants constructed during time period 1, for instance, attributes 27% of unproductive time to a lack of material and tool availability, indicating supply chain management issues that are largely independent from safety requirements.[84]

While the dimensions of the containment building were constant in time period 1 (1976–1987), they changed in time period 2.[92] Based on the information contained in patents and journal papers (Tables S3 and S4), these changes were made in pursuit of design simplicity, constructability, and safety goals, and we therefore assign thicknesses, radii, and heights to R&D. Since the use of cheaper steel and its faster deployment are consequences of the design change, these two mechanisms are also assigned to R&D. Concrete and rebar prices are assigned to "other" (see Tables S5 and S6 for other assignments and data sources).

Altogether, R&D-related activities contributed roughly 30% to cost increases, and on-site, procedural changes (WDD and interferences with the construction process)

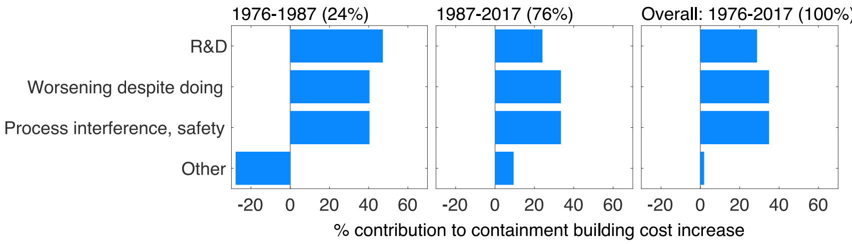

Figure 7. Percentage Contributions of Containment Building High-Level Mechanisms
Contributions to cost increase are shown for period 1 (1976–1987, left), for period 2 (1987–2017, middle), and for the overall time period (1976–2017, right). Different types of R&D are aggregated into one single bar to produce a rough estimate of the cost effect of R&D as compared to other high-level mechanisms.

contributed roughly 70% (see Figure 7). The large influence of these procedural and site-specific mechanisms points to the importance of pursuing innovation in these areas.

Our results also provide a starting point for quantifying the effect of safety regulations. While safety-related considerations likely had an influence on many of the high-level mechanisms studied here, the mechanism most directly related to compliance with regulations is PIS, which contributed approximately 30% to the observed cost increase between 1976–2017. The mechanism representing R&D activities typically addresses multiple objectives at once, and it is thus more difficult to strictly separate this into safety- and non-safety-related activities, and the same holds for productivity slowdowns reflected in "WDD." However, despite these difficulties, it is relevant to note that direct interference to address safety contributed significantly to cost increases observed (roughly 30%) but was not the only driver of cost escalation.

Opportunities for Future Cost Reduction in Nuclear Construction

We conclude by examining scenarios for future reductions in nuclear construction costs. The goal of this analysis is to begin to examine whether factors that have led to cost increases in the past can be addressed through innovation. Each scenario corresponds to a set of changes to the variables in the containment cost model relative to their values in 2017. These "prospective low-level mechanisms" represent the estimated effect of innovations such as advanced manufacturing and high-strength construction materials, which affect multiple variables either directly or indirectly through interactions. We estimate the relative effect of different low-level mechanisms induced by these innovations by populating our containment cost model with current US and future estimated cost data assuming different innovations are implemented (see Section S8.1) and using cost change equations to quantify the contribution of low-level mechanisms to the resultant cost reduction.

We use the same cost change model as for historical years but include formwork costs, drawing on recent data sources. We also estimate the potential contribution of higher-order improvement processes (high-level mechanisms) to cost reductions, which shed light on how the innovations we consider might be developed and implemented at construction sites. These scenarios represent hypothetical development strategies, which could be further explored and validated through detailed engineering models of specific reactor designs.

We consider three scenarios. In scenario 1, cost improvement is pursued along multiple dimensions, which is represented as a 20% change of all variables in a cost-reducing direction (e.g., deployment rates increase by 20%.) Although no real-world design change will induce equal-percent changes across all variables, scenario 1 is meant to test the sensitivity of our model. We change the plant efficiency and the concrete fraction in reinforced concrete by less than 20% to reflect engineering constraints (see Section S8.1).

In contrast to scenario 1, scenarios 2 and 3 represent specific efforts to reduce costs. In scenario 2, we assume that on-site deployment rates improve due to adoption of advanced manufacturing and construction management techniques.[93] We draw on a review article[94] to estimate improved concrete and formwork deployment rates and capital costs of currently available automation equipment (see Section S8.1; Table S7). For rebar, we turn to innovations in process management (e.g., optimized rebar delivery and placement planning[95]).

Scenario 3 is focused on advanced, high-strength construction materials, which have been shown to reduce commodity use and on-site rebar congestion in high-rise buildings and bridges (e.g., development of non-proprietary, ultra-high-performance concrete for use in the highway bridge sector by US Department of Transportation,[96] and cost and ecological feasibility assessments of using ultra-high-performance concrete in highway bridge piers by Nevada Department of Transportation[97]). We model a combination of high-strength reinforcement steel (HSRS) and ultra-high-performance concrete (UHPC).[98] HSRS provides up to 40% more yield strength (i.e., the stress at which a predetermined amount of permanent deformation occurs) than conventional rebar,[99] which is equivalent to a proportionate reduction in rebar amounts per unit of concrete volume (see Section S8.3 for details).

Scenarios 2 and 3 reduce costs by 30%–40% relative to 2017 containment costs, though neither scenario leads to a reduction relative to 1976 costs, primarily due the switch from one to two containment building shells and the associated increase in commodity usage. In scenario 1, reductions in rebar use (represented by f_{con} and referred to as "concrete fraction" in Figure 8), and in ironworker wages are most influential, together causing roughly 30% of total direct cost reductions (Figure 8). Even in a hypothetical scenario where steel for the containment vessel was free, changing the rebar content of concrete would remain the dominant cost changing effect due to labor costs. These results demonstrate the limits to materials-related cost reduction opportunities in nuclear structures due to their large-scale dimensions and labor intensity.

Scenario 2 results in a reduction of containment construction costs to approximately two-thirds of estimated costs in 2017 (−34%). This effect is driven primarily by faster concrete deployment. Although formwork materials cost a fraction of steel, the larger effect of automation on formwork as compared with steel productivity leads to similar contributions to cost reduction. Estimated capital costs for automation equipment are a minor cost driver, comprising approximately 6% of total containment construction costs. Scenario 2 nevertheless represents a 30% cost increase relative to 1976 costs.

Despite the large reduction in commodity usage, scenario 3 only reduces costs by a little over one-third (−37% from 2017 levels). Due to the expensive fabrication of UHPC steel fibers, the price of UHPC is currently ten times that of standard nuclear concrete[96,97,100] (see Section S8.1), and high-strength rebar is 50% more expensive than standard rebar. Cost reductions in scenario 3 could reach 50% if the costs of advanced materials reached current prices of nuclear commodities. Costs have declined in European countries that scaled UHPC production earlier,[97] but similar cost declines have yet to be achieved in North America.

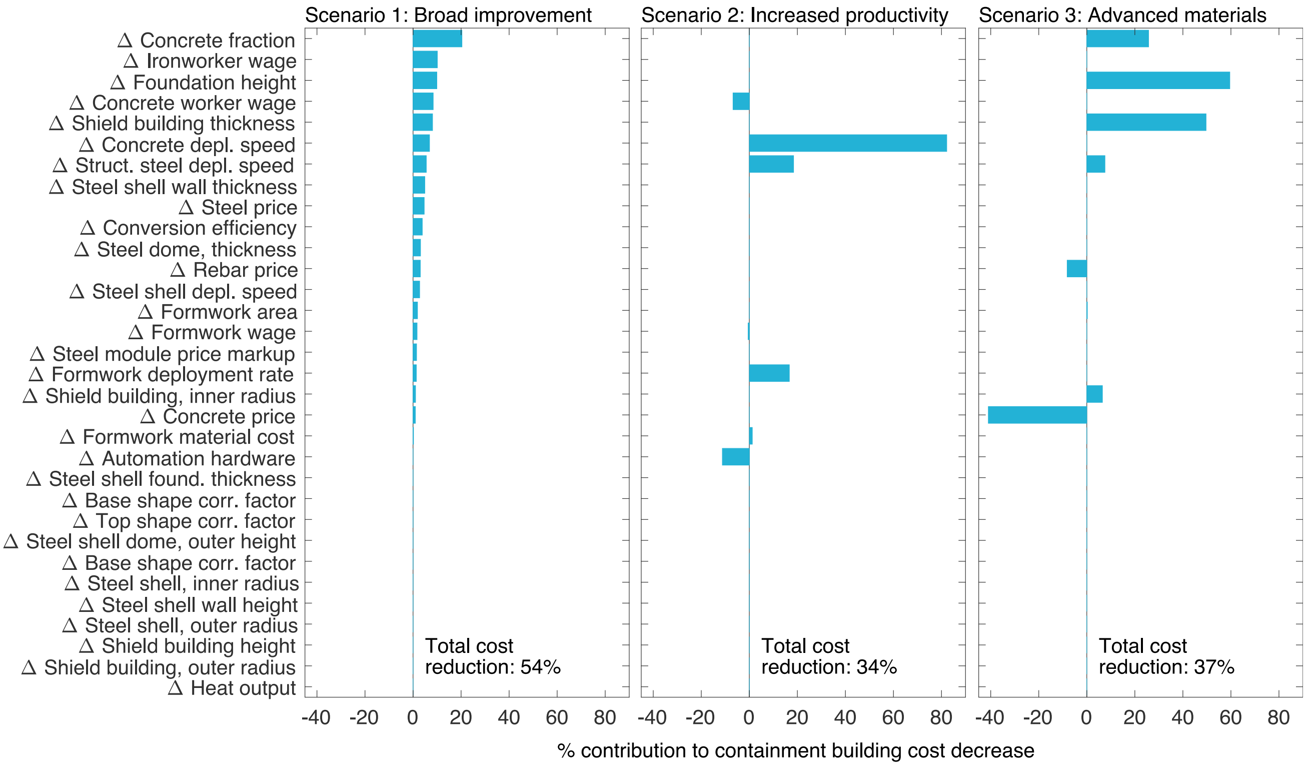

Figure 8. Percentage Contributions of Containment Building Low-Level Mechanisms to Cost Reductions under Three Improvement Scenarios
The three improvement scenarios represent innovation efforts focused on broad improvement across all variables (scenario 1), on productivity increases through automation and better construction management (scenario 2), and on advanced construction materials (scenario 3). In scenario 1 (left), several variables (structure thicknesses, deployment rates, and prices) improve by 20% (i.e., they change by 20% in a cost-reducing direction). In scenario 2 (middle), material deployment rates are assumed to improve due to automation and construction process management. Automation also leads to higher wages for operators of automated construction systems as compared to workers using traditional construction methods. In scenario 3 (right), standard nuclear concrete and rebar is replaced with high-strength, advanced construction materials in order to reduce commodity usage. The improvement scenarios are defined relative to the 2017 containment cost data used in Figure 4, with the addition of formwork costs. Total cost reduction refers to the sum of all mechanisms shown as bars above.

The prospective analysis highlights the challenges in reducing the costs of a field-constructed, site-specific technology under high safety standards. Scenario 1 shows that the rebar fraction in the concrete shield building is twice as influential as other variables, yet this is one of the variables most constrained by safety standards. Scenario 2 demonstrates that both concrete and steel construction would require automation to cut costs by more than 30%, yet challenges remain in the 3D printing of steel. The properties of printed metals under nuclear operating conditions (e.g., their microstructure, corrosion cracking, and irradiation effects) are an active area of research, but no commercially available product currently exists.[101]

We use the assignment scheme presented in High-Level Mechanisms of Containment Building Cost Change to relate low-level to high-level mechanisms but include an additional mechanism to account for the transfer of external innovations to the nuclear industry. We refer to this mechanism as "knowledge spillover" (KS). KS is similar to learning-by-copying in the sense that capabilities developed in one domain are adopted by another.[102] However, activities involved in this process may go beyond copying, since adopting advanced materials or automated construction systems will likely require adaptations to nuclear construction and inspection processes. Although many technologies draw on multiple industries as they evolve, and historical spillovers are, therefore, often

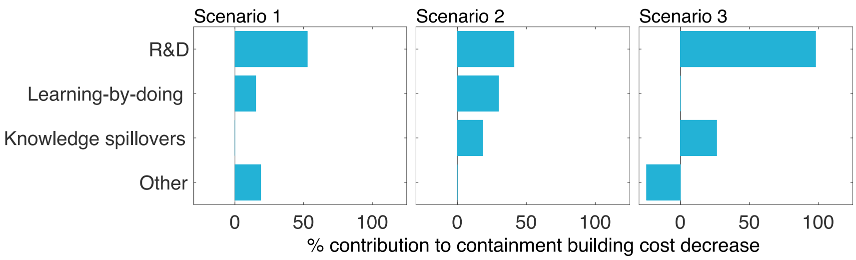

Figure 9. Percentage Contributions of High-Level Mechanisms to Containment Building Cost Decrease

Results are shown for three different improvement scenarios (scenario 1, broad improvement; scenario 2, increased productivity; scenario 3, advanced construction materials). The assignments of low-level to high-level mechanisms are given in Table S8 and are based on an implementation narrative for each scenario that reflects the current state of knowledge on technology availability and implementation experience in the nuclear domain. For example, we assume that integrating automated construction systems on nuclear construction sites (scenario 2) will require some amount of learning- by-doing to gradually optimize the operation of construction robots. In contrast, the modifications to containment building dimensions and construction workflows needed to replace standard by advanced materials can likely be planned off-site and are thus assigned to R&D and knowledge spillover instead of learning by doing. Uncertainties remain about how specific construction innovations will be implemented in practice, and the above percentages thus only provide rough estimates. These estimates could be refined using project- and design-specific information to refine cost models and expand data sets.

difficult to pin down, the scenarios here assume the use of specific, recent innovations whose development outside the nuclear industry is well documented. Given this background, we label the initial implementation of these innovations in the nuclear domain as a spillover.

We assign increases in material prices to the same high-level mechanisms that enable the switch to advanced materials (R&D and KS). In scenario 1, where we do not specify an innovation, we use historical associations between low- and high-level mechanisms as our "best guess" for the future.

As shown in Figure 9, we find that all scenarios require some form of R&D, and that R&D plays a greater role relative to other mechanisms and as compared to the results of the retrospective analysis shown in Figure 7. The contribution of other high-level mechanisms varies across scenarios. LBD is slightly more important when improvements to the construction process are adopted (scenario 2). Knowledge spillovers are less important for cost reductions in scenario 3 (advanced materials) than in scenario 2 because the cost decrease enabled by knowledge spillovers and the use of advanced materials is simultaneously diminished by the higher prices of these materials.

DISCUSSION

In this paper, we model nuclear plant costs over five decades to understand sources of rising construction costs in the US and how these compare to engineering projections. We document cost escalation in nuclear technology with time, even among plants of nominally standard design. Decomposing individual plant costs, we identify declining labor productivity as a major driver of cost increase over time, which we study mechanistically through a case study of the reactor containment building. The findings of this research lead us to revisit how engineering expectations regarding construction, technological performance, and innovation may have contributed to an underestimation of cost factors external to hardware design.

While it is acknowledged that construction costs increased for nuclear plants in the US and other countries, substantial reductions within a given design class (nth-of-a-kind plants) are still commonly expected in engineering cost models. We review nuclear cost estimating practices and industry growth projections, identifying a common expectation that learning effects drive down cost as experience grows.[2,31,32,35,36,40,46,66–69] The notion that improved plant designs can solve cost issues once new designs can be standardized and production scaled has driven substantial public and private R&D investment, but it is unclear what the net effect of such investment has been. While previous empirical evidence shows that costs rise with experience,[47,50,51] our work demonstrates that this effect was also true for NOAK plants of standard reactor technology in the US, indicating that cost reductions from standardization should not be expected as an inherent consequence of industry experience. However, our results should be interpreted within the context that not all plants within each standard design are perfectly identical, and the design differences may have contributed to the unexpected cost increases. Moreover, further work is needed to evaluate NOAK cost trends in other countries.

The rising costs of nuclear plants are often assumed to be associated with increasing stringency of safety regulations (e.g., MacKerron and Komanoff[49,86]). Here, we estimate that prescriptive safety requirements can be associated with approximately one-third of the direct containment cost increase between 1976 and 2017.

Productivity declines played a significant role in cost escalation. We show that nuclear productivity has declined faster than that in the construction industry, and that actual productivity at nuclear construction projects is significantly below industry expectations. The widespread use of estimates that do not match actual experience may be a contributing factor in cost overruns and suggests the importance of a comprehensive update using empirical, country-specific productivity data where available. A limitation of our study is that for data availability reasons we use aggregated productivity data covering multiple construction tasks. Future work involving targeted new data collection could explore productivity trends at the component- or task-level to develop a more fine-grained picture of on- and off-site productivity in the nuclear industry.

Looking to the future, our findings suggest that engineering models used to project future construction costs should be reexamined in light of the limitations of assumed learning rates and current approaches to engineering design solutions to site-specific and variable challenges. Using mechanistic models populated with recent, observed nuclear construction data can relate engineering design changes to cost change and potentially make cost projections more reliable. Moreover, there is some suggestion that cost escalation can be avoided by new strategies to assemble and codify knowledge. In China, Japan, and South Korea, for example, shorter construction schedules have been reported in cases where the same engineering company led projects in multiple countries.[2]

These observations motivate our modeling of scenarios for potential for future construction cost reduction. Our scenarios suggest that reducing commodity usage, for example through employing high-strength composite materials alongside automated construction, could significantly reduce costs. To realize these scenarios, R&D would need to play a more significant role compared with its past contribution to cost change.

Knowledge transfer from other industries, for instance in the form of advanced manufacturing techniques, could be particularly impactful if it enables automated control of process parameters, thereby reducing the costs of human-led construction supervision. However, additional efforts may be needed to ensure that these innovations can be adapted for nuclear applications. For instance, test data on the performance of new materials will likely be required to ensure nuclear standards can be satisfied.[103]

Similarly, while our analysis identifies the rebar density in reinforced concrete as the most influential variable for cost decrease, changes to the amount and composition of containment concrete are constrained by safety regulations, most notably the requirement for containment structures to withstand commercial aircraft impacts. New plant designs with underground (embedded) reactors could allow for thinner containment walls. However, these designs are still under development and pose the risk of high excavation costs in areas or at sites with low productivity.

Our retrospective and prospective analyses together provide insights on the past shortcomings of engineering cost models and possible solutions for the future. Nuclear reactor costs exceeded estimates in engineering models because cost variables related to labor productivity and safety regulations were underestimated. These discrepancies between estimated and realized costs increased with time, with changing regulations and variable construction site-specific characteristics. Our analyses demonstrate the importance of rethinking engineering cost models and design approaches to anticipate these effects and choose designs that are robust to them. Mechanistic models of cost change of the kind presented in this paper could be used to explore potential solutions. In the case of nuclear fission plants, reducing commodity usage and automating some aspects of construction could be particularly important though automation should be evaluated in the context of the effects on jobs and workers. While this study focuses on nuclear fission reactors, other technologies with similarly demanding on-site construction and performance requirements may also benefit from this approach.

Several areas for future research emerge from this work. One important area for further investigation is to extend our analysis of the containment building to the entire plant. An important advance in the methods for doing so would be to explicitly model engineering- and physics-based interactions between plant components. Another approach would be to use expert elicitations to develop insight on how variables affecting cost might change in the future (e.g., Nemet et al.[104]). Furthermore, previous studies have highlighted incomplete designs as one of several possible causes for cost escalation in nuclear power plants and other construction projects.[2,105] Future research could disaggregate various components of total plant costs (such as those shown in Figure 2) to enable mechanistic modeling of the effects of design revisions on home office engineering and other soft costs. Moreover, future work might investigate the institutional and regulatory conditions that best support learning in the nuclear industry to better understand differences in nuclear construction costs across countries and construction firms. Finally, additional research should focus on other technologies with similarly demanding on-site construction and performance requirements to develop better understanding of the potential avenues for preventing cost overruns and supporting innovation.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the Lead Contact, Jessika E. Trancik (trancik@mit.edu).

Materials Availability

Materials generated in this study will be made available on request, but we may require a payment and/or a completed Materials Transfer Agreement if there is a potential for commercial application.

Data and Code Availability

The published article with Supplemental Information includes detailed equations that can be used to replicate the code in this study and also includes detailed tabular data collected during this study. Additional materials supporting the study are available from the Lead Contact on request.

Data

Collection of empirical data from nuclear projects is challenging. Primary data sources are scarce and dated compared with other technologies, as relatively few nuclear plants have been completed by only a handful of companies, and the average plant in the US is over 40 years old. In addition, the use of best-case nuclear data or data from non-nuclear projects is common in nuclear bottom-up cost modeling (e.g., Rasin et al. and Delene and Hudson[14,36]). Changes to project design, schedule, and cost mid-stream are frequent and create another obstacle to finding data that are representative of an entire project.

To address the above issues, we collect data from a broad array of sources and check empirical data against hypothetical and best-case assumptions. For our analysis of nuclear learning rates and NOAK cost trends, we use databases of construction data, including IAEA reactor information, historical government reports, and published data from academic and industry literature (e.g., PRIS,[24] US EIA,[19,72] and Koomey and Hultman[15]). We use "overnight" cost of construction data in our analysis, which excludes financing costs. We use the gross domestic product price deflator to convert nominal costs to real costs, choosing an economy-wide index as the objective is to analyze costs in such a way that they can be compared with other potential technologies and investments. The total cost of a nuclear power plant includes interest on funds used to build the plant, which accounts for approximately 65% of the total cost of plants which began construction in the mid-1970s (up from approximately 35% for plants begun a decade earlier).[19] To study construction productivity changes in the US, we derive material deployment and labor data from reports by the Bureau of Labor Statistics.[106]

Our evaluation of cost estimating guidelines is based upon series of reports prepared under the US Department of Energy and by industry consortia (e.g., Rasin et al.[14] and Delene and Hudson[36]). For containment cost decomposition, we turn to EEDB data on commodity costs, labor costs, labor productivity, and structure dimensions of light-water reactor containment buildings constructed during the 1970s and 1980s and fill in the gaps with US Geological Survey commodity price data. We use containment building data from nuclear engineering specifications and architectural drawings of the Westinghouse AP1000 LWR for analysis of 2017 costs, as this is the only plant design currently under construction in the US. We also draw on AP1000 construction and engineering reports from the VC Summer project in South Carolina.

The resulting dataset is, to the extent possible, representative of the US nuclear industry in all three years studied in our analysis of containment building cost change. In 1976 and 1987, several plants were under construction, and our data represent an industry average.[56] In 2017, our data represent the only nuclear project under construction in the US. Projects using the same containment design are under way in other countries; thus, our findings may be relevant in some non-US markets. Note that overall, while we build on and draw upon existing, peer-reviewed nuclear cost datasets,[26,107] the mechanistic modeling of cost drivers in Sources of Cost Change in Containment Buildings and Opportunities for Future Cost Reduction in Nuclear Construction requires component-level, detailed cost data that are not available from peer-reviewed sources (e.g., construction productivity data at recent nuclear construction sites, containment building dimensions). We use these data and the data appearing in peer-reviewed publications with recognition of data uncertainty, and we address this issue using sensitivity analysis (Section S6).

Retrospective Modeling of Containment Building Cost Change

Containment building costs in 1976, 1987, and 2017 were modeled as the sum of material costs and labor costs, using Equation 5 (Sources of Cost Change in Containment Buildings). We account separately for material and labor costs incurred for the containment foundation, shell, and dome. For details on the cost equations used for individual containment components, refer to Section S4 in the Supplemental Information.

To compute the contribution of each changing variable in the containment cost equation to overall containment cost increase, we apply a previously developed method to decompose cost changes in technologies (Equation 6, Kavlak et al.[78]) to the time intervals 1976–1987, 1987–2017, and 1976–2017. The results are shown in Figures 4 and 5, and the dataset is described in Data. The cost data used in each year are given in Table S1. The approach employed to assign low-level to high-level mechanisms of containment building cost change is described in section High-Level Mechanisms of Containment Building Cost Change.

Prospective Modeling of Containment Building Cost Change

Future containment building cost changes were studied by decomposing estimated cost declines between the year 2017 and a future year by which hypothetical technology development strategies are assumed to be implemented. Changes in the variables relative to 2017 were computed for multi-dimensional improvement efforts changing many cost variables (scenario 1), adoption of advanced manufacturing and construction management techniques (scenario 2) and use of advanced construction materials (scenario 3). Scenario-level cost data are provided in Table S7. We use the same method as applied to past cost change to conduct a prospective analysis of high-level mechanisms. Refer to Section S8.3 for details.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2020.10.001.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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