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Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses

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ABSTRACT

This study investigates the frequency and magnitude of cost and time overruns occurring during the construction of 401 electricity projects built between 1936 and 2014 in 57 countries. In aggregate, these projects required approximately $820 billion in investment, and amounted to 325,515 MW of installed capacity and 8495 km of transmission lines. We use this sample of projects to test six hypotheses about construction cost overruns related to (1) diseconomies of scale, (2) project delays, (3) technological learning, (4) regulation and markets, (5) decentralization and modularity, and (6) normalization of results to scale. We find that nuclear reactors are the riskiest technology in terms of mean cost escalation as a percentage of budget and frequency; that hydroelectric dams stand apart for their mean cost escalation in total dollars; that many of the hypotheses grounded in the literature appear wrong; and that financing, partnerships, modularity, and accountability may have more to do with overruns than technology.

1. Introduction

In the 1970s, the Washington Public Power Supply System (WPPSS) initiated a construction program for seven new nuclear reactors. WPPSS believed that electricity requirements would grow by 5.2 percent each year well into the 1990s and started building nuclear power plants to meet their projections. At the same time, however, a massive backlog of nuclear power plant orders after the 1973 oil crisis caused a severe shortage of skilled nuclear engineers and architects, as sixty-nine new nuclear plants were ordered nationally in 1973 and 1974. Problems with plant design, poor craftsmanship, and labor strikes caused even longer delays, forcing initial five year construction estimates to extend into ten or twelve-year periods for WPPSS. One WPPSS project started in 1970 was not finished until 1984, and the WPPSS annual report in 1981 projected that $23.7 billion was needed to complete one of its plants initially thought to cost less than $2 billion, and this was after $5 billion had already been expended. All the while electricity growth dropped significantly below original projections, diminishing the need for these capacity investments. By the mid-1980s, WPPSS faced financial disaster and all but one of the plants were cancelled, leading to the largest municipal bond default in the United States at that time [26,30].

The entire experience came to be called the "WHOOPS" fiasco, as a play on the WPPSS acronym, and it is an enduring lesson of the risk associated with investing in large power plants. Yet the issue of construction cost overruns is far from limited to the experience with WPPSS. Flyvbjerg et al. [9] surveyed a sample of 258 transportation infrastructure projects worth about $90 billion and concluded that "for a randomly selected project, the likelihood of actual costs being larger than estimated costs is 86%." In the past 13 years, the mean cost of building a power plant increased by a factor of 2.26 in North America and by a factor of 1.93 in Europe which is shown in Fig. 1 [15]. In assessing the severity of magnitude of construction cost overruns, the U.S. Energy Information Administration [37] noted that "cost overruns for nuclear construction projects were not correlated with size, regional factors, construction start date, or experience." In other words, there appeared to be no clear cut factors or rules governing what caused an overrun [34].

In this study, we intricately examine the cost overruns incurred in the construction of 401 electricity projects built between 1936 and 2014 in 57 countries. In sum, these projects required roughly $820 billion in investment, and amounted to 325,515 MW of installed capacity and 8495 km of transmission lines. We use this database, and regression analysis of its findings, to test six

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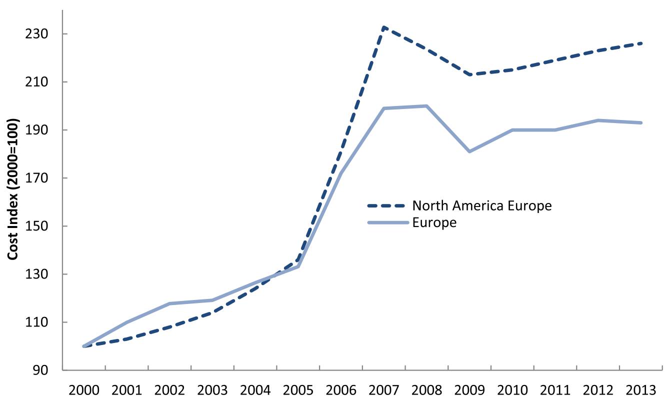

Fig. 1. North American and European power capital costs index, 2000–2013.

hypotheses about construction cost overruns related to (1) diseconomies of scale, (2) project delays, (3) technological learning, (4) regulation and markets, (5) decentralization and modularity, and (6) normalization of results to scale. We find that nuclear reactors are the riskiest technology in terms of mean cost escalation and frequency and that hydroelectric dams stand apart for their mean cost escalation. We note that numerous hypotheses grounded in the literature appear wrong, and that while the historical record may not be a perfect indicator of future costs, it offers instructive lessons for energy analysts, project sponsors, and investors. We conclude with suggestions for better project management as related to financing, partnerships, modularity, and accountability.

2. Research methods and limitations

Our study began by first developing a list of six hypotheses—shown in Table 1—that we wanted to test concerning construction cost overruns. Three of these relate to internal trends within each reference class of technology; one relates to location; and the final two relate to an external comparison between each of the reference classes. We then collected reliable data on construction costs for any type of power plant greater than 1 MW in installed capacity or transmission project greater than 10 km. Our sample consisted of six types of projects: thermoelectric power plants that depend on the combustion of coal, oil, natural gas, or biomass; nuclear reactors; hydroelectric dams; utility-scale wind farms; utility-scale solar photovoltaic (PV) and concentrated solar power (CSP) facilities; and high voltage transmission lines.

We initially searched the energy studies, electricity, transport, and infrastructure literature for reliable peer-reviewed data, which we did find in a few instances [1,13,22,39]. However, we supplemented that information by building our own database through a two-step process of contacting 49 prominent energy experts, listed in Appendix I, and then searching hundreds of project documents, press releases, and reports, listed in Appendix II. Throughout this process, we only included a project in our database when we could find complete data regarding:

- The year the project entered service.
- Its geographic location;
- Its name;
- Its size in installed capacity (in MW);
- Its estimated or quoted construction cost;
- Its actual construction cost; and
- If available, its estimated construction time and actual construction time (confirmed for subsample of 327 projects).

To make our sample of projects as robust as possible, we did not confine our data compilation to any geographic location or time period. We then updated all costs and currencies to US$2012 using historical currency conversions available at Oanda.com and adjustments for inflation from the Statistical Abstracts of the United States. Appendix III presents this data for all 401 projects.

In collecting data in this manner, some caveats and limitations need to be elaborated. While we treat the occurrence of a cost overrun pejoratively, i.e., to be avoided and with negative consequences for project financiers and eventual owners, there is some logic to their occurrence, at least from the perspective of construction firms or contractors. Small cost overruns demonstrate that a project was very close to budgeted cost, and thus a capable manager may desire to slightly overspend so they will not be expected to perform the task on a smaller budget in the future. We see a similar reasoning with budgeting in academic institutions; we are constantly told by superiors that one must always spend their entire budget, perhaps even slightly more, or else they will be apportioned less during the next fiscal year. In much the same way, having a cost underrun could be seen by some as a sign of poor performance, and could also be seen as dangerous, as future customers might believe that they can undercut a contractor's bid due to a past cost underrun.

Table 1
Six hypotheses related to construction risk and electricity infrastructure.

Hypothesis	Dimension	Type of analysis	Explanation
H1: bigger is bad	Diseconomies of scale	Internal (within each reference class)	As units get larger, they are prone to diseconomies of scale and a greater frequency and magnitude of cost overruns
H2: longer is costlier	Project delays	Internal (within each reference class)	There will be a significant correlation between time overruns and delays, and the incidence of cost overruns
H3: later is better	Technological learning	Internal (within each reference class)	Over time, we would expect fewer cost overruns to occur as engineers, managers, and operators learn from experience; similarly, first-of-a-kind projects will incur higher costs
H4: governance matters	Regulatory regimes and markets	Geographic (based on project location)	Industrialized and highly developed economies would have more advanced regulation, improved transparency, and lower costs than developing countries with weaker regulatory governance
H5: small is beautiful	Decentralization and modularity	Comparative (between reference classes)	Smaller-scale options such as wind turbines and solar panels would experience fewer cost overruns than larger, more capital-intensive facilities
H6: tiny is trouble	Normalization of results to scale	Comparative (between reference classes)	Smaller-scale options such as wind turbines and solar panels would experience higher cost overruns per MW of installed capacity

In addition, we searched only in English, so our sample has a likely bias for North American and European projects. We ended our data collection in January 2014, meaning any plant completed or data released after that point was excluded. The definition of a construction start (or end date) was not always clear, given that some studies measure it in terms of the first pouring of concrete, others use the time of groundbreaking, and still others include preconstruction periods inclusive of the permitting process and ordering of equipment [28]. We simply accepted the definition of a "start" and "end" date as reported in project documents or the literature; we did not make any adjustments. In addition, we included only completed projects in our database, not those cancelled or still under construction. This means we exclude some of the "worst" projects where unbearable cost overruns or other factors caused the project to be abandoned prior to completion.

Most important is our definition of a "construction cost," which we treated as "the process of assembling the components of the facility, the carrying out of civil works, and the installation of component and equipment prior to the start of commercial operation" [41]. This definition is also sometimes known as "Engineering, Procurement, and Construction" cost [18]. This definition, while concise, may not always lead to accurate numbers, given that detailed cost information is often proprietary, creating a potential discrepancy between publicly reported figures (which we relied on) and "off-the-books" or private figures [6]. Some of our construction cases may be atypical, representing first-of-kind projects or simpler situations such as adding a unit to an existing location.

To enable readers to determine the strength of our results, we conducted linear regression analysis on our data to give an indication, through R^2 values, for how robust our trend lines are. We employed the "slope-intercept" form of $y = mx + b$. Given a set of data (x_i, y_i) with n data points, the slope, y-intercept and correlation coefficient, we determined r in each of our graphs by using the following:

$$m = \frac{n\sum(xy) - \sum x \sum y}{n\sum(x^2) - (\sum x)^2}$$

$$b = \frac{\sum y - m\sum x}{n}$$

$$r = \frac{n\sum(xy) - \sum x \sum y}{\sqrt{\left[n\sum(x^2) - (\sum x)^2\right]\left[n\sum y^2 - (\sum y)^2\right]}}$$

This type of regression analysis is commonly utilized to determine relationships between scattered variables [31]. Although there is no universally accepted notion of what counts as a "statistically significant" or "strong" R^2 value—even values of 1, 5, or 10 percent are considered "significant" when plotting stock returns, or the results of psychological experiments and clinical trials [3, pp. 347–348,23]—we have treated our results as significant if they exceed 20 percent.

3. Results: testing six hypotheses about construction overruns

Table 2 summarizes some of the main statistical results of our construction cost data for the 401 projects in our data set. Although not presented in Table 2, our results also suggest that, across the entire sample the mean construction time was 73.4 months and the mean cost overrun per project was almost $1 billion, or a mean cost escalation of 66 percent. More than three quarters of projects in the sample experienced a cost overrun, with significant differences for each reference class. The remainder of this section tests each of the six hypotheses mentioned above against the results of our database, including a regression analysis of some of the data trends.

3.1. H1: bigger is bad

Our first hypothesis is that larger projects are prone to a greater frequency and magnitude of overruns because they are more capital and material intensive. Support for this hypothesis comes from a variety of sources. As the EIA [37] concluded when looking at historical construction costs for reactors, "a 25 percent increase in size is associated with an 18 percent increase in lead-time, and the 18 percent longer lead-time is related to a 22 percent increase in the real cost or quantity of land, labor, and material used to construct a nuclear power plant." Flyvbjerg et al. [10] wrote that "both the research literature and media occasionally claim that the track record is poorer for larger projects than for smaller ones, and that cost escalations for large projects are particularly common and especially large." Ruuska et al. [29] suggest that because larger projects tend to involve more firms, such "multi-firm" projects "face the challenge of governing a project's internal complex supply chain of multiple firms, and of simultaneously governing the network of external stakeholders," contributing to higher overall costs.

The explanation for the pursuit of larger projects lies not only in the desire to capture or achieve economies of scale, but in psychology and politics. As one study [8] surmised:

> *Which large projects get built? My research associates and I found it isn't necessarily the best ones, but instead those for which proponents best succeed in designing—deliberately or not—a fantasy world of underestimated costs, overestimated revenues, overvalued local development effects, and underestimated environmental impacts.*

Larger projects, in other words, can become associated with ideas of prestige, progress, and modernity.

Byrne and Hoffman [5] even propose that the single most consistent predictor of whether a society will embrace a large megaproject is their ability to think in the "future tense." That is, planners and promoters will become enthralled by the possible benefits in the *future* and are willing to accept the costs in the *present* to realize them. They will overestimate advantages and discount future costs in the absence of knowledge about current economic or technical compatibility; reality of present risks and costs are discounted by the unrealized possibilities of future gain. Although these psychological benefits are intangible, they are often believed to be real. A cursory look at the genesis of nuclear programs in eight countries—China, France, India, Japan, the former Soviet Union, the United States, Spain, and Canada—reveals that in each case optimism in the technology and an overarching vision of what nuclear energy could deliver in the future played a role in trumping concerns about present costs [33].

The evidence from our database, graphed in Fig. 2 according to a series of polynomial and logarithmic trend lines, partially supports this hypothesis. For transmission projects, a longer physical length (km) has a statistically significant impact on cost escalation (R^2 value of 26.3%), though this is substantially influenced by the 1982 Inga-Kolwezi HVDC Line, an outlier. For hydroelectric projects, we also see a statistically significant (R^2 value of 22.3%) relationship between size in MW and the magnitude of cost escalation. This though was also likely heavily influenced by an outlier, the massive Three Gorges Dam, which had the largest capacity of any project in our sample, and saw an overrun of over 500%. Massive hydro projects were particularly vulnerable to extreme overruns, with five of

Table 2
Summary cost overrun data for electricity projects by reference class.

Description		Hydroelectric dams	Nuclear reactors	Thermal plants	Wind farms	Solar facilities	Transmission lines
Number of projects (N)		61	180	36	35	39	50
N with cost overrun		47	175	24	20	16	20
N with cost overrun (%)		77	92.2	66.7	57.1	41	40
Cost escalation (%)	Mean	70.6	117.3	12.6	7.7	1.3	8
	Min	−50.6	−7.9	−50	−9.1	−40.8	−33.3
	Max	512.7	1279.7	120	44.4	50	260
	Median	30.1	64.8	9.6	1.7	0	0
	Mode	–	189.4	75	0	0	0
	Standard deviation	111.7	152.1	33.5	13.1	17.8	40.4
Cost overrun (millions US$)	Mean	2437	1282	168.5	32.8	−4.2	29.7
	Min	−671.4	−298.8	−1272.7	−158.5	−266.6	−177
	Max	47,630	16,589	2000	526.4	102.3	1522
	Median	99.5	503.1	51.5	0.96	0	0
	Mode	–	41.9	–	0	0	0
	Standard deviation	7054.7	1965.8	579.6	112.9	62.1	217.6
Time overrun (%)[a]	Mean	63.7	64	10.4	9.5	−0.2	7.5
	Min	−28.6	−15	−10.7	−19	−11.2	0
	Max	401.7	261.9	66.7	60	25	203
	Median	32.7	40	0	0	0	0
	Mode	30.9	35.4	0	0	0	0
	Standard deviation	89.8	53.1	19.0	22.6	8.0	30.6
Time overrun (months)[a]	Mean	43.2	35.7	4.8	0.22	−0.2	3.5
	Min	−24	−9	24	−4	−5	0
	Max	241	149	−9	6	5	81
	Median	19.5	24	0	0	0	0
	Mode	12	17	0	0	0	0
	Standard deviation	58.4	30.6	8.9	2.4	2.1	12.8
Cost per installed kW/km[b] (US$)	Mean	3093.2	2427	1943.9	2808	8311.6	906
	Min	146.8	190.7	279	405.6	1773.5	178
	Max	10,359.5	13,260.1	5606.8	5793.7	27,180	1515
	Median	2278.4	1776	1787.9	2459	7199.4	937
	Mode	–	960.2	–	2645.5	–	981
	Standard deviation	2516.1	1888.5	1163.9	1147.4	5099.7	364

[a] Applies only to a smaller subsample $N = 33$ for hydro, 175 for nuclear, 24 for thermal, 18 for wind, 23 for solar, 49 for transmission.
[b] Costs are in hundreds of thousands of dollars per km.

the largest projects responsible for more than two thirds of all overruns in the reference class, despite only making up about a third of capacity.

For the other classes of technology, however, the picture is more complicated. Nuclear reactors have almost no relationship between size and cost escalation; they suffer overruns regardless of how big they are, given that 97% of projects had some type of overrun. Thermal, wind and solar projects, by contrast, do seem to achieve some degree of economies of scale, meaning that larger projects see fewer cost overruns, though the R^2 values (under 6 percent) for these trend lines are less statistically significant. For wind projects, the explanation may be that the larger projects tend to be offshore, meaning they are able to harness greater amounts of wind energy, and that in most cases they are subject to less social opposition (and related lawsuits) [2]. For solar facilities, the explanation may be that larger projects produce manufacturing economies of scale; these larger manufacturing facilities "appear to have played much bigger roles than learning by experience in enabling cost reductions" [24].

3.2. H2: longer is costlier

Our second hypothesis was that project delays contributed to higher rates of cost overruns. This is because longer construction lead-times meet with a plethora of uncertainties during the construction process—including unforeseen changes in consumer preferences, interest rates, availability of materials, exchange rates, severe weather and labor strikes—making planning and financing difficult, especially when the balance of supply and demand for electricity can change rapidly within a short period of time. Delaying construction of a nuclear power plant for two years, for instance, adds about 15 percent to its final cost of electricity [32]. Flyvbjerg et al. [10] found that "with very high statistical significance … cost escalation was strongly dependent on the length of the implementation phase." They estimated that every passing year from decision to build until operations commenced added 4.6 percent to project costs. The EIA [37] reports that "one of the most statistically significant variables that explains variation in the effort and material required to build a power plant, measured by the real overnight costs, is the length of the construction period" and that with all other factors held constant, a 1 percent increase in construction duration added 1.2 percent to real-costs. Ford [11] has also noted that longer construction lead-times can create a mismatch between labor supply and demand that add significantly to project costs.

Indeed, our data does suggest that a statistically significant relationship holds true between mean time overruns and mean cost escalation for transmission networks (R^2 value of 82.2%, though this is strongly influenced by a single outlier in 1982), hydroelectric dams (57.1%), and nuclear power plants (31.6%), illustrated by Fig. 3. However, it holds less true for thermal plants (R^2 value of 5.8%) and wind farms (11.5%). Interestingly, the evidence for solar facilities runs entirely counter to the hypothesis, showing a slight drop in project costs as time delays increase, though this could have been more about rapidly falling module prices than any other factor (i.e., the delay enabled project managers to tap into reductions in price). One possible interpretation for why most reference classes show only a moderate correlation between time and cost overruns could be that attempts to accelerate construction timetables, or to bring a project to completion on time, can lead to

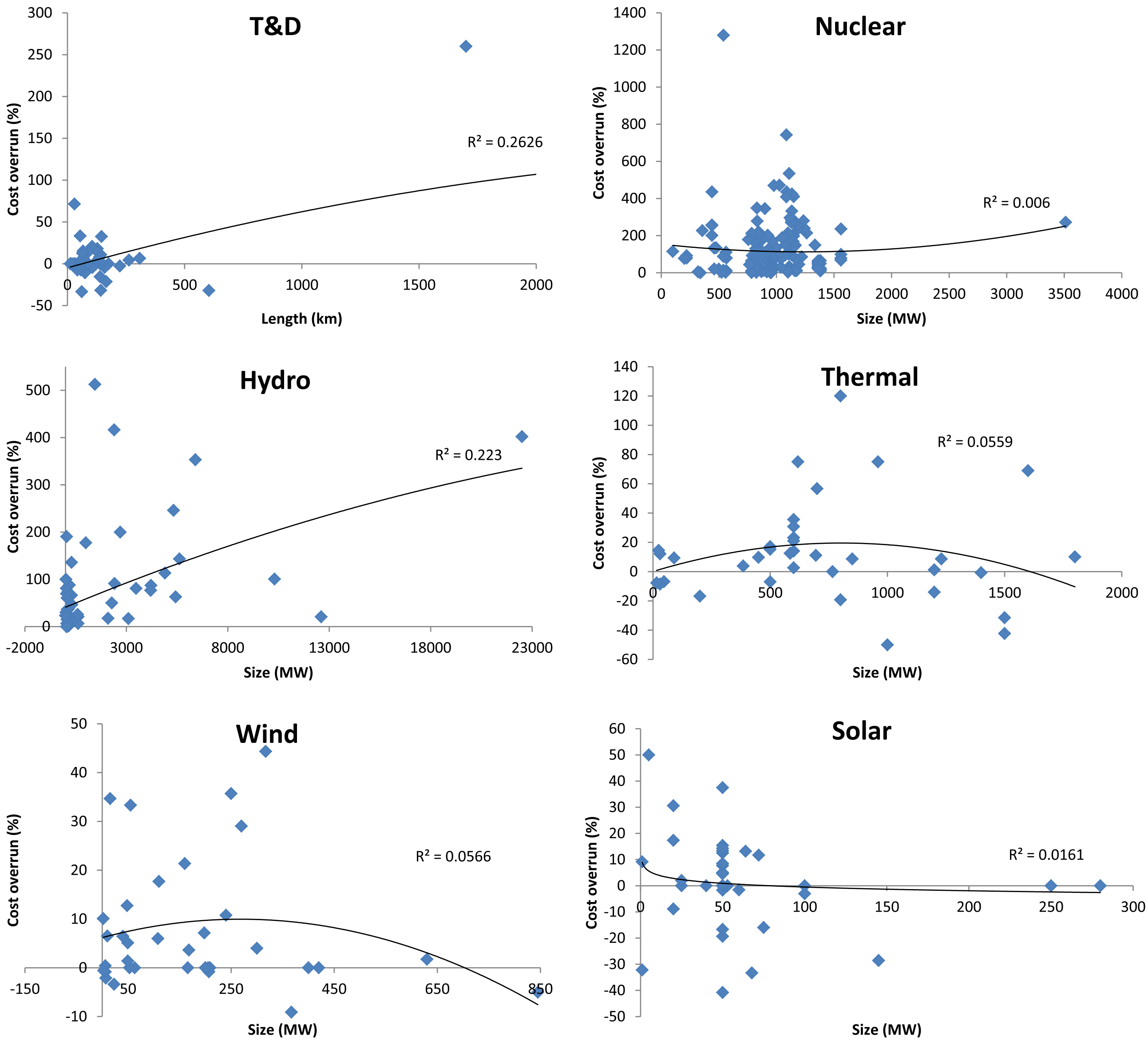

Fig. 2. Polynomial and logarithmic trend lines for mean cost escalation and project size, by reference class.

significant expenditures for overtime costs, higher wages, and hiring expenses.

3.3. H3: later is better

Our hypothesis of "later is better" acknowledges that first-of-kind projects will tend to cost more than those that follow, and that as one gains construction experience, a sort of "technological learning" should occur that drives down costs. As first-of-kind projects are completely unique entities, they are what Joerges [17] calls a "unicate" system with design, manufacturing, and installation entirely site specific. Such projects are "pre-infrastructural" since everything for them must be built from scratch. This unpredictability of having to do something for the first time leads to unknown permutations and risks, adding to overall cost [35]. This is why Levitt et al. [21] found that typical costs for a "first-of-a-kind" wind project tended to be almost twice as much as the "best recent values" for offshore wind farms. A second dimension of this hypothesis relates to positive learning. As managers, builders, and operators gain experience, one would expect that lead-times and real-costs should decrease. Technological improvements should drive costs further down, and these can all occur due to improved resource assessments, software, and modeling (of hydrology for dams, wind for wind farms, solar insulation for solar facilities, etc.); greater use of front end engineering and design practices; and better construction processes [42]. Significant reductions in final costs have been attributed to rapid "learning" for thermal, hydro, and nuclear plants [16], solar facilities [24], and wind farms [2].

Most interestingly, as Fig. 4 documents, there is a statistically significant positive learning curve for transmission projects over time (with an R^2 value of 78.3%, though again influenced strongly by our outlier) and very slight (i.e., not statistically significant) positive learning effects for wind (R^2 value of 0.03%) and solar (R^2 value of 4.3%). However, nuclear projects appear to experience some negative learning over time—that is, cost overruns increase slightly in frequency in the more recent years (R^2 value of 4%). We observe more complicated learning curves for hydroelectric and thermal projects which begin to exhibit positive learning up until the 1970s (for hydro, R^2 value of 15.1%) and 2003 (for

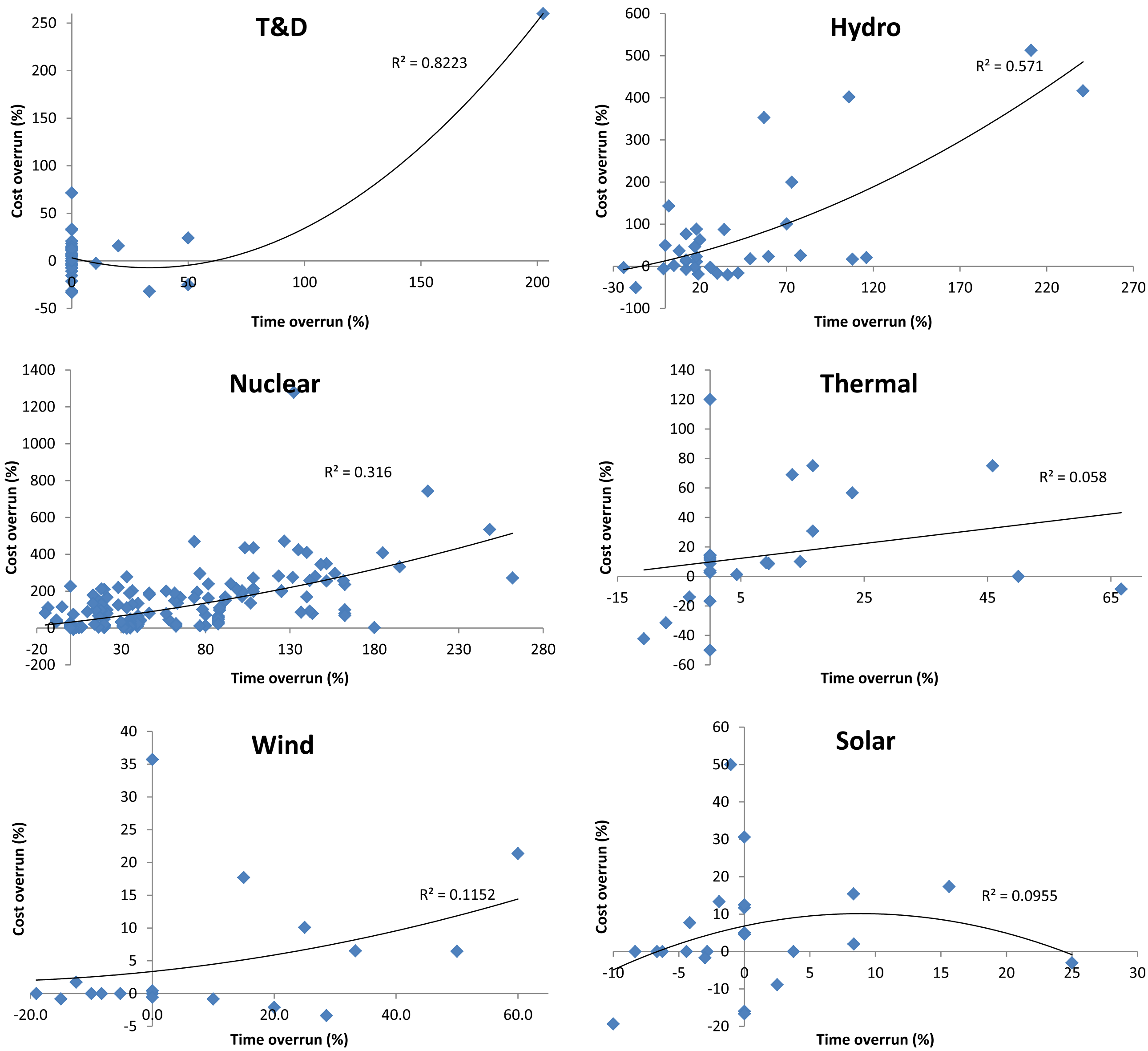

Fig. 3. Polynomial and logarithmic trend lines for mean cost escalation and time overrun, by reference class.

thermal, R^2 value of 35%), only to change direction to incur cost overruns again. For hydro, apart from our trend line being influenced by the major Three Gorges Dam overrun, the change could be due to firmer implementation strategies and better construction techniques in response to more rigorous environmental impact statements after the 1970s, which required (costly) physical and design upgrades with things like fish ladders or better relocation packages [40]. In other words, costs went up because manufacturers were required to expand the scope of a project to meet environmental objectives. For thermal plants, many projects in our post-2003 sample included newer, costlier designs such as integrated gasification combined cycle ("clean coal"), meaning they were often first-of-kind projects, or costlier retrofits of existing facilities. Both hydro and thermal plants also likely saw a large uptick in cost overruns due to increases in material costs in the late 2000s due to massive demand for concrete and other construction material resulting from the economic boom in China.

One further tentative conclusion can be drawn from Fig. 4: learning curves can be dependent on the type of energy system, a conclusion reflected in the energy studies literature. One survey of learning curves looking at reductions in the delivered price of energy for various energy technologies (including construction costs plus operations and other expenses) found that doubling the capacity for a given energy system could reduce costs by 20 percent [16]. However, the largest units were exceptions to this trend. The three largest energy systems studied—nuclear reactors, supercritical coal facilities, and big hydro units—only had respective learning growth rates of 5.8 percent, 3 percent, and 1.4 percent compared to double-digit rates for smaller units such as combined cycle gas turbines, wind turbines, and solar panels. A second, independent assessment from the International Institute for Applied Systems Analysis [7] looked at the learning curves for three types of manufacturing processes: those at "big plants", those with medium sized "modules", and those with smaller-scale systems. The study noted that the "highest learning effects" were observed for the smallest facilities and that "big plants and modules display less dynamic learning effects." Indeed, in some cases, such as the French nuclear sector, reactors have shown a *negative* learning curve with rising costs between each generation of technology, related in part

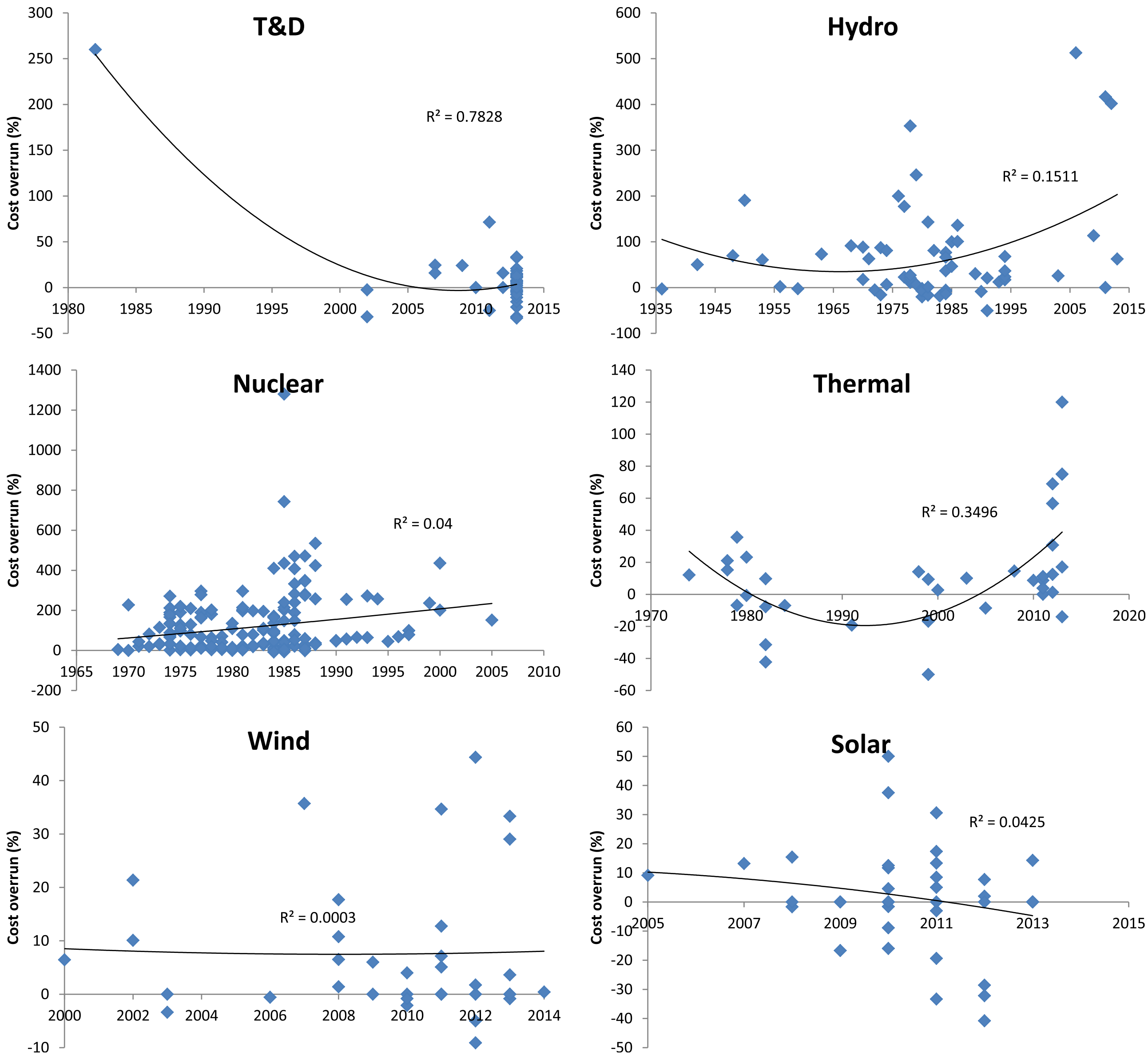

Fig. 4. Polynomial and logarithmic trend lines for mean cost escalation and date of project completion, by reference class.

to additional safety features and regulation but also inescapable problems in technical design [13].

3.4. H4: governance matters

Our fourth hypothesis was that, independent of reference class, location would matter. Countries with more robust governance frameworks—better social and environmental impact assessment requirements, accountability, or stakeholder inclusive permitting—would see enhanced transparency and lower risks of cost overruns than countries with weaker regulatory governance. Compounding the issue is inflation and currency exchange; overrun dynamics in developing countries seem to be particularly volatile, given that foreign currency exchange can severely impact or delay a project due to the need to purchase foreign goods. Additionally, emerging and developing economies are likely to see a comparative lack of experienced teams, potentially increasing labor costs, requiring foreign laborers, and delaying projects. Lastly, foreign projects done under the auspices of development assistance can sometimes be “tied aid;” the proxy reason for building a project is to expand energy supply, but the real reason is something else, like selling arms or promoting democracy. Thus, as the infrastructural costs are really supporting other aims, project costs are not treated critically [20]. Perhaps for these complex reasons, Flyvbjerg et al. [9] noted that for transportation projects, “cost underestimation appears to be more pronounced in developing nations than in North America and Europe.” And the World Commission on Dams [40] concluded that construction “performance was worst” in “Central Asia and South Asia,” with cost overruns averaging 108% and 138%, respectively.

As Table 3 indicates, we almost completely disprove this hypothesis for energy projects. Europe, across all projects, did see the lowest mean cost escalation (26.5 percent), but this figure was tied with that of projects in South America. Africa and the Middle East, and the Asia-Pacific, had mean cost escalation across all projects between 34.9 and 48.1 percent. The worst performer, by a wide margin, was North America, with a mean cost escalation of 115.2 percent. However, this high escalation rate was certainly influenced by nuclear reactors in the North America sample; excluding nuclear reactors reduces the mean cost escalation to only 16.7%. If anything,

Table 3
Summary cost overrun data for electricity projects by location.

Region	Number of projects (*N*)	Mean cost escalation (%)	Standard deviation	Median	Mode
North America	155	115.2	162.4	67	0
Africa and the Middle East	18	34.9	74.4	0	0
Europe[a]	113	26.5	47.2	15.1	0
Asia-Pacific[b]	96	48.1	101.5	12.7	0
South America	19	26.5	49.6	16.9	–

[a] "Europe" includes Russia.
[b] "Asia-Pacific" includes Australia and New Zealand.

the large influence of nuclear overruns is indicative of how frequent and severe reactor overruns were at that time.

The explanation here may lie not only in the large number of nuclear reactors within the North American sample, but also in what historian Richard Hirsh has called "technological stasis." According to Hirsh [14], a general decline of technological improvement in the electricity industry started in the late 1960s and 1970s. Thermal efficiencies for power plants plateaued and then diseconomies of scale and barriers to unit size were introduced as operators tried to order power plants that were simply too big. Engineers and contractors overestimated the importance of digital computers, which they had (mistakenly) believed would overcome problems in design and complexity. Engineers and utility managers (sometimes engineers themselves) believed technological skill alone could overcome these problems, and such unbridled faith led to disastrous business decisions based on assumptions of future improvements and ingenuity that never materialized.

3.5. *H5: small is beautiful*

Our fifth hypothesis was that smaller, decentralized, modular, scalable systems such as wind and solar would see fewer cost overruns by both frequency and magnitude. This hypothesis arises from literature suggesting that distributed forms of electricity supply have benefits in being more modular and, oftentimes, located closer to the point of end-use. Their modularity means that distributed generators can be deployed to precisely match smaller increments of demand. The International Energy Agency (IEA), for instance, has concluded that smaller, more modular devices for electricity and heating can deliver energy security benefits more rapidly, and comprehensively, than larger systems [25]. They have the advantage of being able to provide a "diverse scale of heating" depending on the particular energy service desired by residential and commercial customers. The IEA also concluded that more modular systems ran a lower risk of technical systems failures.

The data trends in Fig. 5 clearly support this hypothesis—as one moves down in project size from hydro (mean project capacity of 1865 MW) and nuclear (987 MW) to thermal plants (710 MW), wind (35 MW), and solar (39 MW), one sees a significant reduction in the mean cost escalation per project and the frequency of project overruns. Interestingly, transmission projects, perhaps also because they are relatively modular, have similar construction benefits. Perhaps this is because like wind and solar systems, transmission projects, excluding substations and transformers, can be built with pre-fabricated, mass manufactured materials; building 10 km is roughly the same as building 100 km.

3.6. *H6: tiny is trouble*

This final hypothesis looks at things a bit differently: it normalizes the results across each project and reference class by MW of installed capacity. Intuitively, smaller projects such as wind and solar would not perform well under this process of normalization, since they have significantly smaller installed capacities than nuclear reactors, hydroelectric dams, and thermal units. As just one example, a tiny 1 MW solar project from our sample with an overrun of $600,000 shows, when normalized, an overrun of 9 percent per MW. Comparably, a massive dam from our sample with a $15.9 billion overrun (200% of expected budget), when normalized, shows as only 0.07 percent per MW because there were so many megawatts to dilute the percentage with.

Intriguingly, this hypothesis is invalidated by our data. As Fig. 6 indicates, when all 351 power plant projects are normalized and plotted together, some solar and wind projects show up on the left side of the axis, towards higher cost overruns per installed MW, but nuclear and hydro still dominate that side of the graph, and to the right cost underruns are prevalent for solar, thermal, and a collection of small hydro projects. This suggests the opposite of the hypothesis, namely that smaller projects also have fewer overruns per installed MW when normalized to scale.

Furthermore, Fig. 7 presents the arithmetic mean of normalized overruns for both each project as well as for each reference class as a whole (a better way of weighting large and small projects together). The top panel shows that hydro and nuclear projects have overruns ranging from $800,000 to $1.3 million per installed MW (in a class of their own) compared to fewer than $250,000 per installed MW for thermal, wind, and solar projects. When taken as a reference class, solar projects actually have a net underrun for each installed MW. The bottom panel divides our normalized results for large-scale power plants into "small" and "large" to determine if any advantages to scale are evident. It documents slight economies of scale for hydro units as they get larger (though the greater magnitude of overruns almost offsets this) and major economies of scale for thermal units as they get larger (almost a 50% drop in installed costs per MW, inclusive of overruns, for facilities greater than 1000 MW), but major diseconomies of scale for nuclear reactors (prices rise 63% per installed MW, inclusive of overruns, for facilities greater than 1000 MW). The implication is that larger hydro units see almost no benefits to scaling up and that nuclear units see a net disadvantage to scaling up.

4. Conclusion and implications

One way of interpreting our data is that power plants and investments in electricity infrastructure are risky ventures, given that the average length of construction for the 401 projects we surveyed exceeded 70 months, a timeframe almost equal to the time it took the countries of Asia, Europe, and North America to fight World War II (72 months and 1 day). Across the whole sample, the average

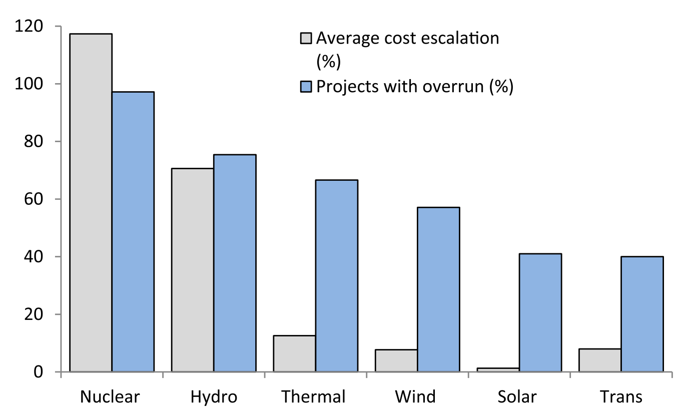

Fig. 5. Frequency and magnitude of cost overruns by reference class.

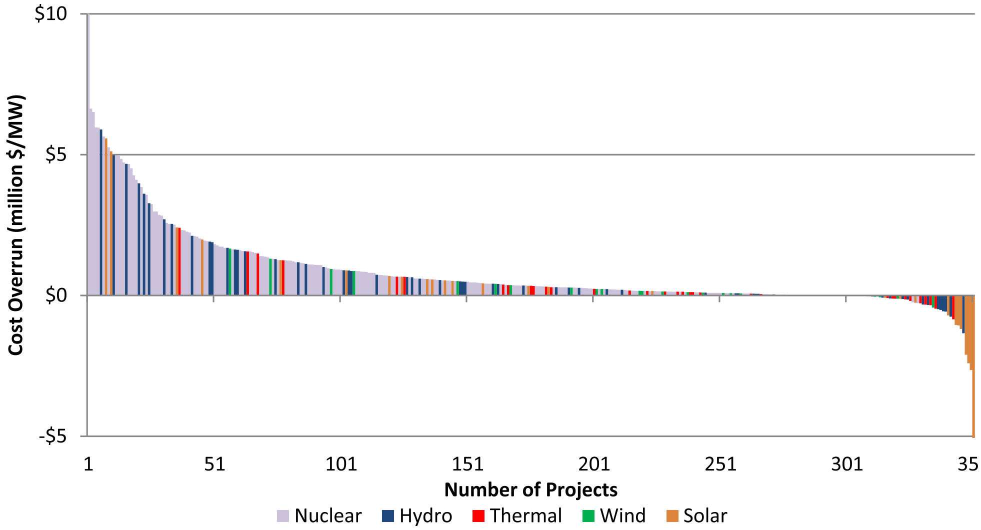

Fig. 6. Cost overruns by reference class normalized to installed megawatt (MW). Note: this figure excludes transmission projects, as these cannot be normalized to $/MW.

cost overrun was $967 million per project or an overrun of 66.3%, rising to $1.2 billion per nuclear project (mean cost escalation of 117%) or $2.4 billion per hydro project (mean cost escalation of 70.6%). As Table 4 summarizes, however, when compared to other types of infrastructure, thermal power plants, wind farms, solar facilities, and transmission projects have a frequency and magnitude of cost overruns lower than "average" transport or even mining projects. Nuclear reactors stand apart at the top of Table 4 for both mean cost escalation and frequency; hydroelectric dams stand apart for their mean cost escalation even if their frequency is lower than transport projects. Normalizing results to scale does not alter this finding: nuclear and hydro facilities still have significantly higher overruns per installed MW ($800,000 to $1.3 million) than thermal, solar, and wind projects (less than $250,000).

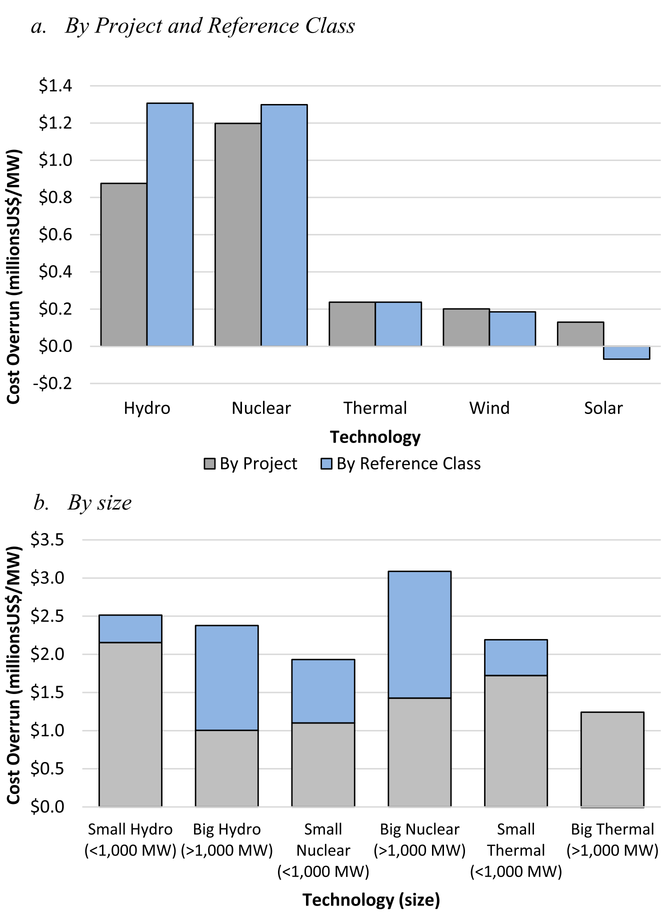

Fig. 7. Normalized cost overruns by project, reference class, and size. (a) By project and reference class. (b) By size.

Rather than merely conclude that electricity infrastructure is inherently risky from a construction standpoint, we advance four other implications with our study. The first is that many of the hypotheses that we aimed to test with our data, some of them intuitive, others grounded in the literature—appear wrong. As Table 5 summarizes, the "bigger is bad" hypothesis about capital intensity is supported only for transmission projects and hydroelectric dams; nuclear reactors seem prone to cost overruns regardless of their size and we see (slight) reductions in overrun risks as solar, wind, and thermal projects get larger. The "longer is costlier" hypothesis about project delays is supported for most projects but the opposite seems to occur for solar facilities. The "later is better" hypothesis about learning is supported for transmission, wind, and solar projects, but not for nuclear, hydro, and

Table 4
Mean cost escalation for various infrastructure projects.

Technology	Mean cost escalation (%)	Frequency (%)	(n) For the sample
Nuclear reactors	117	97	180
Hydroelectric dams	71	75	61
Railway networks	45	86*	58
Bridges and tunnels	34	86*	33
Roads	20	86*	167
Mining projects	14	70	63
Thermal power plants	13	67	36
Wind farms	8	57	35
Transmission projects	8	40	50
Solar farms	1	41	39

* Flyvbjerg et al. do not disaggregate cost overrun frequencies by type of project across their sample, and instead state that "Costs are underestimated in almost 9 out of 10 projects. For a randomly selected project, the likelihood of actual costs being larger than estimated costs is 86%." Data for electricity infrastructure comes from this study. Data for mining projects comes from Ref. [4], where they state that out of 63 projects, 44 experienced overruns. All other items come from either this study or Ref. [10].

Table 5
Summary results for six hypotheses about construction overruns by reference class.

Hypothesis	Reference class	Validated (true)	Invalidated (opposite is true)	Inconclusive (no correlation)	Statistically significant ($R^2 > 20\%$) trend line?
H1: bigger is bad	Transmission	✓			Yes
	Nuclear			✓	No
	Hydro	✓			Yes
	Thermal		✓		No
	Wind		✓		No
	Solar		✓		No
H2: longer is costlier	Transmission	✓			Yes
	Nuclear	✓			Yes
	Hydro	✓			Yes
	Thermal	✓			No
	Wind	✓			No
	Solar		✓		No
H3: later is better	Transmission	✓			Yes
	Nuclear		✓		No
	Hydro			✓	No
	Thermal			✓	Yes
	Wind	✓			No
	Solar	✓			No
H4: governance matters	North America		✓		–
	Africa and the Middle East		✓		–
	Europe	✓			–
	Asia-Pacific		✓		–
	South America		✓		–
H5: small is beautiful	Transmission	✓			–
	Nuclear	✓			–
	Hydro	✓			–
	Thermal	✓			–
	Wind	✓			–
	Solar	✓			–
H6: tiny is trouble	Transmission	–	–	–	–
	Nuclear		✓		–
	Hydro		✓		–
	Thermal		✓		–
	Wind		✓		–
	Solar		✓		–

thermal projects. The "governance matters" and "tiny is trouble" hypotheses about location and normalization of results to scale are proven almost entirely untrue. Only in the "small is beautiful" hypothesis do we see a significant relationship between decentralized energy projects and fewer frequency and magnitude of overruns. This gap between academic expectations and reality indicates a possible discrepancy in what peer-reviewed journal articles and books deem to be crucial contributors to cost overruns, and what actual experience with 401 projects "on the ground" suggests.

Second, while we have only investigated historical overruns, we believe many lessons are relevant for future projects. In a sense, it is perhaps unfair to draw lessons from "classic" dams like Hoover and Grand Coulee, which have little in common with newer units using state-of-the-art hydroelectric dam design, or from Generation II and III reactors, compared to European pressurized reactor vessels being built in Europe. If one wanted to look at how learning curves would work for the steel-plate, modular construction methods used in the AP-1000, probably the best place to look will be the Finnish ship building industry, which uses the same methods to manufacture and assemble large cruise ships, rather than older reactors. Newer reactor designs, moreover, are trying to learn from the benefits of scalability and decentralization, especially the push for "small modular reactors" and high-precision, high quality fabrication into more controlled factory settings [27]. In short: history may not be the best guide for what future construction risks will confront the electricity industry. That said, the other side of the argument is that even modern nuclear and hydro projects in our sample were plagued with cost overruns, and that if one adjusts our sample to look only beyond 1990 or even 2000, the majority of projects still suffered overruns. We believe, as Zerger and Noel [41] have written, that "lessons learned from the past construction periods or from the ongoing construction projects are very important for the increased number of utilities and regulators involved in building new nuclear power plants." Or, as Koomey and Hultman [19] concluded in their own assessment, "the historical record, while not predictive, can nevertheless be instructive."

Third, and most importantly, the fact that transmission lines, wind, solar, and smaller thermal projects tended to have the least risk of cost overruns, even when normalized per installed MW, raises some salient points about how to (potentially) best manage electricity projects. In terms of funding, these types of projects are often financed through state or municipal bonds, or backed by cooperatives, and implemented as public–private partnerships, which can lower overall construction risk [12]. In terms of modularity, the risk of having a component breakdown or being delayed is limited to a single turbine or panel; most of these have components that are also mass produced. In terms of marketing their energy, most wind and solar power is sold under power purchase agreements, so the risk of cost overruns is irrelevant from the point of view of the buyer. In some cases, turbine or solar panel suppliers will even offer fixed price units including delivery to the site, construction of foundations, erection and commissioning; lenders often force these types of contracts from bonded companies. In terms of risk, most of these smaller projects have contingencies for overruns (between 3 and 10 percent of project budget), and almost all risk is transferred to the seller, which is expressed in the rate of profit.

This contrasts with common practices for nuclear and hydro projects. These projects are often state sponsored, and even then have large subsidies such as loan guarantees or limited liability for major accidents. In terms of marketing their energy, fixed price supply contracts seem to be nonexistent. In terms of modularity, a far greater complexity of systems results in a greater likelihood that trouble with a single component, or delays in its delivery, affect the entire project; most components are custom built. In terms of risk, there are practically no merchant large-scale nuclear or hydro owners and the cost of overruns is often passed onto customers or other stakeholders. Indeed, the nonpartisan Congressional Budget Office [36] in the United States found that who had to pay for an overrun significantly influenced their scope and severity; most overruns for nuclear reactors occurred when their costs could be passed on as an "allowable charge" to ratepayers.

Fourth, financiers or sponsors may commit to a project even though they know it will result in a cost overrun—that is, the risk of "negative learning" does not stop the momentum of the project. Flyvbjerg et al. [9] suggest that "cost inaccuracy" results from "intentional deception" or "strategic misrepresentation," basically big words that mean "lying." As they put it, "it is found with overwhelming statistical significance that the cost estimates used to decide whether such projects should be built are highly and systematically misleading. Underestimation cannot be explained by error." Such cost underestimation appears "to be a global phenomenon" and "no learning that would improve cost estimate accuracy seems to take place". One factor driving this trend is likely the "sunk cost hypothesis," also known as the "escalation-of-commitment hypothesis," which states that once started, project sponsors will "throw good money after bad" to see it through to the end [39]. As Walker [38] concludes, "embedded commitments can create inertia, causing inferior technologies and technology paths to survive long after they should have been abandoned."

What this boils down to is that, for better or for worse, "the type of accountability appears to matter more to cost escalation than type of ownership" [10]. It may be non-technical factors such as the degree of bias within projected budgets, nature and type of financing, degree of cost-sharing or partnership, and, ultimately, who has to pay for an overrun that is the most significant determinant of whether one occurs. This may serve as an uncomfortable reminder that the same "social" factors contributing to the risk of an overrun may also be those least under the control of constructors and contractors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2014.07.070.

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