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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

Table 1
Summary cost overrun data for electricity projects by source.

Project type	Number of projects (*N*)	Average cost escalation (%)	Standard deviation	Average cost overrun (millions of US$)	Standard deviation (millions of US$)	Average time overrun (%)	Standard deviation	Average time overrun (months)	Standard deviation (months)
Hydroelectric dam	61	70.6	111.7	2437	7054.7	63.7	89.8	43.2	58.4
Nuclear reactor	180	117.3	152.1	1282	1965.8	64	53.1	35.7	30.6
Thermal plant	36	12.6	33.5	168.5	579.6	10.4	19.0	4.8	8.9
Wind farm	35	7.7	13.1	32.8	112.9	9.5	22.6	0.22	2.4
Solar facility	39	1.3	17.8	−4.2	62.1	−0.2	8.0	-0.2	2.1
Transmission	50	8	40.4	29.7	217.6	7.5	30.6	3.5	12.8

largest total cost overrun amount (almost $2.5 billion per project) and time overrun amount (43.2 months).

One major factor that impacted our statistical results for hydroelectric dams was a skewed distribution of cost overruns. As Table 2 summarizes, the most significant overruns occurred only at dams with large reservoirs, not smaller run-of-river designs, and some individual projects, such as the Three Gorges Dam in China, La Grande 2 Dam in Canada, and Sayano–Shushenskaya Dam in Russia, had between $17 and $48 billion in cost overruns. Seventeen projects experienced overruns exceeding $1 billion. Thirteen projects had cost overruns equal to or exceeding 100 percent of project costs. In other words, 5 projects were responsible for more than two-thirds of all hydroelectric overruns while only representing 36% of hydro capacity in our sample. These projects were all massive in scale, ranging in size from 2700 to 22,500 MW; most notably, the 22,500 MW Three Gorges Dam had a cost overrun of more than $47 billion, by far the largest overrun in our entire sample.

Perhaps the single biggest factor contributing to hydroelectric cost overruns is the time needed for their construction. The typical dam in our sample, for instance, had a construction period exceeding 118 months; for comparison, that is longer than World War II, which lasted less than 72 months. These long construction lead times expose hydroelectric projects to multiple types of uncertainties during the construction process, including unforeseen changes in demand, interest rates, availability of materials, exchange rates, severe weather, labor strikes, and even war. In fact, the hydroelectric projects included in our dataset confirm that unexpected price increases, inflation, unfavorable currency devaluation compared to the U.S. dollar (which we converted to), tax changes, and political events are common and significant causes of overruns. One reason why dams can take so long to build is because they are more materials-intensive, on a per-megawatt basis, than all other types of electricity supply [26]. The World Commission on Dams has also argued that there are elements of construction unique to dams, such as the need to build coffer dams, excavate large amounts of subsurface rocks, and meet multiple purposes with the same project (such as a dam that simultaneously provides flood control, irrigation, and electricity) [27].

Uncertainty in pre-construction planning for dams also seems to contribute to long construction time, time overruns, and cost overruns. Although dam planners employ various methods to

Table 2
Hydroelectric projects with the largest overruns by amount and mean cost escalation.

Rank	Date	Name	Location	Type	Cost overrun (millions of US$)
1	2012	Three Gorges Dam	China	Reservoir	47,630
2	1979	La Grande 2	Canada	Reservoir	17,460
3	1978	Sayano–Shushenskaya	Russia	Reservoir	17,299
4	1976	Nurek	Tajikistan	Reservoir	15,910
5	1984	Tucuruí Dam Stage 1	Brazil	Reservoir	7091
6	2006	Sardar Sarovar Dam	India	Reservoir	6773
7	1991	Itaipu Dam	Brazil/Paraguay	Reservoir	5147
8	1986	Guri (Raul Leoni)	Venezuela	Reservoir	5130
9	1981	Robert-Bourassa	Canada	Reservoir	5010
10	2011	Bakun Hydroelectric Project	Malaysia	Reservoir	3916
11	1974	Tarbela Stage 1	Pakistan	Reservoir	3072
12	2009	Longtan Dam	China	Reservoir	2380
13	1973	Grand Coulee Dam II	United States	Reservoir	2306
14	1968	W.A.C. Bennet	Canada	Reservoir	2099
15	1971	Churchill Falls	Canada	Reservoir	1511
16	1942	Grand Coulee Dam I	United States	Reservoir	1495
17	1986	Chixoy	Guatemala	Reservoir	1083

Rank	Date	Name	Location		Cost overrun (%)
1	2006	Sardar Sarovar Dam	India	Reservoir	513
2	2011	Bakun Hydroelectric Project	Malaysia	Reservoir	417
3	2012	Three Gorges Dam	China	Reservoir	402
4	1978	Sayano–Shushenskaya	Russia	Reservoir	353
5	1979	La Grande 2	Canada	Reservoir	246
6	1976	Nurek	Tajikistan	Reservoir	200
7	1950	Vinstra	Norway	Reservoir	190
8	1977	Kariba Stage 2	Zambia/Zimbabwe	Reservoir	177
9	1981	Robert-Bourassa	Canada	Reservoir	143
10	1986	Chixoy	Guatemala	Reservoir	136
11	2009	Longtan Dam	China	Reservoir	113
12	1986	Guri (Raul Leoni)	Venezuela	Reservoir	101
13	1985	Third Power	Swaziland	Reservoir	100

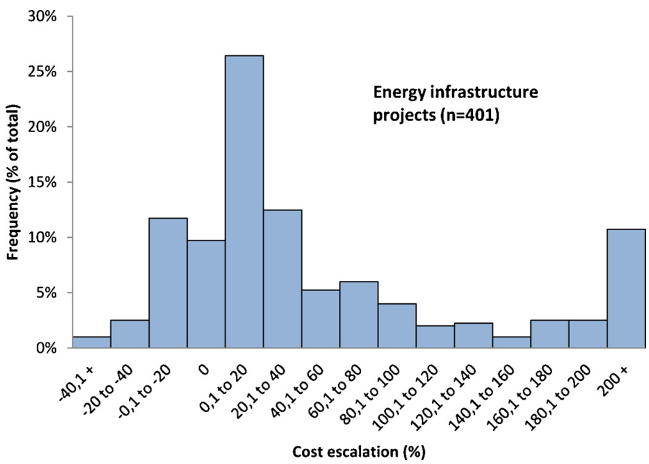

Fig. 1. Frequency and cost escalation of electricity infrastructure projects.

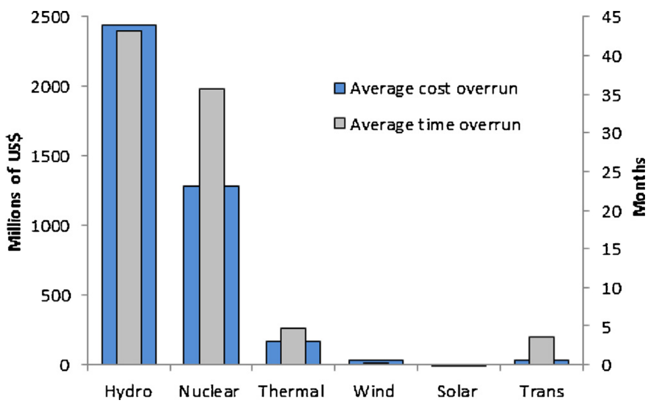

Fig. 2. Average cost and time overruns for electricity infrastructure projects ($n = 401$).

estimate costs, "highly compressible areas and pockets of high pore pressure" can be difficult to detect before construction begins [28]. In fact, well into the construction stage (post-planning) geotechnics teams must continually monitor and control the excavation process. As a result, "the process of refining the geological model is an endless activity" and events such as landslides, induced seismicity, cave-ins while tunneling, and finding different formations than expected can occur despite extensive exploration [28]. Accordingly, changes in project scope to account for unpredictable events is a fairly unique and common cause of time and cost overruns for hydroelectric projects, a fact that is strongly supported by the examples in our dataset.

3.2. Nuclear power

Nuclear power comprised the largest single class of our sample, including 180 nuclear reactors with a combined installed capacity of 177,591 MW costing $459 billion to construct and incurring approximately $231 billion in cost overruns. As Fig. 3 depicts, these overruns afflicted more than 97 percent of nuclear projects and led to a mean cost escalation of 117 percent per project. Sixty-four projects in our sample had cost overruns exceeding $1 billion, and Table 3 summarizes the 14 projects that displayed more than $5 billion in overruns per project as well as the 10 projects that each experienced a cost escalation of more than 400 percent. Notably, overruns were split almost evenly across Boiling Water Reactors and Pressurized Water Reactors, though the single largest overrun in terms of cost was for a CANDU reactor.

Most nuclear power plants incurred time overruns, due to both engineering issues and public opposition. Considering the long development times of such plants and the large amount of capital required, these time overruns likely caused large increases in interest charges and contributed significantly to the large levels of overruns seen [29]. Moreover, as Table 3 indicates, the most severe cost overruns for nuclear power were confined to the United States and the 1980s, it is likely that they were significantly influenced

Table 3
Nuclear reactors with the largest overruns by amount and mean cost escalation.

Rank	Year	Name	Location	Type	Cost overrun (millions of US$)
1	1993	Darlington	Canada	CANDU	16,589
2	1988	Nine Mile Point 2	United States	BWR	7392
3	1985	Shoreham	United States	BWR	6641
4	1986	River Bend 1	United States	BWR	5835
5	1987	Clinton	United States	BWR	5792
6	1985	Diablo Canyon 1	United States	PWR	5718
7	1984	WPPSS 2	United States	BWR	5574
8	1988	Fermi 2	United States	BWR	5514
9	1987	Beaver Valley 2	United States	PWR	5512
10	1987	Shearon Harris 1	United States	PWR	5365
11	1986	Limerick 1	United States	BWR	5292
12	1986	Hope Creek	United States	BWR	5200
13	1986	Millstone 3	United States	PWR	5107
14	1986	Palo Verde 1	United States	PWR	5105

Rank	Year	Name	Location		Cost overrun (%)
1	1985	Shoreham	United States	BWR	1280
2	1985	Diablo Canyon 1	United States	PWR	743
3	1988	Fermi 2	United States	BWR	535
4	1987	Clinton	United States	BWR	472
5	1986	River Bend 1	United States	BWR	470
6	2000	Rajasthan Atomic Power Station III and IV	India	PHWR	436
7	1985	Waterford 3	United States	PWR	435
8	1988	Nine Mile Point 2	United States	BWR	424
9	1984	WPPSS 2	United States	BWR	410
10	1986	Diablo Canyon 2	United States	PWR	408

Note: BWR refers to Boiling Water Reactor. PWR refers to Pressurized Water Reactor. PHWR refers to Pressurized Heavy Water Reactor. CANDU refers to CANada Deuterium Uranium, a specially designed PHWR.

Table 4
Wind farms with the largest overruns by amount and mean cost escalation.

Rank	Year	Name	Location	Type	Cost overrun (millions of US$)
1	2012	Sheringham Shoal	United Kingdom	Offshore	526
2	2013	Centrica Lincs	United Kingdom	Offshore	352
3	2007	Cedar Creek II	United States	Onshore	128

Rank	Year	Name	Location		Cost overrun (%)
1	2012	Sheringham Shoal	United Kingdom	Offshore	44
2	2007	Cedar Creek II	United States	Onshore	36
3	2011	EVCSA Wind Power	Costa Rica	Onshore	35
4	2013	Mumbida	Australia	Onshore	33

by the nuclear power accidents at Three Mile Island and Chernobyl. These accidents resulted in "regulatory ratcheting" where safety requirements were significantly altered in the middle of construction periods, with meaningful 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" [30]. This resulted in significant price increases and further delays.

3.3. Wind energy

Our sample included 35 onshore and offshore wind farms representing 6201 MW of installed capacity and $20.1 billion in investment. These projects incurred $1.1 billion of cost overruns, the second smallest in our sample. Wind farms had a mean cost escalation of 7.7 percent per project, and cost overruns afflicted slightly more than half (57 percent) of projects, though the mean amount of that cost overrun was $32.8 million. As Table 4 indicates, both onshore and offshore projects had some major overruns, but only three projects in the entire sample had a cost overrun greater than $100 million and only four had cost overruns in excess of 30 percent of their budget. Interestingly, our data also reveals that wind farms, as a reference class, had the lowest standard deviation for mean cost escalation (13.1 percent) across the entire sample, compared to 17.8 percent for solar, 33.5 percent for thermal, 111.7 percent for hydro, and 152.1 percent for nuclear. The implication seems to be that wind developers have the most reliable forecasting and construction estimates.

One possible reason for this could be the mass production, pre-assembly and testing associated with wind turbine manufacturing. For example, major turbine manufacturers such as General Electric, Vestas and Gamesa all assemble the majority or entirety of a turbine's nacelle, which contains all of the complicated electronics and engineering components (such as the generator, gearbox if necessary, yaw drive, transformer, etc.), in controlled offsite facilities [31,32]. As one Director of Construction at Gamesa put it, "more items have been designed for pre-assembly, such as installing auxiliary wires into nacelles, which use to be done in the field. Not only does this help streamline the installation process, providing greater turbine availability, but it has also improved the quality of work" [33]. Additionally, the manufacturer will often simulate operation and test electrical performance to verify quality before the turbines are shipped to the wind farm for installation [34].

Another associated possibility for the low standard deviation and magnitude of cost overruns is that, unlike hydro and nuclear units, wind farms demonstrate much quicker construction lead times. Pre-assembly (which also applies to large sections of turbine towers) means that "installing a turbine onto its foundation and completing final assembly can be done in a day" [35], and a turbine will be energized within hours of installation [36]. Although pouring bases and laying cables can be more time consuming and challenging, as Fig. 4 indicates, wind farms still had the fastest average construction time (12.4 months) of any class of project, even beating out solar projects (26.9 months) and thermal plants (57.4 months). Faster construction times reduce the risks of construction costs rising, political events and tax changes occurring, inflation being higher than expected, and other exogenous factors.

3.4. Solar facilities

Thirty-nine solar PV and CSP power plants, representing 2374 MW of installed capacity and $16.5 billion worth of investment, were analyzed. (These are utility-scale infrastructure projects, thus they do not include the familiar rooftop solar collectors on buildings or residential configurations.) These projects as a class actually came in $4.2 million less than budgeted, or $200,000 less than expected per project. These solar systems had the lowest average cost escalation per reference class (1.3 percent), the least

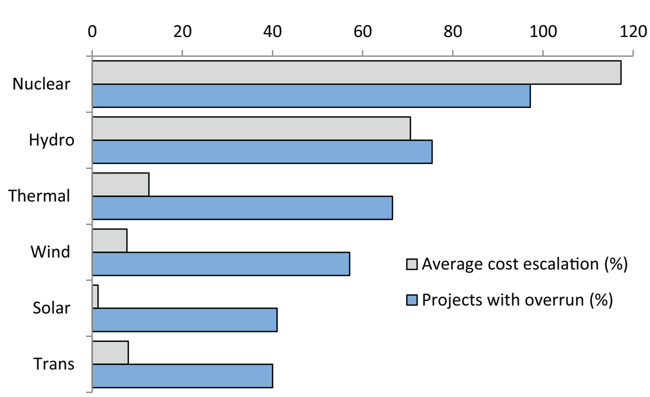

Fig. 3. Average cost escalation and frequency of cost overruns for electricity infrastructure projects ($n = 401$).

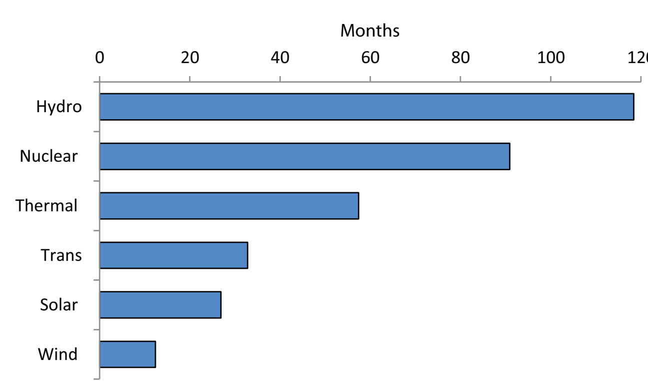

Fig. 4. Mean construction time for electricity infrastructure projects by reference class.

Table 5
Solar facilities with the largest overruns by amount and mean cost escalation.

Rank	Year	Name	Location	Type	Cost overrun (millions of US$)
1	2011	ISCC Kuraymat	Egypt	CSP	102
2	2010	Solnova 1	Spain	CSP	100
3	2008	Andasol-1 (AS-1)	Spain	CSP	63

Rank	Year	Name	Location		Cost overrun (%)
1	2010	Archimede	Italy	CSP	50
2	2010	Solnova 1	Spain	CSP	37
3	2011	ISCC Kuraymat	Egypt	CSP	31

Note: CSP refers to Concentrating Solar Power.

time overruns (an average of 2 months ahead of schedule), and the lowest standard deviation for amount of overruns and time overruns. They also had the largest total amount of cost underruns, with the entire class of projects costing $163.9 million less than budgeted, though some of this may be explained by dramatic reductions in cost over the past 4 years. As Table 5 indicates, only 3 facilities had overruns greater than $50 million and only 3 facilities had cost overruns greater than 30%, all of which were CSP facilities rather than large-scale solar PV apparatuses.

A critical factor in the performance of solar power plants is technological innovation leading to cost reduction. Although solar investment costs are much higher per installed kW than others in our sample, rapid innovation and increasing economies of scale have been driving prices down. Further, government support caused manufacturing overcapacity and led to a dramatic fall in global prices, with the cost of solar panels falling 50% in 2011 alone [37]. As the majority of PV projects in our sample were built during the times of rapid price declines, actual costs may have fallen below initial budgets, thus minimizing overruns or causing underruns. Declining technology investment costs have also been realized at CSP plants, though to a lesser degree [38].

One hypothesis specific to CSP is that project development learning curves have similarly caused actual costs to fall below initial projections. Two conditions make this a strong possibility. First, CSP is experiencing a significant resurgence in development since 2006, before which a 15-year period of no new installations somewhat stunted specialized development experience in this sector. Secondly, the resurging CSP market has been dominated by only two countries and a very small pool of project management entities [39]. Of nearly 4 GW of global capacity, 3.7 GW are installed in the United States and Spain, and more than 2 GW was developed by one of only three companies, Abengoa, Acciona and Cobra (as developer and/or an engineering, procurement and construction contractor) [40]. Additionally, these three entities represented over 72 percent of the CSP projects in our dataset. The implication is that a few entities have been gaining significant experience managing CSP projects, presumably improving supply chains, and working out managerial problems. The possibility that this has led to enhanced cost performance is supported by the fact that all of the instances in our dataset in which the same developer took on a CSP project that essentially duplicated a former project that they had done (e.g., Andasol I and II, Palma del Rio I and II, etc.), the second project showed an appreciably smaller overrun, or an underrun. This confirms IRENA's predictions of significantly decreased capital costs of CSP based upon experience curves, including manufacturing, operational and other "learning" [41,42]. Assuming only that initial CSP budgets are based partially on previous experience, it is rational to conclude that these capital cost reductions have at least partially been realized in the form of low cost overruns and underruns.

3.5. *Fossil-fueled thermal plants*

Our sample included 36 thermoelectric plants representing 25,575 MW of installed capacity, mostly coal-fired, but a few fueled by natural gas, oil, and biomass. These projects accrued $44.1 billion in investment and exhibited $6.1 billion in cost overruns, with a mean cost overrun of $169 million per project, or an escalation equivalent to 12.6 percent of projected budgets. Thirty percent of thermal plants however realized an underrun. As Table 6 indicates, all but one of the projects with the greatest overruns were coal-fired. Only four projects had overruns greater than $1 billion and seven projects with overruns exceeding 30 percent of projected budgets, and most of these related not to combined cycle natural gas plants but to newer, "first of a kind" integrated gasification combined cycle (IGCC) and super-critical coal-fired facilities, such as Prairie State (designed to be IGCC but later scrapped) and Edwardsport (IGCC), or expensive retrofits (Cliffside and Argenne).

That said, thermal power plants as a class experienced the third highest magnitude of cost overruns, after nuclear and hydro projects. Thermal projects had the third longest mean

Table 6
Thermal plants with the largest overruns by amount and mean cost escalation.

Rank	Date	Name	Location	Type	Cost overrun (millions of US$)
1	2012	Prairie State	United States	Coal	2000
2	2013	Edwardsport	United States	Coal	1500
3	2013	Argenne	United States	Coal	1485
4	2013	Cliffside	United States	Coal	1188

Rank	Date	Name	Location		Cost overrun (%)
1	2013	Cliffside	United States	Coal	120
2	2013	Edwardsport	United States	Coal	75
3	2013	Argenne	United States	Coal	75
4	2012	Prairie State	United States	Coal	69
5	2012	El Tebbin	Egypt	Oil and natural gas	57
6	1979	Ramagundam	India	Coal	36
7	2012	Hempstead	United States	Coal	31

Table 7
Transmission lines with the largest overruns by amount and mean cost escalation.

Rank	Date	Name	Location	Type	Cost overrun (millions US$)
1	1982	Inga-Kolwezi	Democratic Republic of the Congo	HVDC	1522
Rank	Date	Name	Location		Cost overrun (%)
1	1982	Inga-Kolwezi	Democratic Republic of the Congo	HVDC	260
2	2011	Alamathy-Sriperumbudur	India	HVDC	71
3	2013	Clear Crossing to West Shackelford	United States	HVDC	33
4	2013	Clear Crossing to Dermott	United States	HVDC	33

Note: HVDC refers to High Voltage Direct Current.

construction time, at 57 months, increasing exposure to rising material costs; further, some time overruns likely contributed to additional interest costs at certain plants. Rising construction costs and competition for power plant design worldwide during the mid to late-2000s may have driven final costs at many thermal plants higher, in addition to resulting in a large number canceled projects [43]. In our sample, 10 of the 16 projects with the highest percentage overrun were constructed during this decade.

3.6. Transmission lines

Our database included 50 transmission projects with 8495 km of lines capable of serving upwards of 17,000 MW of supply. These projects required $8.3 billion in investment and suffered cost overruns of $1.5 billion, equating to a mean overrun of $30 million per project and a mean escalation of 8 percent per project. Thirty percent of projects also had an underrun, and as Table 7 shows, only one project had an overrun greater than $1 billion and only four project overruns were greater than 30 percent of their respective budgets. All of these projects with large overruns, moreover, were of the High Voltage Direct Current variety. The single project with the largest overrun (both in terms of total cost and percentage) was indeed an anomaly: The Inga-Kolwezi HVDC line was the longest in the world when built in 1982 and it was also constructed in incredibly difficult conditions, given its location in the Katanga Province of the southeastern corner of the Democratic Republic of Congo.

To be fair, there are several limitations to our sample of transmission projects. Notably, it is more heavily weighted toward the United States than other classes and is less evenly distributed in time, with all but one project occurring after 2002. While it does include some HVDC projects, many projects were AC. All projects are onshore transmission projects, excluding costs from more expensive offshore transmission projects that could potentially have higher instances of overruns. Also, excluding the Inga-Kolwezi HVDC line reduces the mean cost overrun to ~$37 million, implying that transmission investments are relatively safe from overruns.

There may be several major reasons for the comparative insulation of transmission projects from major overruns. First, transmission is a mature technology that has been around for more than 100 years, reducing the possibility of overruns from engineering issues. Second, relatively minor material requirements, compared to other power projects, protect transmission projects from increasing construction material prices. Third, transmission projects have relatively short construction times, with the average construction time in our sample at 33 months. This further reduces vulnerability to changing component costs. Fourth, one factor that may drive differences between estimated and actual costs is siting. Transmission projects have larger siting issues than other projects, as they typically cross land with many different owners. This can lead to local opposition and can require lengthy eminent domain proceedings, potentially causing a time delay. As such, most projects propose multiple routes that enable planners

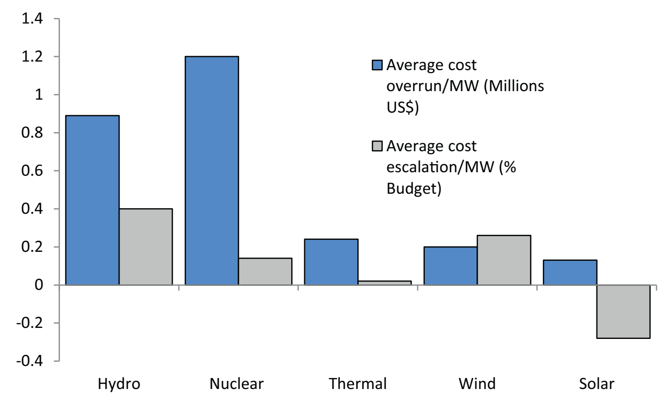

Fig. 5. Normalized average cost escalation and magnitude of cost overruns for electricity infrastructure projects ($n = 351$). Note: Transmission projects are excluded from this figure because they cannot be normalized to installed MW.

to choose the "best one" that they can select prior to construction commencement.

3.7. Normalization of results

Interestingly, when results are normalized according to installed capacity, none of our findings substantially changes. As Fig. 5 indicates, nuclear and hydro facilities still have the largest normalized overruns, with hydro seeing an average of $890,000 in overruns per installed MW and nuclear seeing $1.2 million in overruns per installed MW, compared to only $240,000 per installed MW for thermal plants, $200,000 for wind farms, and $130,000 for solar facilities. Even when normalized to project budgets, which would ostensibly penalize smaller projects (since a smaller overrun in magnitude could still be a larger share of a budget), solar and thermal come out ahead with minor risks of overruns as a percentage of original project estimates. Only wind farms see a slightly heightened risk here, one likely explained by their smaller overall budgets.

4. Conclusions

Ultimately, our database, limited as it may be, implies that power plants and investments in electricity infrastructure carry with them substantial construction risk. Across our entire sample of 401 projects, the average length of construction exceeded 70 months, the average cost overrun exceeded $967 million per project, and 75.1 percent of projects incurred some type of cost overrun. Taken together, these 401 projects resulted in almost $388 billion in cost overruns. Thus, as a reference class, most types of projects in our sample involved at least a degree of construction risk, though that risk varied by technology. Hydroelectric dams were the most susceptible to time overruns and experienced the largest magnitude of overruns. Nuclear reactors were most likely to

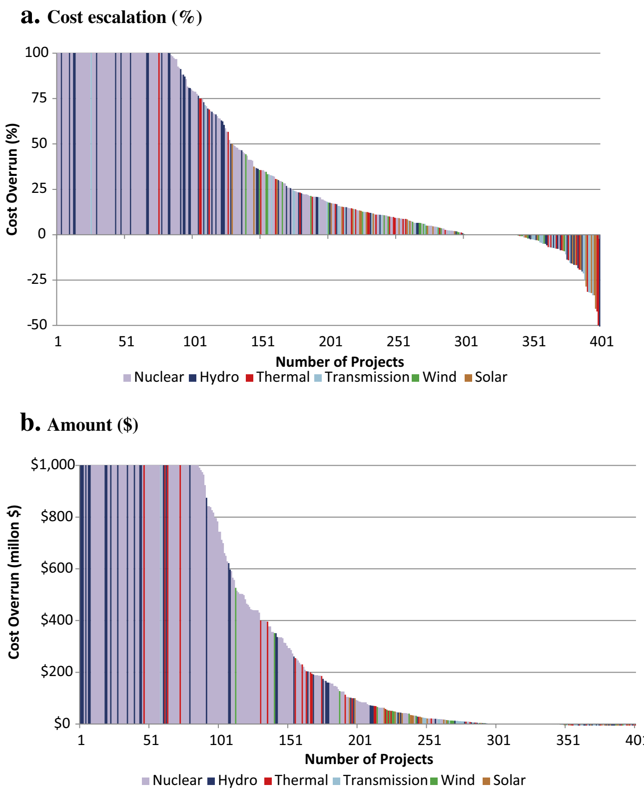

Fig. 6. Distribution of construction overrun costs by technology ($n = 401$).

experience a cost overrun, and such an overrun was most likely to double their project cost. Normalizing results to scale still revealed a significantly higher amount of overruns for hydro and nuclear facilities ($890,000 to $1.2 million per installed MW) than for thermal, wind, and solar facilities ($240,000 or less per installed MW). Put another way, and as Fig. 6 summarizes, across the entire sample nuclear and hydro project are those most exposed to persistent extreme overruns, thermal plants occasionally exhibit a large overrun, and solar and wind projects present the least risk of an overrun.

In short, construction of electricity infrastructure faces a high risk of cost overruns. Cost overruns are bad for planners, who cannot adequately compare the costs of different options; bad for investors, who lose money on a project, or in the extreme, go bankrupt; and bad for environmentalists, who may be inadvertently supporting infrastructure that does not get built when, and at what cost, they thought it would. As such, investors, electric utilities, public officials, and energy analysts need to rethink and reevaluate the methodologies they use to predict construction timetables and calculate budgets. During the course of a project many variables can change: material and components cost, engineering requirements, regulatory approvals, interest charges, construction time, and public support. When developing energy infrastructure stakeholders must recognize these risks, determine how to incorporate them into project budgets, and actively manage them during implementation. When governments and corporate decision-makers choose to ignore the risk of cost overruns, civil society groups and local communities must find ways to hold them accountable.

Considering the likelihood of overruns therefore could be critical for major energy policy trends and decisions, such as climate change mitigation options and determining the overall cost efficacy of energy projects. To date, wind and solar projects have come in smaller capacities, often ranging from 1 to 250 MW. Thus, more projects must be built to meet large segments of electricity demand (smaller unit size is also characteristic of smaller natural gas plants). Hydro and nuclear units, by contrast, are most often built in chunks of 500 MW or even 1000 and 1500 MW – which is why they are often referred to as "lumpy" investments. The downside, suggested by our study, is that while these large, lumpy systems can provide very large increments of power, making them attractive from an emissions standpoint or even an industrial or urban access standpoint, they also suffer the greatest risk of an overrun. In other words, the climate and energy security benefits of nuclear and hydro are achieved only through enhanced financial risk. On the other hand, our data suggests that expansion of wind and solar projects, including a movement to larger projects, would not carry the same risk of cost overruns.

Our findings also point to the need for further research. At the top of this list is a call for more reliable data and a larger sample. For about half a year, we exhaustively searched through cost and price data, combing through estimates involving the world's roughly 170,000 generators operating at 75,000 power plants in addition to at least 5000 high-voltage transmission projects. Of these, only about 400 projects had construction data documented for both quoted and actual costs. Furthermore, we have grouped technologies together into reference classes but these could become more nuanced. "Thermal" plants could have been broken down into natural gas, coal, oil, and biomass; they could even be disaggregated into operating profile (baseload versus peaking) or manufacturer. "Hydroelectric" facilities could be assessed based on reservoir versus run-of-river or on their types of turbines. "Wind" can be separated into offshore and onshore, "solar" into PV and CSP, and so on. Ownership and management structures could be assessed, such as public/state-owned versus private, as well as types of energy markets, regulated versus de-regulated, liberalized, privatized, and restructured. Important distinctions between site built and mass produced technologies may exist. This is a matter of degree, because even photovoltaic panels, which are produced in a factory, have installation costs that are susceptible to the same kinds of factors that lead to cost overruns in purely site built technologies. Technologies whose costs are mostly dependent on factory production may have less variability in their total costs than those that are mostly site built. Conducting analysis along these lines would only augment our understanding of how, and why, electricity projects seem unescapably prone to construction cost overruns.

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