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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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Abstract

Nuclear plant costs in the U.S. have repeatedly exceeded projections. Here we use data covering five 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 on-site labor supervision, contributed over half of the rapid cost rise from 1976-1987. Relatedly, reactor containment building costs more than doubled from 1976-2017, due only in part to safety regulations. Labor productivity in recent plants is up to thirteen 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 on-site construction requirements.

1 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., [1,2,3,4]). 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 electricity, relies on significant uranium resources, and shows low fuel price volatility and operating costs compared to fossil-fired power plants[10,11].

The U.S. plays an important role in the global nuclear industry in several ways. The U.S. 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]. U.S. federal investment in nuclear research and development is second highest among International Energy Agency member countries[13], and international cost estimating guidelines are based heavily upon U.S. 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 U.S. 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 U.S. since the 1970s[17,18,19]. 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 U.S. Recent projects in Finland (Olkiluoto 3) and France (Flamanville 3) have also experienced cost escalation, cost overrun, and schedule delays[22]. Cost estimates

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for a plant under construction in the United Kingdom (Hinkley Point C) have been revised upwards[23]. In contrast to the experience in Western Europe and the U.S., however, China, Japan, and South Korea have achieved construction durations shorter than the global median since 1990 [24,25,2]. Cost and construction duration tend to correlate (e.g., [26]), but it should be noted that independently verified cost data[1] from these countries are largely missing[27,28].

Despite historical precedence for rising costs, nuclear industry, government, and research agencies continue to forecast cost reductions in nuclear construction[29,30,14,31,32,33]. 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[34,2,35,14,36]. This notion is applied to all commercial reactors, though the anticipated cost reductions are greatest for small modular reactors (SMR) due to expected learning effects in factory settings[37,38,32]. The first SMR has yet to be built.

The projected role of nuclear power in many decarbonization scenarios (e.g., [39,40]) also stands in contrast to recent trends. In the U.S., 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 U.S. 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, 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 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 U.S. 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 learning[47,49,50,15,51].

Cost increases have been associated with reactor upscaling, with a lack of technology standardization, fragmented industry structure and plant ownership, and with increasing plant complexity[2] [47,52,17,53]. 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 in the second group have provided cost benchmarks for plant construction in the U.S.[56,57,58,59,60,61,62,63] and other countries (e.g., [64]). Other, forward-looking studies have outlined strategies for cost reduction, such as modularization, off-site manufacturing, passive cooling, and advanced construction materials[65,35,33,2]. 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 quantifying 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[66,36] 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 costs will decline with experience, empirical trends of nuclear construction indicate that costs have escalated as industry experience has grown [47,49,50,15,51]. 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 U.S. 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 U.S. even for plants of the same design class. This finding is missing in previous literature. Next, we examine what types of

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[1] Cost data that is provided and audited by entities not actively involved in plant procurement and construction (e.g., data from international organizations or government agencies as opposed to data from utilities and reactor equipment providers).

[2] Studies often consider increases in number of plant components, new control systems, redundancy in equipment, and added safety features to be indicative of increasing complexity.

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 re-thinking engineering design to adapt to these factors, for example through reduced commodity usage and automated construction processes.

2 Results

2.1 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.,[35,2]), and this assumption is reflected in a large number of projections and estimating guidelines, typically expressed in terms of technology learning rates.[3] In its cost guidelines for advanced reactors, for example, Oak Ridge National Laboratory[66,36] 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 use similar learning rates to assess the role of nuclear power in future energy strategies and greenhouse gas mitigation scenarios (e.g.,[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 rely on nuclear learning rates between 1% and 7%, while global scenarios of the International Atomic Energy Agency (IAEA) expect higher learning rates[40,69,31].

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 U.S. (Fig. 1).

We first examine the overnight cost of construction of 107 nuclear plants from across the U.S. nuclear experience (Fig. 1a). Similar curves are shown in Grubler[47], Koomey and Hultman[15], Cooper[50], and Lang[71]. Echoing previous findings[47,49,50,15,51], 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 U.S. capacity. Nevertheless, the costs in Fig. 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 if 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 installed in the U.S. that exceeded 8GW_e of installed capacity, 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.

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 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 shows the sharp disparity between empirical estimates and projections.

Next we examine the assumption of model-specific cost reduction, plotting experience curves separately for each prominent technology class in Fig. 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.,[72,19]) and previous publications (e.g.,[15,68,67,26,50,47]) lack information on reactor type. Berthelemy and Rangel[48] is the only study we find which

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[3] Technology costs are often fit to a power law model $C \sim x^{-b}$, where x is the cumulative production of the technology. The learning rate LR is given by $\mathrm{LR} = 100(1 - 2^{-b})$, 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.

quantifies the cost effect of model standardization. Their results show that standardization decreased cost in the U.S. and France, while design innovation increased construction costs.

2.2 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[56,57,60,59,63]. 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 Eq. 1 below, represent individual plant components and services needed to install these components. Q_E is the electrical output capacity of the plant.

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

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

$$\Delta c_i = \frac{c_{i,2} - c_{i,1}}{\sum_{i=1}^{61} c_{i,2} - \sum_{i=1}^{61} c_{i,1}} \tag{2}$$

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

Fig. 2 depicts the effects of the most important accounts, and SI section 1 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 contribute 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[73]. 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[73].

Indirect costs caused most (72%) of the cost increase during period 1 (1976-1987), in particular indirect expenses incurred by home office engineering services (engineering design, purchasing and expediting, estimating and cost control, planning and scheduling), field job supervision (salaries, 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, 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:

$$Z_i = \sum_{\omega} \frac{C_{i\omega}}{\sum_i C_{i\omega}} B_\omega \tag{3}$$

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 SI section S3.

Fig. 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.

Recognition of the cost-interdependence of direct and indirect accounts motivate going beyond these simplified assumptions in our subsequent analysis into the technical and economic mechanisms of cost change. In section 2.2 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.

2.3 Sources of cost change in containment buildings

In this section we further examine mechanisms that led to increases in cost components discussed in section 3.2., 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 for two reasons: 1) as the largest safety-grade structure of a nuclear power plant, the containment 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

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

We focus on steel, rebar and concrete and omit other, less costly materials used for formwork (see Supplementary 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 Eq. 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 $(\frac{w_i}{v_i})$:

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

In Supplemental 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 U.S. nuclear construction: From 1976 to 1987 (period 1), the era characterized by changing public opinion, rising nuclear regulations, and the events surrounding the Three Mile Island accident. From 1987 to 2017 (period 2), the recent era characterized by protracted construction periods, development of new generations of reactor design, the 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[74], 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

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

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.

As shown in Figs 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 section 3.4.

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[75,76,77]. 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.

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 ten 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 total 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 Fig. 4 but examine the effects of currently available indirect cost data on total containment cost change in Supplemental 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 Supplemental 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.

2.4 Further evaluation of construction productivity changes

In section 3.3 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 U.S. construction productivity during the period[2,19], but has not looked at the nuclear industry specifically.

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[56,57,58,59,60,61,62,63] and recent AP1000 engineering construction reports[78,79], 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 to 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 Fig. 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[80], 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 U.S. 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 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 of 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[81].

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[82].

2.5 High-level mechanisms of containment building cost change

What were the higher-level human activities and strategies behind low-level mechanisms of cost change discussed in sections 3.3 and 3.4? A common view is that safety regulations have increased the costs of nuclear power plant construction[83,49,84,4,2]. 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)[74].

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 (Supplemental 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 Supplemental 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[85]. 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[85,86]. Note that these processes may be indirectly linked to safety regulations through complex, project-specific interactions but have not been directly mandated by regulations, and we therefore distinguish between process interference-safety (PIS) and worsening despite doing (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 motivations for innovations and drivers of productivity changes (see Supplemental section S7). A complete list of assignments for the low-level mechanisms shown in Fig. 4 is given in Supplemental 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[83]. 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[87]. Since these interferences directly affected construction practices[87,88], 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[80].

While the dimensions of the containment building were constant in time period 1 (1976-1987), they changed in time period 2[89]. Based on the information contained in patents and journal papers (Supplemental Tables S3 and S4), these changes were made in pursuit of design simplicity, constructibility, 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 Supplemental 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 (worsening-despite-doing and interferences with the construction process) contributed roughly 70% (see Fig. 7). The large influence of these procedural and site-specific mechanisms points to the importance of 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 process interference, safety, 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 into safety- and non-safety related activities, and the same holds for productivity slowdowns reflected in 'worsening by doing'. 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.

2.6 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 U.S. and future estimated cost data assuming different innovations are implemented (see SI 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 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 Supplemental 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[90]. We draw on a review article[91] to estimate improved concrete and formwork deployment rates and capital costs of currently available automation equipment (see Supplemental section S8.1 and Table S7). For rebar, we turn to innovations in process management (e.g., optimized rebar delivery and placement planning[92]).

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.,[93,94]). We model a combination of high-strength reinforcement steel (HSRS) and ultra high-performance concrete (UHPC)[95]. HSRS provides up to 40% more yield strength (i.e., the stress at which a predetermined amount of permanent deformation occurs) than conventional rebar[96], which is equivalent to a proportionate reduction in rebar amounts per unit of concrete volume (see Supplemental 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 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 Fig. 8) and in ironworker wages are most influential, together causing roughly 30% of total direct cost reductions (Fig. 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 to 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 10 times that of standard nuclear concrete[97,94,93] (see Supplemental 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[94], but similar cost declines have yet to be achieved in North America.

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[98].

We use the assignment scheme presented in section **??** 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). Knowledge spillover is similar to learning-by-copying in the sense that capabilities developed in one domain are adopted by another[99]. 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 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 Fig. 9, we find that all scenarios require some form of R&D, and that R&D plays a greater role relative to other mechanisms compared to the results of our retrospective analysis shown in Fig. 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.

3 Discussion

In this paper we model nuclear plant costs over five decades to understand sources of rising construction costs in the U.S. 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 U.S. 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[66,36,68,67,32,40,69,31,35,2,46]. 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 U.S., 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. Further work is needed to evaluate NOAK cost trends in other countries.

Rising costs are often assumed to be associated with increasing stringency of safety regulations (e.g.,[83,49]. 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 expectations 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 to 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 standards can be satisfied[100].

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 expectations in engineering models because cost variables related to labor productivity and safety regulations were underestimated. These discrepancies between expectation 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 reactors, reducing commodity usage and automating construction could be particularly important. 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.,[101]). Furthermore, previous studies have highlighted incomplete designs as one of several possible causes for cost escalation in nuclear power plants and other construction projects[2,102]. Future research could disaggregate various components of total plant costs (such as those shown in Fig. 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.

4 Experimental Procedures

4.1 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).

4.2 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 potential for commercial application.

4.3 Data and Code Availability

The published article with Supplemental Information includes detailed equations that can be use 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.

4.4 Data

Collection of empirical data from nuclear projects is challenging. Primary data sources are scarce and dated compared to other technologies, as relatively few nuclear plants have been completed by only a handful of companies, and the average plant in the U.S. is over forty years old. In addition, the use of best-case nuclear data or data from non-nuclear projects is common in bottom-up cost modeling (e.g.,[14,36]). Changes to project design, schedule, and cost mid-stream are frequent and create another obstacle to finding data that is 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 nth-of-a-kind (NOAK) cost trends, we use databases of construction data, including International Atomic Energy Agency reactor information, historical government reports, and published data from academic and industry literature (e.g., PRIS[24], U.S. EIA[72,19], 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 to 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 U.S., we derive material deployment and labor data from reports by the Bureau of Labor Statistics[103].

Our evaluation of cost estimating guidelines is based upon series of reports prepared under the U.S. Department of Energy and by industry consortia (e.g.,[36,14]). 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 U.S. 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 U.S. We also draw on AP1000 construction and engineering reports from the VC Summer project in South Carolina.

The resulting data set is, to the extent possible, representative of the U.S. 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 represents an industry average[56]. In 2017, our data represent the only nuclear project under construction. Projects using the same containment design are under way in other countries, thus our findings may be relevant in some non-U.S. markets. Note that overall, while we build on and draw upon existing, peer-reviewed nuclear cost datasets[26,104], the mechanistic modeling of cost drivers in sections 3.3 and 3.6 requires component-level, detailed cost data that is not available from peer-reviewed sources (e.g., construction productivity data at recent nuclear construction sites, containment building dimensions). We use this data with an understanding that a lack of peer-review introduces uncertainty, and we address this issue using sensitivity analysis (SI section S6).

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Author Contributions

PEG: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization; MMK: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization; GK: Conceptualization, Methodology, Writing - Review & Editing; JM: Conceptualization, Methodology, Writing - Review & Editing; JB: Conceptualization, Writing - Review & Editing, Funding Acquisition; JET: Conceptualization, Methodology, Writing - Review & Editing, Funding Acquisition, Supervision.

Declaration of Interests

The authors declare no competing interests.

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