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An international comparative assessment of construction cost overruns for electricity infrastructure

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ABSTRACT

Earlier this year, we assessed the construction costs affiliated with 401 electricity infrastructure projects worldwide. We found that these projects collectively involved $820 billion worth of investment, and represented more than 325,000 MW of installed capacity and 8500 km of transmission lines. Taken together, these projects incurred $388 billion in cost overruns, equivalent to a mean cost escalation of $968 million per project, or a 66.3 percent overrun per project. In this article, we extend upon that earlier analysis to explain how hydroelectric dams, nuclear reactors, wind farms, solar facilities, fossil fueled thermal plants, and transmission lines pose distinct construction risks. We highlight that electricity infrastructure is prone to cost overrun issues almost independently of technology or location, that hydroelectric dams and nuclear reactors have the greatest amount and frequency of cost overruns, even when normalized to overrun per installed MW, and that solar and wind projects seem to present the least construction risk. Consequently, investors, electric utilities, public officials, and energy analysts need to rethink and reevaluate the methodologies they use to predict construction timetables and calculate budgets.

1. Introduction

Dependable projections of construction costs and schedules are of vital importance to the electric utility industry. Utility commissioners, utility managers, and manufacturers all use estimations of construction cost as an economic justification both for project timetables and for financing arrangements [1]. The Power Capital Costs Index, which tracks construction costs for power plants, noted that from 2000 to 2013, the average cost for building a power plant rose 226% in North America and by 193% in Europe [2]. As one analyst recently put it, "the future trend in construction costs is a critical question for the power industry" [3].

Industrial sources of construction data, however, leave many questions unanswered. How do rising construction costs and other factors impact the final expense of projects? How do construction risks differ for energy systems as diverse as hydroelectric dams, nuclear reactors, and fossil fueled thermal power plants? Do emerging clean electricity technologies – utility-scale wind farms and solar facilities – present their own set of risks? How do construction risks for electricity systems compare to other types of infrastructure? What implications might different construction risks have for energy investment choices and energy policy issues such as climate change?

Building on earlier work, this study answers such questions by assessing the construction costs affiliated with 401 electricity infrastructure projects built between 1936 and 2014 in 57 countries. Collectively, these projects involved about $820 billion worth of investment, 325,515 MW of installed capacity, and 8495 km of transmission lines. We document that costs are underestimated in about 75 percent of projects across the entire sample and that cost risks differ across type of infrastructure. The findings of this study do not bode well for climate change mitigation efforts, given that two of the largest "wedges" [4] that we have to mitigate emissions – hydroelectric dams and nuclear reactors – have the greatest amount and frequency of cost overruns, even when results are normalized to scale.

Cost overruns are not only about dollars and cents, they connect to a number of key themes raised by this journal and in the energy studies literature as a whole [5]. For one, the issue underpins the accuracy and optimality of investment decisions in energy infrastructure. As one study put it:

> *The economic impact of a construction cost overrun is the possible loss of the economic justification for the project. A cost overrun can*

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> *also be critical to policies for pricing electricity on the basis of economic costs, because such overruns would lead to underpricing. The financial impact of a cost overrun is the strain on the power utility and on national financing capacity in terms of foreign borrowings and domestic credit* [6].

Yet we believe that the topic extends well beyond the domain of economics. It touches on scenarios, forecasting, and integrated resource planning, showing us how unexpected events can throw off cost projections and lead to delays [7,8]. It touches on externalities, since cost overruns are often hidden and passed onto consumers, creating a lag on resources and socializing construction risks [9]. It touches on the justification of government support for certain technologies, as many larger power plants, backed by national champions, are frequently bailed out by ratepayers and taxpayers [10]. It touches on geography and scale, asking us to consider what the right "size" of an energy system is, and pondering if bigger projects lead to more overruns [11]. It touches on communication strategies, and how project sponsors "sell" or "frame" their projects to engender commitment [12–14]. It touches on risk, accountability, and bias, and how sunk costs can convince planners to continue throwing "good money" after "bad" to see a project through [15]. It, finally, touches on climate policy, revealing how some major "low-carbon" sources of electricity have perhaps underappreciated risks, changing how we ought to prioritize the next 10 years of climate change mitigation efforts [16].

2. Research methods

As summarized in an earlier study, our primary source of information for this study is a database that we compiled encompassing construction costs for any type of power plant, worldwide, greater than 1 MW in installed capacity, or transmission project above 100 kV in size [17]. Our sample included six types of projects or reference classes: [18] thermoelectric power plants that depend on the combustion of coal, oil, natural gas, or biomass; nuclear power plants; hydroelectric dams; utility-scale wind farms; utility-scale solar photovoltaic (PV) and concentrated solar power (CSP) facilities; and high voltage transmission lines. We only included a project in our database when we could find complete data regarding:

- Its name;
- The year the project entered service;
- Its geographic location;
- Its size in installed capacity (MW) or electrical current (kV);
- Its estimated or quoted construction cost;
- Its actual construction cost;
- 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 collection to any geographic location or time period. We did limit our search to electricity infrastructure, given that transport projects have already been analyzed comprehensively by Flyvbjerg and his colleagues, who compiled a database of 258 transportation infrastructure projects worth $90 billion [19,20]. To compare across time and location, we updated all costs and currencies to US$2012 using historical currency conversions and adjustments for historical inflation from the Statistical Abstracts of the United States. An Appendix presenting this data for all 401 projects is available online in the supplementary material from [21].

In collecting data in this manner, six qualifications deserve mentioning. First, we searched only in English, so our sample has a likely bias for North American and European projects, which comprised two-thirds of our included projects.

Second, we ended our data collection in January 2014, meaning that projects completed or data released after that point were excluded.

Third, we define "construction cost" 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" [22]. This meant we did *not* utilize "overnight construction costs" because these fail to account for interest and financing charges and construction duration [23]. Interest and financing charges play a large role in the completed cost of a project and can be a major contributor to cost overruns when there are time overruns; defining constructions cost in this way allowed us to more fully account for the actual costs associated with electricity infrastructure.

Fourth, we did not correct for national inflation or purchasing power parity between countries, given the number of countries (more than 50) and time periods (eight decades) involved. We also relied upon official exchange rates rather than black market rates which may have been more accurate for some projects.

Fifth, we took estimates at face value from a variety of sources, including government reports, peer-reviewed academic articles, project documents, industry assessments, electric utility annual reports, and public utility commission briefings. Each of these sources may define costs and construction periods differently.

Sixth, we included only completed projects in our database, not those canceled or still under construction. This means that many of the "worst" projects, that were simply scuttled prior to completion, were not included. For instance, of 117 privately owned nuclear reactors in the United States that began construction in the 1960s and 1970s, 48 were canceled, and almost all of them "experienced significant cost overruns" [24]. Similarly, the GAO has reported that from 1980 to 1996, 31 of the Department of Energy's "80 major projects" were "terminated prior to completion, after expenditures of over $10 billion" [25]. Excluding these types of projects from our sample means that we do not account for a major cost of energy infrastructure: expenditures on facilities that end up not being built but nonetheless may impact investors, ratepayers and industry members.

3. Analysis and discussion

Across the 401 energy infrastructure projects with reliable data, Table 1 highlights that the mean construction time was 73.4 months, and the average cost overrun per project was almost $1 billion, indicating a 66 percent mean cost escalation per project. Moreover, 75.1 percent of projects in the sample experienced a cost overrun, though, as Fig. 1 illustrates, the magnitude of that overrun differs substantially across all projects. Unlike other projects, overall construction costs for both solar facilities and wind farms have declined dramatically in the past 4 years, so their current costs are substantially below the average between 1936 and 2014 as shown in this paper.

3.1. Hydroelectricity

Our sample documented $271.5 billion in construction costs for 61 hydroelectric dams constituting 113,774 MW of installed capacity. As a reference class, these projects experienced a total of $148.6 billion in cost overruns and exhibited a mean cost escalation of 70.6 percent. Cost overruns also affected 75.4 percent of projects within the sample. As Fig. 2 illustrates, these dams had the longest mean construction time (118.4 months) of all projects, as well as the