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Construction Cost Overruns and Electricity Infrastructure: An Unavoidable Risk?

An analysis of 401 power plant and transmission projects in 57 countries suggests that costs are underestimated in three out of every four projects, with only 39 projects across the entire sample experiencing no cost overrun or underrun. Hydroelectric dams, nuclear power plants, wind farms and solar facilities each have their own unique set of construction risks.

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I. Introduction

Those outside the construction industry may be surprised to learn that the cost of building power plants has escalated in recent years. The Power Capital Costs Index, which tracks the expense of power plant materials and components, showed an increase in North America by a factor of 2.26 between 2000 and 2013, and in Europe by a factor of 1.93 over the same period (IHS Costs and Strategic Sourcing, 2014). These expenses exclude other ''soft costs'' such as contingency fees, risk premiums, land, and permitting (Severance, 2009). The nuclear energy industry has been particularly hard hit, with material, labor, and engineering costs for nuclear power plants jumping more than the average over the same period, meaning a plant that cost $4 billion to build in 2000 would cost almost $12 billion today (Findlay, 2010).

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But how do the risks of construction cost overruns compare across different forms of electricity infrastructure? How do utility-scale renewable sources of electricity such as wind farms and solar facilities perform compared to thermal plants, nuclear reactors, and hydroelectric dams? Where do high-voltage transmission networks fall on this continuum of overrun risk?

This article answers such questions by exploring initial construction budgets and final costs associated with 401 separate power plant and transmission projects, spread across 57 countries, representing nearly $820 billion worth of investment and 325,515 MW of installed capacity. We find that although costs are underestimated in three out of every four projects, the frequency and magnitude of those overruns differ substantially by size, location, and fuel source, as **Figure 1** summarizes. Independent of their type, we conclude that construction costs for electricity projects are difficult to predict, as only 39 projects across the entire sample were completed at or under budget. We also find that hydroelectric dams, nuclear power plants, wind farms, and solar facilities each have their own unique set of construction risks, which we elaborate on below.

II. Research Methods

In defining the scope of this study, we first decided to limit our assessment to electricity infrastructure, given that transportation projects have already been assessed extensively by Flyvbjerg and his colleagues, who compiled a database of 258 transportation infrastructure projects worth $90 billion (Flyvbjerg et al., 2002, 2004). Secondly, we decided to investigate only actually completed utility-scale projects greater than 1 MW in size. This excluded forms of distributed generation such as fuel cells and Stirling engines, smaller-scale generation sources such as diesel generator sets and microhydro dams, and projects canceled or still under construction in late 2013 and early 2014. As locating reliable data for both the original cost estimate *and* the actual cost of a project was surprisingly difficult, we choose not to confine our data collection to any geographical area or period of time in order to make our database as large, and robust, as possible.

To begin collecting data, we first searched the energy, electricity, transport, and infrastructure literature for reliable peer-reviewed data, which we did find in a few instances (Flyvbjerg et al., 2002, 2004; De Bondt and Makhija, 1988; Marshall and Navarro, 1991; Grubler, 2010; Ansar et al., 2014; Bacon and Besant-Jones, 1998). However the rest we compiled ourselves by searching hundreds of project documents, press releases, and reports (Appendix I). We only included a project in our database when we could find complete information regarding:

- The year the project entered service;
- Its geographic location;
- Its name;
- Its size in installed capacity (in MW or kV);
- Its estimated or quoted construction cost;

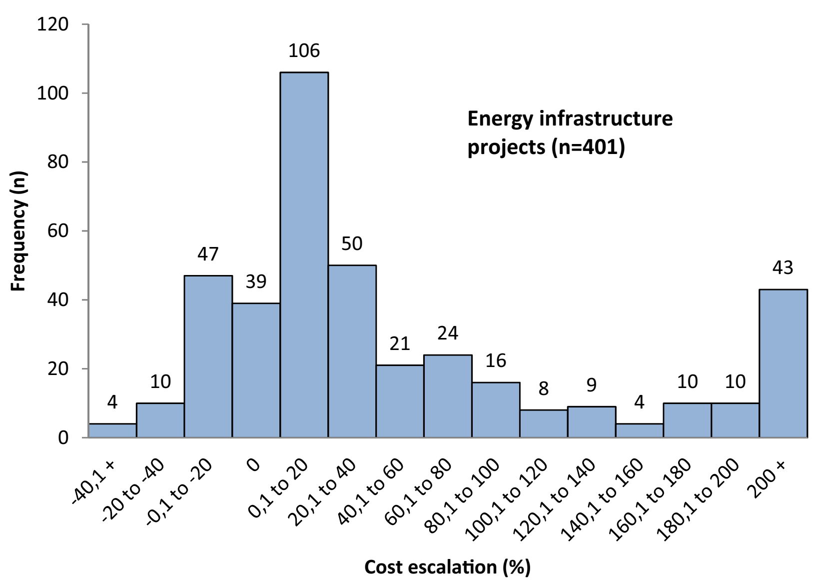

Figure 1: Frequency and Cost Escalation of Electricity Infrastructure Projects

- Its actual construction cost; and
- If available, its estimated construction time and actual construction time (which we were able to find for a smaller subsample of 327 projects).

We 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. Our final dataset encompassed 401 projects (Appendix II).

In building our database this way, some caveats deserve mentioning. We searched only in English, so our sample has a likely bias for North American and European projects (66 percent of those in the database). We also built our database from September 2013 to January 2014, meaning any newly released data post-Jan. 31, 2014, would not be included. By ''construction cost'' we refer to ''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'' (Zerger and Noël, 2011). This means we investigated so-called ''installed costs'' rather than ''overnight construction costs'' (Koomey and Hultman, 2007). Because we are cognizant that the term ''cost overrun'' is a pejorative term that project sponsors may not want to publicize, we not only detected them when documents used that precise phrase, we also inferred them if there was a difference between the quoted cost at the start of project and quoted cost at the completion of project.

III. Results

Across our entire sample of more than 400 projects, the average installed capacity was 927 MW for a power plant, and the average length was 193 km for a transmission line. The mean installed cost per kilowatt (kW) was $3,185. The average, randomly chosen project took 73.4 months to construct and had a cost overrun of $1 billion (or a mean budget escalation of 66 percent). Overall, 75.1 percent of projects in the sample experienced a cost overrun. As this section of the article explains, the particular construction cost overrun risks differ meaningfully between hydroelectric dams, nuclear power plants, wind farms, and solar energy facilities.

A. Hydroelectric dams

Sixty-one hydroelectric dams made it into our sample representing 113,774 MW of installed capacity worth $271.5 billion of investment. These projects experienced a total of $148.6 billion in cost overruns (38.3 percent of the total overrun cost across the entire sample) and exhibited a mean cost escalation of 70.6 percent. Cost overruns also afflicted more than three out of every four (75.4 percent) of the hydroelectric projects in the sample. Hydroelectric dams had the longest mean construction time of all projects, as well as the largest total cost overrun amount per project, as Figure 2 reveals.

One possible explanation for why hydroelectric projects suffer the largest mean cost overrun of any project is that they are, on average, more materials-intensive than other energy sources. On a per GW basis, for instance, they need three times as much concrete as a nuclear reactor (Sovacool, 2010). The

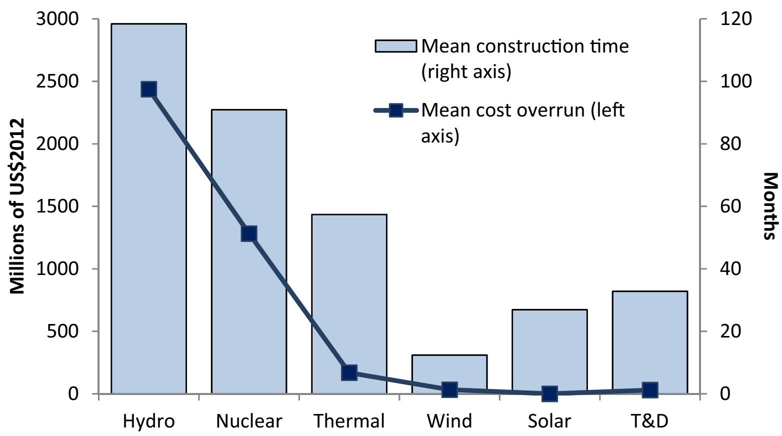

Figure 2: Mean Construction Times and Cost Overruns for Electricity Infrastructure by Reference Class. **Note:** Construction time data are from a smaller sample of projects

World Commission on Dams has also posited that large dams are unusually prone to unforeseen excavation and construction problems given that geotechnical conditions at the site, such as the quality of foundational rocks and composition of construction materials, cannot be precisely evaluated until after construction begins (World Commission on Dams, 2000). Building dams thus involves a great deal of (expensive) trial and error.

Other studies seem to confirm our findings about hydroelectric infrastructure being prone, excessively, to cost overruns. One recent study from Flyvbjerg and his colleagues utilized reference class forecasting to assess the outcomes and costs of 245 dams—186 of which were hydroelectric—built between 1934 and 2007, across five continents and 65 countries (Ansar et al., 2014). These dams collectively involved more than $353 billion worth of investment. The study found ‘‘overwhelming evidence that budgets are systematically biased below actual costs of large hydropower dams’’ and that ‘‘actual costs were on average 96 percent higher than estimated costs.’’ The authors highlighted that these cost overrun figures are exceptionally conservative as they *exclude* inflation, substantial debt servicing, and other environmental and social costs. Similar conclusions were reached by the World Commission on Dams, who surveyed 81 large projects and found that the mean cost escalation was 56 percent and that about three-quarters of projects were afflicted by cost overruns (World Commission on Dams, 2000). In parallel, the World Bank has noted meaningful cost overrun trends in some of their assessments of large hydropower projects (Merrow and Shangraw, 1990; Bacon et al., 1996).

B. Nuclear power plants

One hundred and eighty nuclear reactors in our sample, representing 177,591 MW of installed capacity and $459 billion worth of investment, generated almost $231 billion in cost overruns (59.5 percent of all overruns across the sample), the largest of any class of technology. As **Figure 3** indicates, such reactors had a mean cost escalation of 117.3 percent, and cost overruns afflicted more than nine out of every 10 of the projects in our sample.

Interestingly, 64 percent of nuclear projects had a time overrun yet close to all of them (97.2 percent) had a cost overrun, which does cast some doubt on the monotonic relationship between time overruns and cost overruns. One explanation for this mismatch between project delays and cost overrun trends could be that costly attempts were made to accelerate schedules so as to minimize delays. This could have resulted in higher wages and overtime costs, used to attract workers, leading to a decrease in lead times but an increase in expenses (U.S. Energy Information Administration, 1986).

Another possible reason nuclear plants were prone to such a large total amount of cost overruns (almost two-thirds of all costs in our sample of 401 projects) could be that atomic energy was not technically or economically feasible when it was originally embraced in the 1940s and 1950s. For example, the Dwight D. Eisenhower Administration decided to develop nuclear power plants in the 1950s for entirely political reasons, seeking to demonstrate positive aspects of nuclear energy after World War II, and to instigate a technology race with the Soviet Union (Byrne and

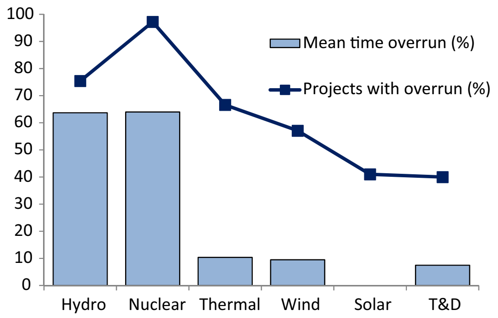

Figure 3: Mean Time Overruns and Percentage of Projects with a Cost Overrun for Electricity Infrastructure by Reference Class. **Note:** Construction time data are from a smaller sample of projects

Hoffman, 1996). Similarly in France, Charles de Gaulle promoted nuclear power plants as a mechanism to reconstruct French national identity. Nuclear technology was seen by French policymakers as a way to simultaneously rebuild French infrastructure and reestablish its role as a world leader (Hecht, 1998). In both the French and American cases, government created a market for nuclear power, rather than the other way around—meaning cost considerations came second to political ones.

A third reason nuclear plants experienced major cost overruns relates to the process of ''regulatory ratcheting.'' Dozens of reactors in our sample were under construction during the major nuclear accidents at Three Mile Island (in 1979) and Chernobyl (in 1986). After these events, regulatory requirements were significantly tightened, with significant impacts on equipment needs, construction designs, labor, and materials. As Cohen writes, ''ratcheting applied to plants under construction caused much more serious problems. As new regulations were issued, designs had to be modified to incorporate them'' (Cohen, 1990). This resulted in significant price increases and delays.

A fourth reason involves ''negative learning.'' Researchers from the International Institute for Applied Systems Analysis looked at the learning curves for three types of general manufacturing processes (i.e., used throughout industry and not necessarily only the energy industry): those at ''big plants,'' those with medium-sized ''modules,'' and those with smaller-scale systems that were ''continuously'' operated. They found that the ''highest learning effects'' were observed for the smallest facilities and that ''big plants and modules display less dynamic learning effects'' (Christiansson, 1995). Indeed, in some cases, such as France, nuclear power reactors have shown a *negative* learning curve with rising costs between each generation of technology (Grubler, 2009).

Nuclear technology was seen by French policymakers as a way to simultaneously rebuild French infrastructure and reestablish its role as a world leader.

A fifth and final reason, at least for reactors in the United States, which composed a large part of our sample, is that that there was no universally accepted or standardized plant design when most facilities were being built throughout the country. Consequently, engineering costs for almost every single plant were much higher than they would be otherwise. Researchers at Georgetown University, the University of California at Berkeley, and the Lawrence Berkeley National Laboratory assessed a three decade historical database of delivered costs from each of 99 conventional nuclear reactors operating in the United States (at that time) (Hultman et al., 2007). Their assessment found a significant group of plants with extremely high historical costs: 16 percent in the more than 8¢/kWh category. The authors pointed out two unique attributes of reactors that made them prone to unexpected increases in cost: (1) their dependence on operational learning, a feature not well suited to rapidly changing technology and market environments subject to local variability in supplies, labor, technology, public opinion, and the risks of capital cost escalation; and (2) difficulty in standardizing units, or the idiosyncratic problems of relying on large generators whose specific site requirements do not allow for mass production.

C. Wind and solar farms

Thirty-five onshore and offshore wind farms, constituting 6,201 MW of installed capacity and worth $20.1 billion in investment, generated $1.1 billion of cost overruns, the second smallest in our sample. These wind farms had a mean cost escalation of only 7.7 percent, and while cost overruns afflicted slightly more than half (57 percent) of projects, the mean cost overrun amount was only $32.8

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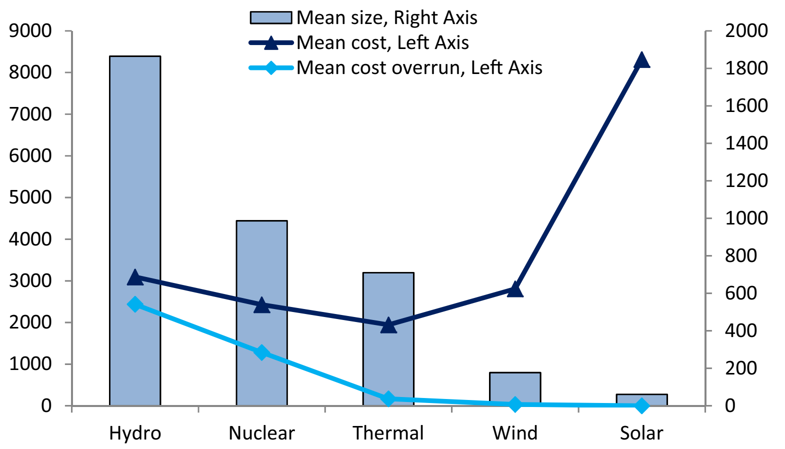

Figure 4: Mean Size (MW), Cost Overrun (Millions of USD), and Cost (per installed kW) for Electricity Infrastructure by Reference Class

million. Thirty-nine large solar PV or CSP power plants, representing 2,374 MW of installed capacity worth $16.5 billion worth of investment, actually came in as a class $4.2 million under budget, or $200,000 less than expected per project, with a mean cost escalation (overall, when it did occur) of 1.3 percent. These solar systems had the highest rate (28.2 percent) of cost underruns, when excluding transmission projects, as well.

However, our class of solar facilities also had, by far, the highest construction costs per installed kW, in some instances exceeding more than three times that of thermal and nuclear plants. (Wind farms had a far lower mean cost per kW, coming third in terms of cheapness after thermal and nuclear plants). The implication—evident in Figure 4—seems to be that as facilities grow smaller, construction lead times drop significantly, and the amount of the average cost overrun declines along with the percentage of cost escalation. However, the price per installed kW jumps—suggesting that one must ''pay'' for the mitigation of construction risk that these smaller projects offer.

As to the subtle differences between wind and solar—both are considered forms of distributed generation and are built in much smaller increments than thermal, nuclear, and hydro facilities—perhaps wind experienced a greater degree and extent of cost overruns due to recent trends specific to that sector. Rapid growth in demand has led to shortfalls of equipment, and macroeconomic drivers such as labor costs and commodity prices have led to higher capital and operating expenses (Levitt et al., 2011; Bolinger and Wiser, 2009). Bolinger and Wiser (2012) attribute much of the increase to ''turbine scaling,'' making individual units larger, which they found to have been the largest single contributor to a price doubling of wind energy from 2000 to 2008, although they emphasize that the incremental cost of scaling is justified by greater energy capture, resulting in a lower levelized cost of wind generated electricity. Solar facilities, by contrast, have benefited from lower priced inputs such as silicon and faster rates of technological learning (Nemet, 2006, 2009).

IV. Discussion

What, then, accounts for the prevalence of cost overruns across these distinct classes of electricity projects? While not an exhaustive explanation, this section proposes at least three fundamental reasons.

First, construction cost overruns are multi-causal; they cannot be reduced to a single factor, which means even having one thing ''go wrong''—such as a delay, missing component, or shortage of labor—can impact construction schedules. The U.S. Energy Information Administration (EIA) made this argument when looking at the factors causing cost overruns in the nuclear industry in the 1980s, and concluded that ''increases in the quantities of land, labor, material, and equipment'' as well as increases in financing charges all played contributory roles (U.S. EIA, 1986). Similarly, technical construction problems, poor implementation by suppliers and contractors, changes in economic and regulatory conditions, and resettlement costs all play contributory roles to cost overruns for hydroelectric dams

(World Commission on Dams, 2000).

Second, poor management and/or accountability can be just as influential in causing an overrun as difficulties with technology and equipment. The EIA confirmed this point when they compared cost overruns between utilities that performed their own construction management and those that outsourced it. They found that ''the management structure under which a power plant is constructed is an important determinant of real overnight costs'' and that direct utility participation in the construction process contributed to lower costs and increased learning (U.S. EIA, 1986). A separate study of the Japanese nuclear power industry reached much the same conclusion, noting that nuclear power plant operators with large ownership stakes exercised more diligent cost control than when overruns were spread over a larger number of co-owners (Lyon and Mayo, 2005).

Third, cost overruns may not always be accidental, and can, in a sense, be strategic. That is, project sponsors can misrepresent costs and benefits of a project in order to motivate stakeholder involvement and then commitment (Sovacool and Cooper, 2013). Flyvbjerg has found that large-scale energy and transport projects are consistently approved on the basis of underestimated costs, overestimated revenues, undervalued environmental impacts, and overvalued economic development effects. This misinformation *intentionally* distorts risk assessments and conceals the true risk of projects from investors, taxpayers, and regulators until it is ''too late'' to abandon a project. Contractors eager to have their projects accepted may produce overly optimistic assessments at the genesis of a project expecting that

it will be too far along to back-out by the time its viability can be more accurately assessed (Flyvbjerg et al., 2003). According to Flyvbjerg and his colleagues, contractual penalties for producing overly optimistic assessments are lower than the potential profits to be gained by misrepresentation, providing a perverse incentive for contractors to game the system even if they *are* held accountable later (Flyvbjerg, 2006). The solution, for Flyvbjerg, is to improve accountability. As he concludes, ''the key principle is that the cost of making a wrong forecast should fall on those making the forecast, a principle often violated today'' (Flyvbjerg, 2005).

V. Conclusion

Essentially, our data suggests that power plants and investments in electricity infrastructure are risky ventures. The average length of construction for the 401 projects we surveyed exceeded 70 months, which, by the way, is longer than the duration of World War II. In addition, for some specific technologies, mean construction times surpassed 118 months (hydroelectric dams) and 90 months (nuclear reactors). Across the whole sample, the average cost overrun was $967 million per project or an overrun of 66.3 percent, rising to $1.2 billion per nuclear project (mean cost escalation of 117 percent) or $2.4 billion per hydro project (mean cost escalation of 70.6 percent). Also, across the entire sample 75.1 percent of projects suffered cost overruns.

Revealingly, while solar and wind have lower overall construction risks, they were still susceptible to cost overruns. Almost one in three solar projects (28.2 percent) suffered an overrun and more than half (57 percent) of wind projects did. However, the mean amounts of $1.3 million (solar) and $7.7 million (wind) pale in relationship to the others. As **Table 1** summarizes, when compared to other types of infrastructure, nuclear reactors, and hydroelectric dams stand in a class of their own concerning the risk of a construction cost overrun.

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Table 1: Mean Cost Escalation for Various Infrastructure Projects.

Technology	Mean Cost Escalation (%)	(*n*) for the Sample
Nuclear reactors	117	180
Hydroelectric dams	71	61
Railway networks	45	58
Bridges and tunnels	34	33
Roads	20	167
Mining projects	14	63
Thermal power plants	13	36
Wind farms	8	35
Transmission projects	8	50
Solar farms	1	39

Source: Data for electricity infrastructure comes from this study. Data for other items come from (Flyvbjerg et al., 2002, 2004).

In sum, electricity infrastructure seems prone to cost overrun issues independent, almost, of technology or location. Each of these different types of electricity infrastructure poses different construction risks. The findings of this study do not bode well for climate change mitigation efforts, given that two of the largest ''wedges'' (Pacala and Socolow, 2004) that we have to mitigate emissions—hydroelectric dams and nuclear reactors—have the greatest amount and frequency of cost overruns. Yet as systems get smaller in overall capacity (moving to wind and solar) we see generally higher per installed kW costs but also less risk to overruns and lower rates of overruns that are less costly when they occur. This may imply that utilities and project sponsors face the dilemma of having to ''pay'' for risk protection: you pay higher costs per kW to achieve more predictable risks/investment ratios due to solar and wind's modularity.

Appendices I and II. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tej.2014.03.015.

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❖ *Meetings of Interest* ❖

Conference	*Date*	*Place*	*Sponsor*	*Contact*
Energy Policy Institute Research Conference	Sept. 4–5, 2014	San Francisco	Boise State University	epi.boisestate.edu/conference

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