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Abstract

The massive size of the investment in the electric power sector—along with other important consequences—hinge on the relative cost of different types of power plants. Surprisingly, within the literature on energy modeling and forecasting there has been little attention to the factors that determine these capital costs. Where scholars have studied these factors in detail they have focused mainly on a particular subset of power plants. This essay offers a review of these capex factors along with a case study on China. Our aim is to help the energy modeling community take a closer look at pivotal assumptions in their models and suggest ways of framing future scenarios for capital costs. We suggest that capital costs for new power plants is likely to vary worldwide to a much greater degree than widely assumed—largely because labor costs and various state-sponsored mechanism for risk management vary so much. We also suggest that labor saving innovations, such as in robotics and through international trade in pre-assembled components, may substantially lower costs even for plants that have long been thought immune to such improvements, such as large coal and nuclear facilities.

1. Introduction

The central scenario in International Energy Agency (IEA)'s World Energy Outlook (WEO) 2011—the so-called New Policies (NPS) Scenario which assumes recent government policy commitments are implemented in a cautious manner—envisions that world primary demand for energy will increase by one-third between 2010 and 2035 (IEA, 2011). Electricity is expected to grow faster than any other final form of energy. Of the total $38 trillion in global investment in energy-supply infrastructure IEA projects will be needed, the power sector alone will claim about half. Those investment needs vary, of course, with scenario. In IEA's "450 Scenario"—a scenario which prescribes strong policy actions to limit climate change— total investment is slightly lower but the share for electricity is higher as IEA's model assumes there are advantages to reducing world emissions through even more rapid electrification (IEA, 2011). While we focus here on the IEA results, other large world energy models make similar projections.

Pivotal to these forecasts is the capital cost of building new power plants. While other costs—notably fuel—along with plant performance play central roles in determining which power plants and fuels will be selected, capital costs are central. For some technologies, such as nuclear and hydro, nearly all of the levelized cost of electricity stems from construction costs and related charges such as interest. In the last decade, capital costs have been rising much faster than inflation in all developed countries, and that trend has led analysts to expect that capital costs will be high into the future as well. Yet the experience in other countries—including in the most capital intensive technologies such as nuclear power—suggests that this trend is not universal. For example, a Joint report by the IEA and the OECD Nuclear Energy Agency (NEA)—which examined the cost of building a wide array of types of power plants—found that while costs vary substantially. Nuclear costs are as low as 1,560 USD/kWe (Korea) and 1,750 USD/kWe (China), or about half the overnight costs in the United States and one-third the likely cost in Belgium (IEA and NEA, 2010). Many analysts have explored the reasons for these variations in costs, including whether low costs in one country might be "portable" to other jurisdictions (e.g., Yang 2011 which includes a comparison of U.S. and Chinese nuclear costs). Yet, for the most part, the results of detailed assessments of the driving factors of plant costs are not accessible in the energy modeling community, and a close look at those analyses suggests that the long-term future for capital costs could be quite different from the assumptions that typically drive these models.

The assumed level of capital cost for power plants has potentially profound implications for policy. Capital (and fuel) costs play a central role in determining the structure of the energy system and thus on the kinds of externalities such as insecurity and environmental emissions that have been a central focus of policy makers. There is a huge literature that looks closely at how policy instruments could affect deployment of technology (e.g. Victor, 2002; Rai, et al., 2010; Fischer et al., 2008; Nemet, 2012). The choice of those policy instruments and design of the interventions depends, in part, on the existing and potential relative costs of different technologies—factors that partially determine the level of expenditure (and difficulty in attaining political support) required for policies that try to advance otherwise uneconomic technologies. These challenges are particularly apparent today as fiscally constrained governments attempt to deploy renewable energy technologies that are more expensive than fossil-based rivals (Victor and Vanosek, 2011). For decades there has been an active literature on national systems of innovation; a few scholars have applied those concepts to innovation in energy-related technologies in particular (Gallagher et al., 2012). For policy makers, one implication is that efforts to enhance innovation in energy policy—a goal that many recent studies have advocated (Holliday, et al, 2010; Victor, 2011; Pielke, 2011; Wessner and Wolff, 2012; Chu and Majumdar, 2012)—should look at the full array of policy factors that affect how firms mobilize and deploy capital for fixed investments such as power plants.

This paper offers an in-depth review of major studies on capital costs of building new power plants while exploring the major factors that determine these costs with an eye to how those driving forces might change in the future. In addition, it offers a brief case study on how those same factors affect capital costs in China. We make six arguments.

First, the capital cost of new power plants varies substantially across countries. Costs for most power generating technologies including both fossil fuel plants (e.g., advanced coal) and renewables (e.g., onshore wind) are much lower in some emerging Asian countries, particularly China. The cost to build a supercritical power plant in China, for example, is possibly less than one third of building the similar one in the United States. The variation in costs for constructing nuclear plants appears to be even greater.

Second, on average the cost of building new plants in the advanced industrialized world has risen three times faster than inflation over the last decade. The financial crisis imposed a short-lived decline, but costs have rebounded quickly due to sustained economic growth in Asia that has yielded higher commodity prices and shortages in supply of skilled labor and engineering services. Over the last decade, major energy models have reflected this pattern by substantially raising their assumed cost for the construction of new power plants. However, since the patterns of the last decade are extremely unusual and likely a very poor guide for long-term evolution of capital costs, it would be questionable whether the trend will continue into the future or not, assuming real costs actually stabilize as the construction market reaches equilibrium.

Third, while there has been much scholarly attention to “learning,” three other factors also play major roles in determining capital costs: the price of commodities (e.g., steel), labor, and a country’s business and regulatory context. (This last factor includes environmental regulation, subsidies and other incentives, and the broader context that how government and business interact.) For mature technologies, labor costs are usually the single largest contributor to total cost. In a nuclear plant built in a typical western country, labor is 90% of the total cost. For emerging technologies “learning” plays a larger and often-decisive role.

Fourth, China has surged as a worldwide leader not only in building most of the world’s energy efficient super-critical coal power plants but in renewable powers such as solar and wind at a much faster speed and at much cheaper costs. The so-called “Chinese Price,” which for mature technologies is about one half to one-third of western levels, notably reflects the country’s large pool of low-cost highly skilled and semi-skilled labor, even with sharply rising labor costs in recent years. The country's system of state capitalism has also reinforced the factors that allow for low capital costs (and possibly hidden the real cost of projects that have proved more costly).

Fifth, it is an extremely challenging task to project future capex of building power plants and there is an urgent need for a critical review of information and data available. Almost all published capital cost estimates have been constantly revised upward overtime and these adjustments are made not only on the nuclear power—a notable example of cost escalation—but on almost all other power generating technologies including coal, wind, solar, etc. The projection challenge is further reflected by the fact that the major widely-cited studies as well as the energy models they use show a wide range of cost estimates for future capex of building power plants and some of their projections are fundamentally different from each other on the future cost trend—whether the costs will decrease, increase, or keep constant.

Last, the paper suggests the possibility that costs could come way down—partly from labor-saving innovations in robotics and other fields, which have barely made a dent in the power plant industry, and partly from pre-assembly of major components overseas, particularly from Asian countries like China, which could reduce costs in the developed nations.

We proceed in four parts. First is an overview of the most recent literature on trends in the costs of new power plants, drawn mainly from industry tracking services. Second is an effort to decompose those costs and identify the major driving factors. Ideally that decomposition would be quantitative; since most studies are not presented in a comparable fashion we, instead, offer a qualitative assessment. Third is a case study on China, aimed at explaining the so-called "Chinese Price." Fourth is a summary.

2. General Trends in Power Plant Costs

There is voluminous literature conducted by international agencies, academic and industrial institutions which examines capital costs of building new power plants. Table 1 lists the most recent major studies we have examined. Our selection concentrated on studies that report information across multiple technologies in ways that allow for comparisons across technologies and markets. Thus we exclude, for the purpose of the present paper, the large number of studies that focus on single technologies—such as the studies that concentrate on particular renewable technologies and their improvement through "learning." Notable examples include Hultman et al. (2007), CBO (2008), Schlissel and Biewald (2008), Du and Parsons (2009), and NEI (2011) with a focus on nuclear, Zhao et al (2008) on coal, Blanco (2009) and GWEC (2010) on wind, IEA (2010) and EPIA (2011) on solar photovoltaic. Most of these studies we review focus on a single country such as the study conducted by AATSE (2011) in Australia and another one by EIA (2010) in the U.S., while a few of them compare capital costs across multiple countries. A few are more comprehensive—covering all markets and all major technologies (e.g., IEA and NEA, 2010; IEA, 2011; EIA, 2011). Although most of these studies are technically oriented, a few also explore the political legal contexts that shape these technical factors. For example, Kalpan (2008) explains how policy (including regulation) affects uncertainty (and thus cost) in power plant costs. We have also selected studies that include a substantial focus on underlying driving forces (e.g. Mott MacDonald, 2011), rather than simply reproducing cost estimates from other sources.

Table 1: Summary of Most Recent Literature on Capital Costs of Building Power Plants

Year	Organization/Author	Summary
Nov 2011	International Energy Agency (IEA)	World Energy Outlook (WEO) annually includes both current and projected data on power plants' investment costs, operation and maintenance costs and efficiencies in major countries/regions worldwide. Assumed data is provided in two different major scenarios, the New Policies and 450 Scenarios (IEA, 2011).
July 2011	IHS CERA	IHS CERA Power Capital Costs Index (PCCI) and European Power Capital Costs Index (EPCCI) track a portfolio of power generation plants in North America and Europe, covering coal, gas, wind and nuclear power plants (IHS, 2011).
June 2011	Electric Power Research Institute (EPRI)	Provided an overview of near-term (2015) as well as longer term (2025) electricity generation technology costs and performance including total plant costs and levelized costs. The technologies reviewed include central stations (advanced PC, IGCC, NGCC, and nuclear) and renewable resources (wind, biomass, solar thermal, and solar photovoltaic) (EPRI, 2011).
April 2011	U.S. Energy Information Administration (EIA)	The Annual Energy Outlook (AEO). AEO 2011 includes estimated costs for various types of power plants, starting with the forecast year 2016 (EIA, 2011).
March 2011	Australian Academy of Technological Sciences and	Reports current and projected levelized costs of electricity including capital costs, for a range of new power generating technologies (CCGT w/o CCS, SC w/o CCS, IGCC, wind, solar,

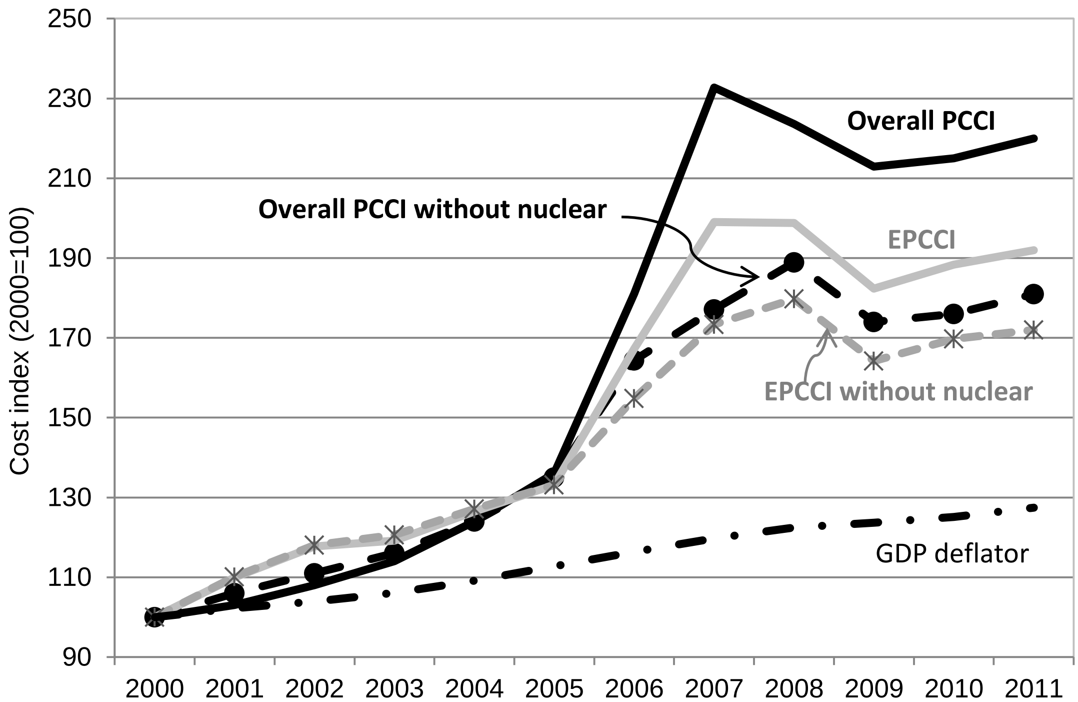
	Engineering (AATSE)	geothermal, biomass steam, etc.) in Australia in 2020, 2030, and 2040, respectively (AATSE, 2011).
May 2011	Mott MacDonald	Provides current and future costs of renewable and other low carbon generation technologies in the UK and the prospects is up to 2050 (Mott MacDonald, 2011).
March 2011	Melbourne Energy Institute	Reviews both current and future costs of three forms of renewable energy technology including wind, photovoltaic and solar thermal and compared data from a range of international and Australian-specific studies (Hearps and McConnell, 2011).
November 2010	U.S. Energy Information Administration (EIA)	Summarizes current cost estimates for the generic utility-scale generation plants in the U.S., including detailed breakdowns for estimates of material and installation costs, indirect costs, fees and contingencies, etc (EIA, 2010).
June 2010	Mott MacDonald	Assesses current and future costs for the main large scale power generation technologies applicable in the UK (Mott MacDonald, 2010).
May 2010	Carter	Reviews other studies of the cost of electricity from various types of generating technology, including anecdotal cost data reported by utilities in press releases or to utility commissions (Carter, 2010).
2010	International Energy Agency (IEA) and the Nuclear Energy Agency (NEA)	Presents levelized costs of a wide range of electricity generation technologies for almost 200 plants in 21 countries including coal and gas w/o CCS), nuclear, hydro, onshore and offshore wind, biomass, solar, wave and tidal as well as CHP

		(IEA and OECD NEA, 2010).
February 2009	Lazard Ltd.	Compares the levelized cost of energy for various conventional and alternative energy generation technologies, focusing on capital cost inflation in mature technologies along with the potential for significant cost reductions over time for alternative energy technologies such as wind and solar (Lazard, 2009).
November 2008	Kaplan	Projects for 2015 costs for new fossil, nuclear, and renewable plants, focusing on factors that determine those costs, including government incentives/regulations (Kaplan, 2008).

While the existing literature—even the sample shown in table 1—is large and complex, most studies are consistent with at least three main conclusions.

First, across the advanced industrialized world—where there is reliable longitudinal tracking of costs—capital costs have been rising rapidly for the last decade. The IHS Cambridge Energy Research Associates (CERA) Power Capital Costs Index (PCCI) tracks and forecasts the costs associated with the construction of a portfolio of 30 different power generation plants in North America including coal, gas, wind and nuclear power plants, while the IHS CERA European Power Capital Costs Index (EPCCI) tracks and forecasts the costs associated with the construction of a portfolio of power generation plants in Europe (IHS, 2011). Both are indexed to year 2000 and show that the costs of building new power plants have shown an overall upward trend—rising much faster than GDP—despite several years of temporary decline during the most recent worldwide financial crisis (see Figure 1). In particular, capital costs of building new nuclear power plants are soaring. The IHS PCCI without nuclear, for example, has a much flatter trend than the overall PCCI.

Figure 1: North America and European Power Capital Cost Index (PCCI and EPCCI)

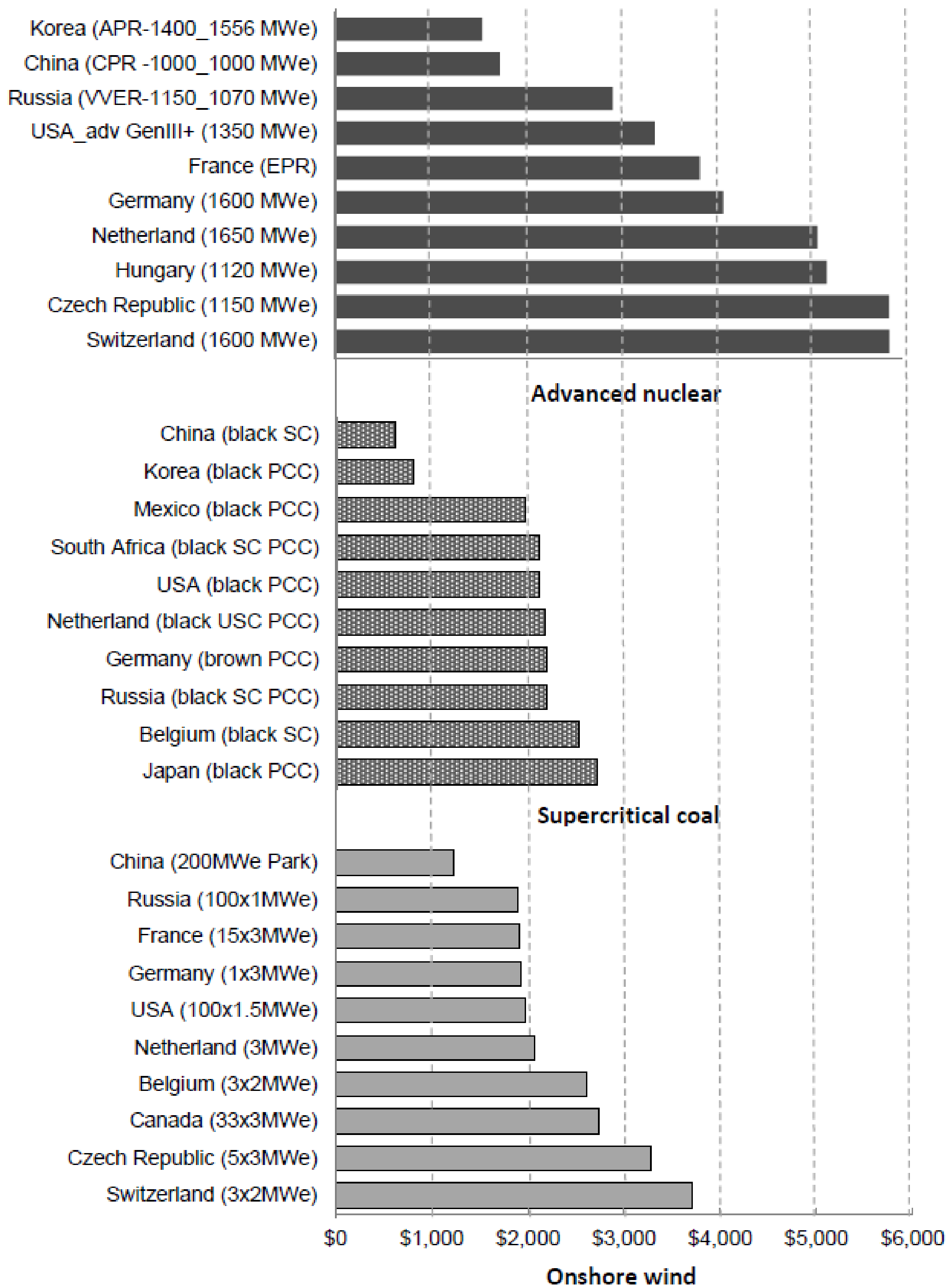


Data source: IHS (2011) and U.S. Bureau of Economic Analysis (2012)

The cost increases have been attributed to many factors such as global commodity prices—notably steel, copper, and aluminum—and the demand for power generating equipment. Shortages of construction services have also played a role, as have regulatory delays.

Second, there is huge cost variation across countries. For example, Figure 2 presents cross-national comparisons for three clusters of power generation technologies (advanced supercritical coal, nuclear pressurized water reactors, and onshore wind) drawn from the systematic analysis of the IEA and the OECD Nuclear Energy Agency (NEA).

Figure 2: 2010 Overnight Capex for Selected Power Generating Technologies (2010 USD/kWe)



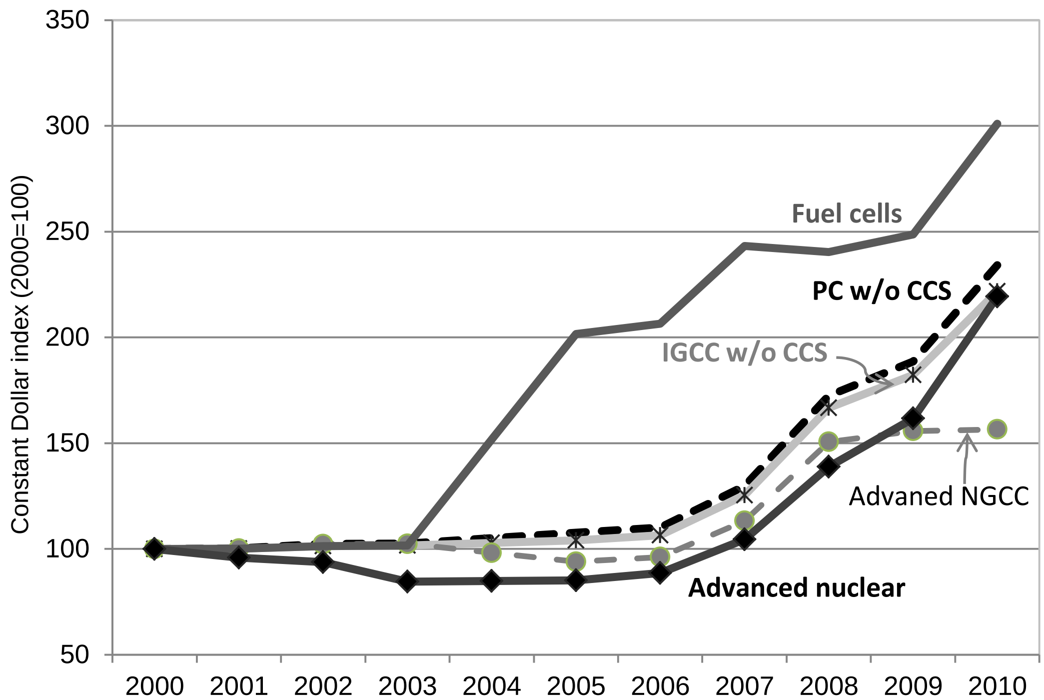
Note: Data is only available for ultra-supercritical coal in The Netherlands. Advanced nuclear here includes different Generation III technologies including the European pressurized reactor (EPR), other advanced pressurized water reactor designs as well as advanced boiling water reactor designs. Please be noted that these numbers are the results of the work carried out in 2009 and focus on the expected plant-level costs of baseload electricity generation by power plants. Real costs today may be higher than what have been presented here. For example, overnight costs of a supercritical coal power plant in the United States could be easily over $3,000/kW (EIA 2010), well above the number quoted in Figure 2.
Data Source: IEA and NEA (2010).

Studies on individual countries and component technologies confirm these patterns. Prices for the flue gas desulphurization (FGD) market, for example, had stabilized around $150/kW, when after a few years of production, the Chinese manufactures had brought prices down to $75/kW for product delivered in China (Mott MacDonald, 2011). The so-called "China price"—that power plants can be built in China much cheaper— is strongly evident in figure 2 (which also suggests that for nuclear and coal technologies the phenomenon should be called the "China/Korea price"). A study utilizing Chinese data, for example, indicated that the cost of constructing an IGCC plant in China would be almost half the cost of constructing an equivalent plant in the United States (Zhao et al., 2008).

Third, the few studies that have simultaneously looked at historical patterns while also making projections point to the difficulty of serious forecasting. There is suggestive evidence that much forecasting in this area is done retrospectively. Analysts use current costs to anchor their expectations for long-term future costs rather than modeling capital costs as the result of fundamental forces of supply and demand. This is evident, for example, at how major modeling teams have adjusted the assumed future cost of generation technologies in response to short-term variations in the real world based on current cost of those same technologies. All published capital cost estimates for building new power plants by utility company, investment firms, and organizations have almost all been continually revised upward in recent years; what is unclear, however, is whether those revisions reflect fundamental shifts in technology markets (and thus likely to occur in the real world) or if they merely reflect variations in current conditions that could have little bearing on the situation 5 or more (let along 50) years in the future. To illustrate, we look at this phenomenon from two perspectives.

One perspective is the updating of base capital costs. For this, we focus on the EIA's Annual Energy Outlook—not to criticize the report but, rather, because EIA reliably publishes its estimates and revisions and thus analysts such as ourselves can make ready comparisons. Figure 3 presents variations in EIA's base year estimates of overnight capital costs for five generation technologies over the period 2000 to 2010. Comparing Figure 3 with Figure 1 suggests that the base year estimates in EIA's forecasts lag real world conditions by about 2 years. When looking back its past projections, EIA realized the need to significantly raising their cost estimates. The EIA has assumed no real cost increases until 2008 in AEO 2008 (except for fuel cell whose cost estimates were significantly raised as earlier as in AEO 2004), when it for the first time significantly raised costs by at least 15 percent over AEO 2007 levels for all conventional and renewable energy technologies. Overnight capital cost estimates of building new nuclear power plants in 2011, for example, are 37% higher than those in 2010, increasing from $3,901/kW to $5,339/kW and for advanced PC without CCS cost estimates in 2011 are 25 percent higher than those in 2010, rising from $2,271/kW to $2,284/kW.

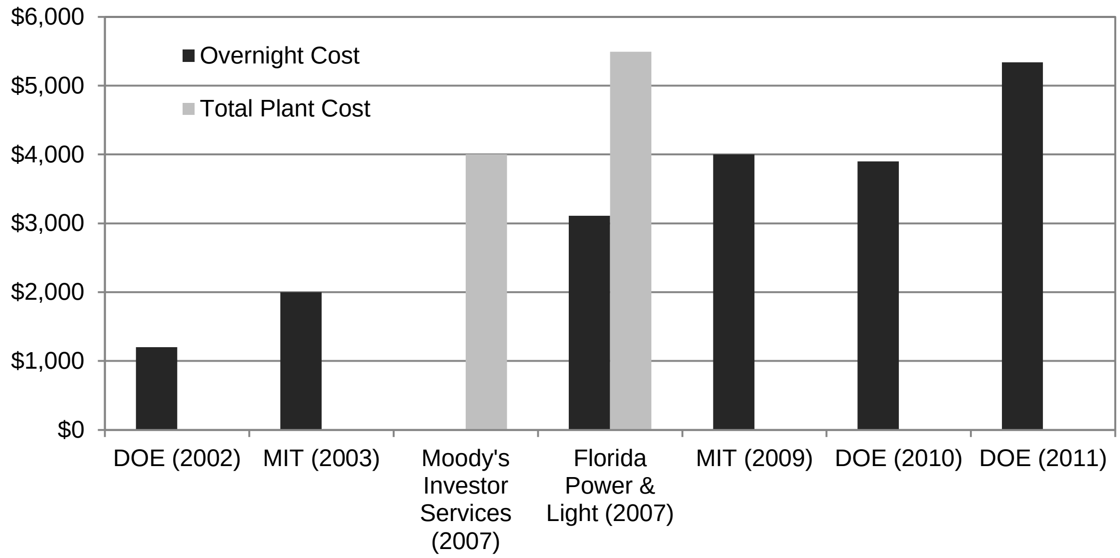
Figure 3: EIA's Base Overnight Capital Costs Estimates (2001-2010)



Data sources: Assumptions to Annual Energy Outlook 2001 through 2011

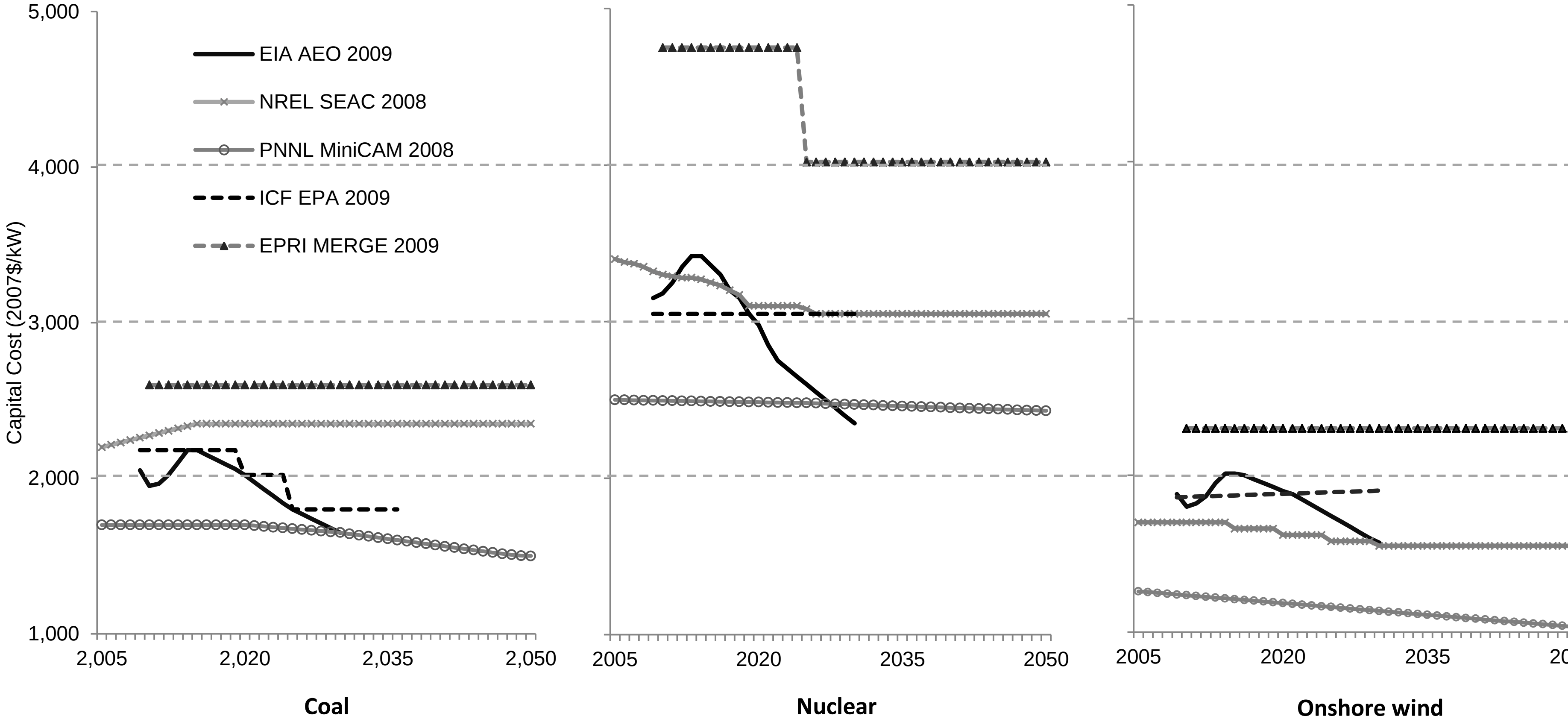
A second perspective comes from looking at the technology that is most capital intensive: nuclear. Published capital cost estimates for nuclear by utility company, investment firms, and organizations have all been continually revised upward. For example, in 2002 and 2003 the Department of Energy and MIT envisioned that the cost of new nuclear plants would be $1,200/kWe to $2,000 (MIT, 2003). At the time, the MIT number was striking for its high value. At the end of that decade costs had more than doubled (see Figure 4). The same researchers looking at the same phenomenon yielded massive changes in estimated costs over a period that was about half the time needed for full planning, siting and construction of a nuclear plant.

Figure 4: Recent Nuclear Construction Costs Estimates Summarized in Major Studies



The difficulty in making projections is further underscored by comparing the assumptions in different studies—something that the National Renewable Energy Laboratory (NREL) did in 2010 for six credible and widely discussed models: U.S. EIA, IEA, NREL, Pacific Northwest National Laboratory (PNNL), ICF International, and Electric Power Research Institute (EPRI). Although the models had nearly identical base years and aimed to explain the same underlying phenomena, neither in base year nor in projected years was there any convergence around particular values (see Figure 5). For example, the studies by U.S. EIA, ICF International, and PNNL all suggest the future capex of coal-fired power plants is expected to continue declining, while the other two project a stabilized future.

Figure 5: Comparison of Overnight Costs of Selected Technologies in the U.S. in Selected Studies

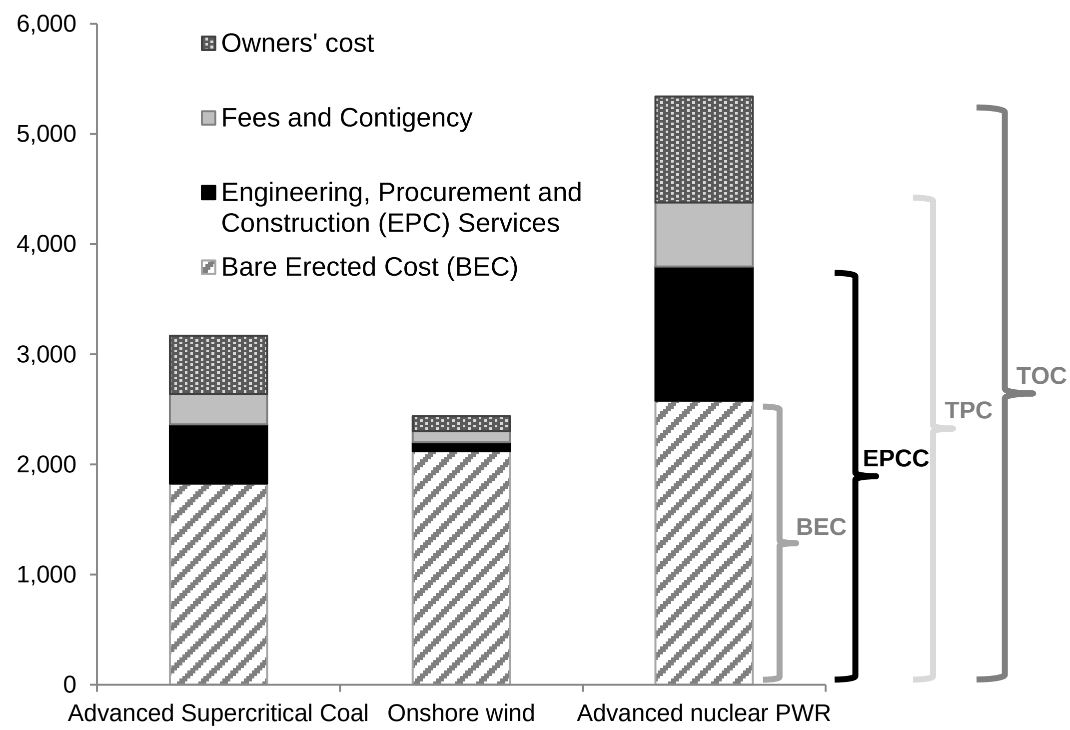


Data source: DOE NREL (2010)

3. Component Cost Analysis: What Are Major Capex Drivers?

Building new power plants is a complicated process affected by numerous factors. One is definitions since "capital cost" is a general term. Capital costs of building power plants can be defined at five levels: the Bare Erected Cost (BEC), the Engineering, Procurement and Construction Cost (EPCC), the Total Plant Cost (TPC), the Total Overnight Capital (TOC), and the Total As-Spent Capital (TASC). As shown on figure 6, the first four are "overnight" costs, which are the focus of this paper and expressed in "base-year" dollars (for definitions of these terms, please see the caption). By contrast, the last one, TASC, comprises the TOC plus both escalation and interests on debts during the capital expenditure period and therefore, is expressed in "mixed, current-year" dollars.

Figure 6: Base Plant Site Capital Cost Estimates for Selected Technologies (2010$/kW)



BEC: refers to Bare Erected Cost which comprises the cost of process equipment, on-site facilities and infrastructure that support the plant and the direct and indirect labor required for its construction and/or installation.

EPCC: refers to the Engineering, Procurement and Construction (EPC) Cost which comprises the BEC plus the cost of services provided by the EPC contractor. **EPC Services** refers to the cost of services provided by the EPC contractor including detailed design, contractor permitting (i.e., those permits that individual contractors must obtain to perform their scopes of work, as opposed to project permitting, which is not included here), and project/construction management costs.

TPC: refers to the Total Plant Cost which comprises the EPCC plus **process and project contingencies**.

TOC: refers to the Total Overnight Capital which comprises the TPC plus **owner's costs** which include preproduction (start-up) costs, inventory capital, and cost of securing financing but excluding interest during construction, etc.

Data source: DOE NETL (2011)

BEC normally accounts for the largest share of the total capex, ranging from 45 to 85% percent of the total depending on power technologies. For onshore wind, for example, over 80% of the cost is BEC, mainly referring to the cost of the wind turbine generator and its installation. By contrast, for the nuclear power plant BEC accounts for less than a half of the total capex and EPC services could be as high as one quarter of the total, reflecting the factor that a significant share of the capex for the nuclear is labor. In fact, if excluding a significant share of labor input already embodied within the equipment, the equipment costs could be as low as 10% for nuclear (Mott MacDonald, 2011). In this paper we have used "capital cost" principally to mean BEC or EPCC—a definition that corresponds closely to the concept of "overnight" capital cost.

The literature suggests that four factors dominate capital cost trends for most large power plants. (There is not much literature with a focus on capex drivers of power plants. Most of literature in Table 1 discusses non-policy factors including learning, materials, and labor.

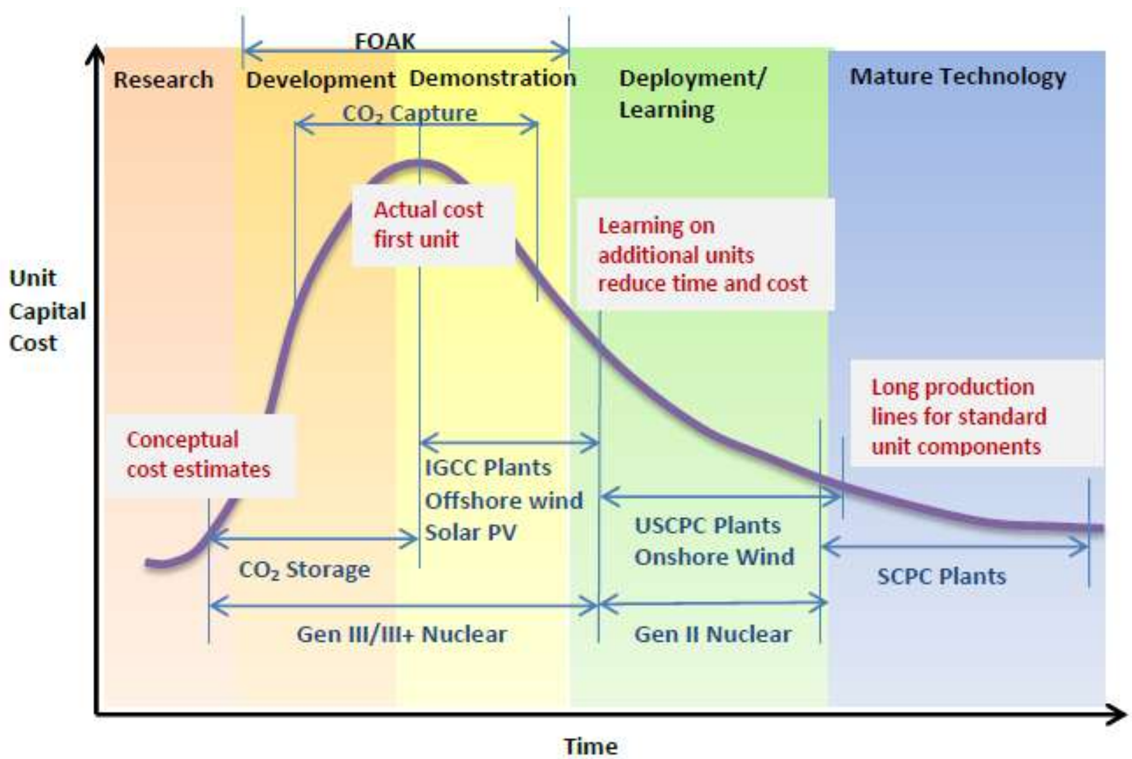
MacDonald (2011) presents a full list, but it only focus on low-carbon technologies and does not rank all influential factors.) We start with the factor that is already most extensively analyzed in the energy modeling literature: learning effects.

3.1 Learning effects

Technologies change through experience—either through innovation (true learning) or through economics of scale. Since 2000, the learning curve or experience curve concept has become an increasingly popular tool to analyze the cost development of electricity generation technologies, particular low-carbon technologies, as a function of cumulative production (e.g., OECD/IEA, 2000; McDonald and Schrattenholzer, 2001; Papineau, 2006; Jamasb and Köhler, 2008, etc.). The use of the learning curve is based on a deeper history of studying technological change in the energy industry (Grubler, et al., 1999). Strictly speaking, "learning" applies only from the moment that the first commercial demonstration projects are built. Learning rates—the level of improvement for every doubling of installed capacity—have often been observed at the rate of about 30% for immature technologies, slowing to 10% to 20% as the technology matures and then flattens. At extremely large deployments the concept of "learning" may become less relevant, not least because other factors—such as labor costs and materials—can swamp learning effects.

The concepts are familiar and summarized in figure 7. An emerging technology moves from a concept whose uncertain concept through a costly first-of-a-kind demonstration into niche markets and then more widespread deployment. As many units are built, the low costs become more certain and buyers will face lower project risks. Currently, various power generation technologies face their different phases of learning curves with different cost trends. Subcritical coal (SCPC) plants, for example, are considered as a mature technology and their unit capital costs are expected to stabilize. By contrast, advanced Gen III/III+ nuclear technologies are still in the phase of development or demonstration with highly uncertain cost estimates. Its unit capital cost is expected to decline through learning as more units are built until the technology matures and the cost trend line becomes flat. Because learning has been subjected to extensive prior analysis (e.g. Grubler, et al., 1999; OECD/IEA, 2000; McDonald and Schrattenholzer, 2001; Papineau, 2006; Jamasb and Köhler, 2008, Gallagher et al., 2012, etc.) we don't examine it in more detail here. We note that the exact role and wisdom of studying these phenomena as "learning" remains controversial since "learning" is general term that can obscure lots of other processes at work; moreever, learning must compete with other factors that affect performance, such as forgetting (Benkard, 2000; Nordhaus, 2009).

Figure 7: Capital Cost of Learning Curve for Power Generation Technologies

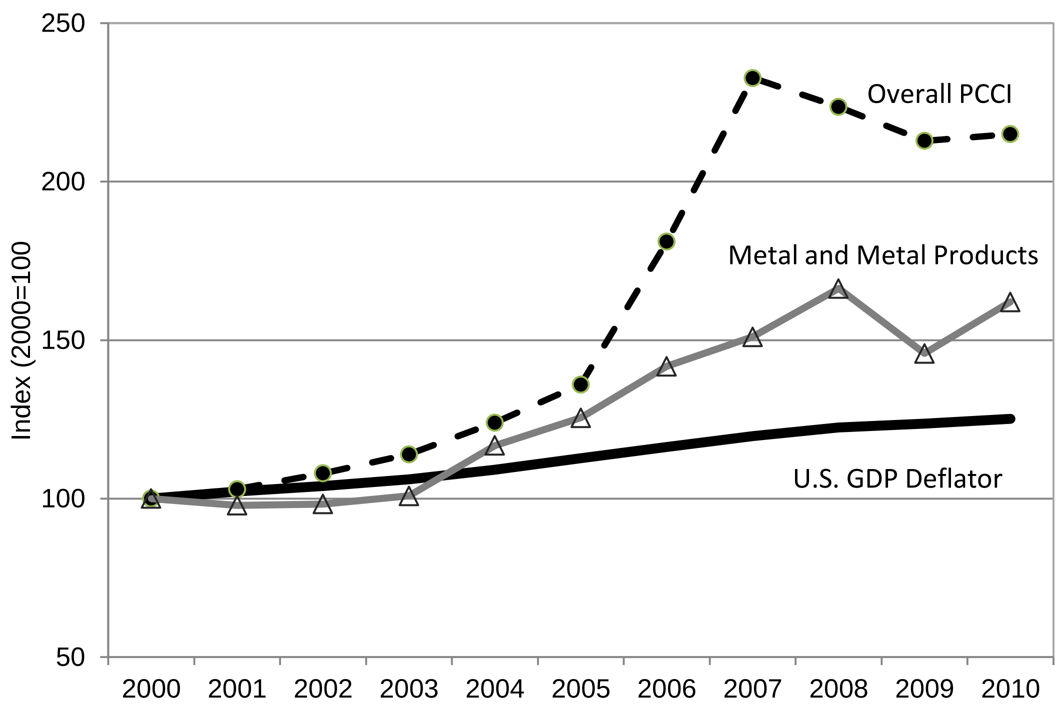


Source: Adapted from EPRI (2011) and Kee (2010)

3.2 The commodity market

A second major factor that determines total cost for a plant is raw material (e.g., steel, cement). For mature technologies—that is, technologies for which learning effects are small—the cost of raw materials is widely believed to be the largest source of revision in assumed capital costs. The last decade has seen dramatically increasing raw materials prices, tightly linked to a rise in actual capital costs. These trends are seen in figure 8, which shows the overall PCCI (reprinted from figure 1) along with the index for metal prices.

Figure 8: U.S. Commodity Prices and Power Plant Capital Cost over Years



Data sources: IHS (2011) and U.S. Bureau of Economic Analysis (2012)

The cost increases in raw materials have been much faster than the growth in GDP in mature economies (figure 8 shows the US). This decoupling is due to high global demand for commodities (notably from China's rapidly expanding economy) and lagging investment in new output capacity; higher production and transportation costs (in part owing to high fuel prices, which are driven by the same underlying phenomena) along with a weakening U.S. dollar all play a role as well (EPRI, 2011).

However, it is highly unlikely that rising costs for raw materials will lead to a major rise in the total capital cost of power plants. The direct linkage between rise in raw material prices and total capital costs is weak. Mott MacDonald (2011)'s study, for example, indicates that for low-carbon technologies the basic raw materials even at the peak of the market typically account for less than 5% of capital cost.

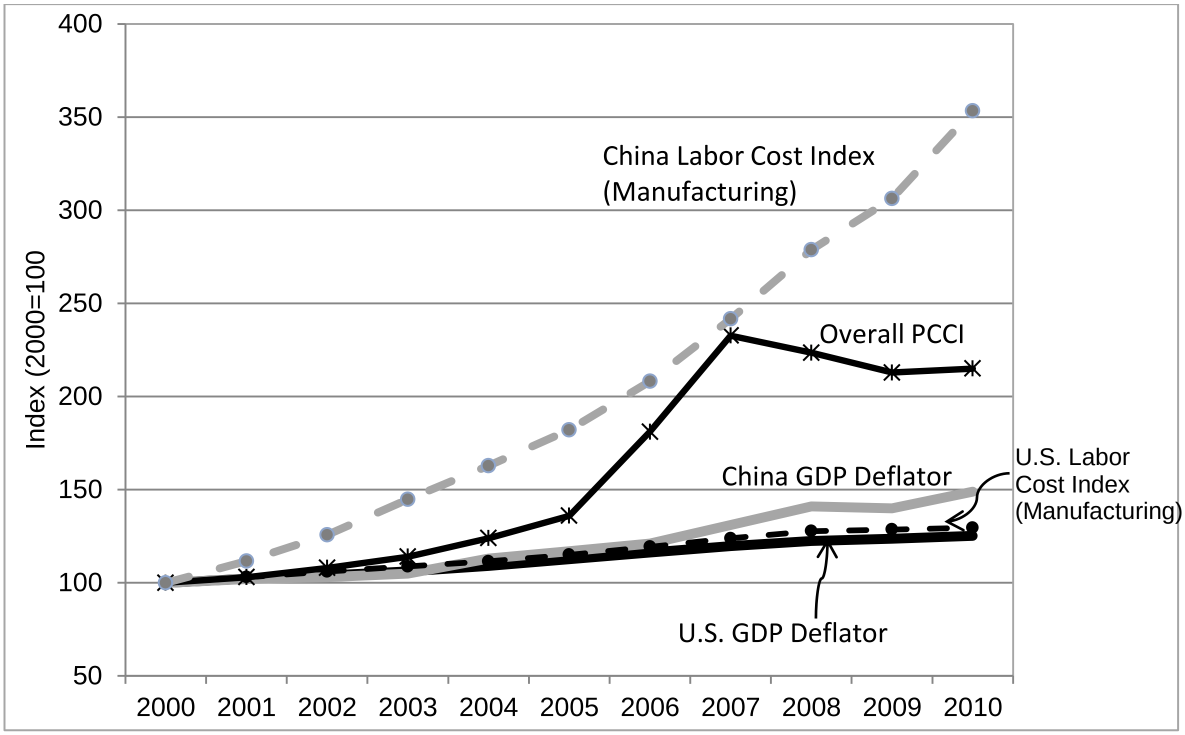
This decadal rise in commodity prices has been referred by some analysts as a "super cycle" and is, perhaps, immune to the normal forces that bring prices back to historical patterns (Cuddington and Jerrett, 2008). In fact, a return to normalcy may be under way at this writing. Following more than two years of strong growth and reaching a peak in early 2011, commodity prices has recently declined on concerns about global macroeconomic and financial outlook and slowing demand in emerging markets, notably in China (World Bank, 2012). According to World Bank's forecasts, despite of both downward and upward risks, commodity prices are most likely to decline into the medium term for all metals with the exception of aluminum, which is expected to rise and supported by higher costs for power and other inputs (World Bank, 2012). Looking to the longer term, commodity markets are inherently volatile and cyclical with booms and slumps (Cashin et al., 2012). Prices will depend not just on future demand from emerging economies but also the prospects for expanded investment in supply as well as innovation in the methods for extracting and processing existing materials and reduction in demand due to lightweighting and switching to substitutes (Streifel, 2006). We are mindful that even for high end uses of metals such as aluminum—which for decades had a prized position in some industries such as aircraft manufacture—rivals exist. During the Second World War Howard

Hughes built a troop airplane from wood because aluminum was in short supply. (It flew once and was a financial disaster.) Today, about half the airframe of the Boeing 787 is carbon fiber, plastics and other composite materials. (It appears to be a commercial success, and earlier experience with composites on aircraft, such as in the tail of the Boeing 777, indicate that composites don't just replace aluminum and weigh less—they also require lower maintenance.)

3.3 The labor market

Third, we look at labor costs. Labor comes in many forms--low-, semi- and highly-skilled—and all are relevant for power plants. Figure 9 shows both U.S. and China's labor cost index in the manufacturing sector over the last decade. Between December 2000 and December 2011, in the United States the general inflation rate (measured by the GDP deflator) increased about 27 percent and during the same period, the country's cost of manufacturing labor increased about 31 percent, slightly higher than the rate of general inflation. By contrast, China's labor cost has increased dramatically, more than tripling within ten years with a double digit growth rate annually.

Figure 9: Labor Cost and Power Plant Capital Cost Over Years



Data sources: IHS (2011), U.S. Bureau of Economic Analysis (2012), and National Bureau of Statistics of China (2012).

There are growing concerns about a gap between demand and supply of skilled construction labor. In most developed countries, the average age of the current construction skilled workforce is rising rapidly, and high attrition rates in construction are compounding the problem. Demand for such workers is expected to outpace supply over the next decade (DOE, 2006), and within the power industry there are perennial concerns about how to address problems in the aging workforce. In developing countries, even China with the world's largest labor force, there appear to be growing shortage of sufficiently skilled workers. According to the Institute of Population and Labor Economics at the Chinese Academy of Social Sciences (CASS), China already reached a "Lewisian turning point," where rural surplus labor is depleted to such a level that continuing industrialization cannot be supported cheaply (Cai, 2007). A 2011 report published by the U.S. Bureau of Labor Statistics (BLS) stated that from 2002 to 2008, hourly labor costs in the manufacturing sector in the United States increased by 19%, while the corresponding figure in China grew 100% (Banister and Cook, 2011).

Increased labor costs have a direct impact on capital costs. A large contributor is the cost of highly-skilled professionals—such as workers involved in engineering, procurement and construction (EPC) services. Prices for EPC services have risen sharply in the last decade, and a backlog of projects at the four major EPC firms—Fluor Corporation, Bechtel Corporation, The Shaw Group Inc., and Tyco International Ltd—has grown. Between 2005 and 2006 alone the backlog rose one-third (from $4.1 billion to $5.6 billion), although that pipeline of projects includes a wide array of EPC activities—in addition to power plants there are roads, port facilities and water infrastructure (Chupka and Gregory, 2007). Over the same period, this severe tightening in the EPC market affected EPC costs for particular power plants. A filing by Oklahoma Gas & Electric Company (OG&E) indicated, for example, that the estimate for EPC services for a new coal power plant had increased by more than 50% during the nine month period in 2006, contributing to an overall 10% increase in the expected capital cost of the plant (Chupka and Gregory, 2007).

One major source of uncertainty in future labor costs concerns the prospects for labor-saving innovations, such as from robotics. For decades, robots have become a strategic technology for industries like agriculture (if considering mechanization as an earlier version of robotics), automobile, metalworking, and machinery manufacture. The incentives to robotize for these industries are to lower unit costs of production and to improve product quality (Siciliano and Khatib, 2008). However, robotics has yet made a significant dent in the utility industry. The only partial exception is in nuclear power plants where robots have been used to reduce radiation exposure to human workers and also to reduce plant downtime (Moore, 1985;

Kim, 2010; Sugisaka, 2011). The wider application of robotics in the sector could be revolutionary. It is reported, for example, new robots are building solar power plants in the U.S. (V-Kraftwerker, 2012). Since building open area solar parks is mostly manual work and identical processes are repeated hundreds of thousands of times, the new robots are able to massively reduce labor costs by tackling the whole building process.

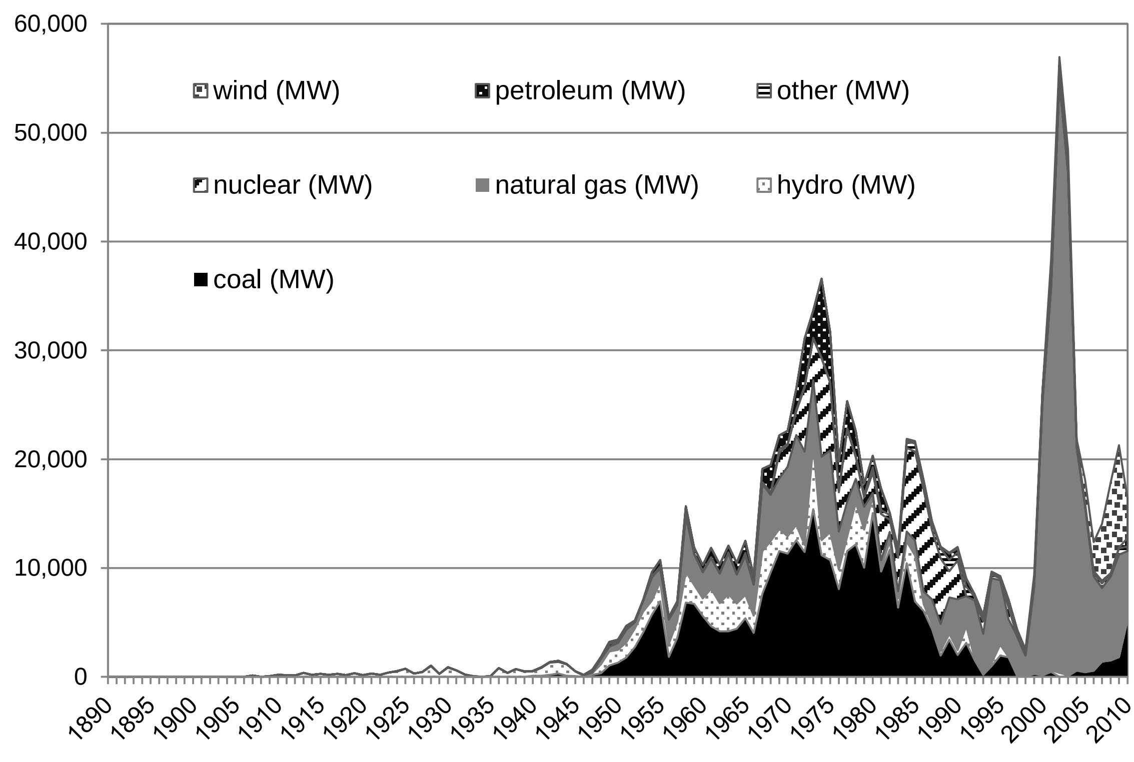
Another possible huge cost-savings may come from the import of pre-assembled major components overseas. In effect, pre-assembly allows markets where labor costs are high to take advantage of the lower costs in other manufacturing countries; as pre-assembly expands it can be applied not just to low-value labor operations but also highly skilled activities (Mahmud, 2008). It is reported, for example, that a $7.2 billion repair of the San Francisco-Oakland Bay Bridge could save at least 400 million by importing pre-assembled bridge decks from China (Pyle, 2011). Looking to the future could see a larger role for major component imports. Over a longer time horizon, a shift to modular nuclear reactors could allow for international trade—rather than assembly in place—of the most expensive elements of nuclear plants.

3.4 Regulation and Other Policy Interventions

Regulation, in some settings, may also be a major factor in the cost of building new power plants. However, in many integrated assessment models major regulations are resolved independently and treated, in effect, as a form of technological change. For example, models typically treat base coal plants differently from plants that include carbon capture and storage technologies; some models also treat other pollution control technologies (e.g., scrubbers and SCR) separately. A few studies have looked at the scope for changes in such technologies—such as learning by doing and other forms of innovation in scrubbers (Taylor, et al. 2005).

Due to tightened and changing health and safety compliance requirements, for example, very few coal-fired power plants have been built in the US in the past decade and the share of newly built coal-fired plants among the total has declined for years (see Figure 10). (Looking to the future, those regulations along with low prices for natural gas suggest that little if any new coal-fired capacity with be built.) Since 1990, more than 80% of new capacity has been natural gas-fired, which are cost-competitive with coal and emit no SO_2, no mercury, no other hazardous air pollutants, and only about half of the warming emissions of coal-fired units (EIA, 2011). Recently, U.S. EPA is proposing a series of regulations on coal-fired power plants. As of a result, a large number of old plants will have to retrofit or even retire. Some of these retired units will be replaced by new capacity, of which some will be coal-fired, but most replacements are likely to be natural gas combined cycle units (McCarthy and Copeland, 2011).

Figure 10: U.S. Power Plant Capacity, by Type and Year It Entered Service



Data source: EIA (2011).

Other types of power plants also face regulatory interventions—notably nuclear power, where regulatory burdens and growing public concern led to higher costs and longer delays. The time from project initiation to ground breaking, for example, was increased from 16 months in 1967, to 32 months in 1972, to 54 months in 1980 (Cohen, 1990). In the aftermath of Three Mile Island no new plants were initiated until a new regulatory framework was crafted in the late 1990s and a license to build two reactors was just recently approved by the U.S. Nuclear Regulatory Commission, which is the first in over 30 years (Hargreaves, 2012). Even with this new framework, the construction and operation of a nuclear power plant in the U.S. is subject to many veto points. Siting in other countries has been much easier. In Korea and China—the two countries that are most active builders (and lowest cost providers) of nuclear plants today see few delays in siting and construction (Yang, 2011).

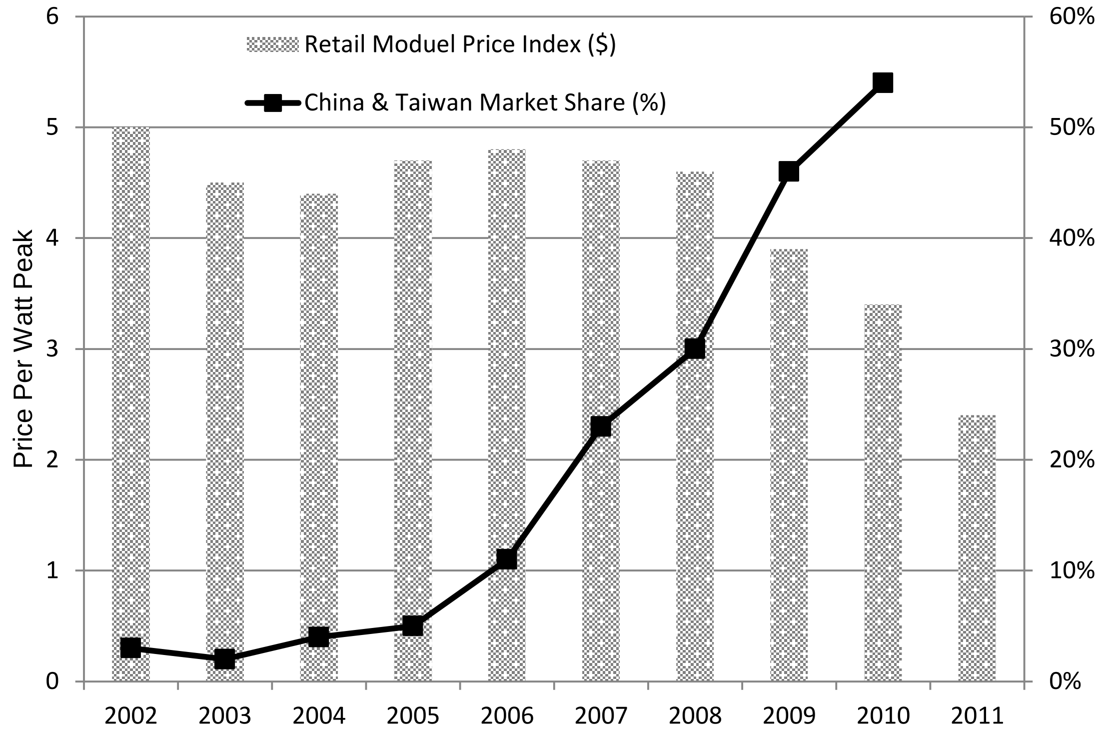
Policy makers intervene in markets with many tools beyond just regulation, and their interventions don't always raise costs. A wide array of policies aimed at supporting novel technologies—such as R&D funding and guaranteed purchases—have led (usually in tandem with learning) to lower costs. For example, the German Feed-In Tariff, part of the German Renewable Energy Sources Act of 2000 (Ernaeuerbare-Energien-Gesetz, EEG), has been the most important driving force in that country's expansion of renewable energy in the electricity sector (Frondel et al., 2008). In the U.S., an important policy driver for renewable energy has been production and investment tax credits (along with cash payments in some circumstances). Government has also played a role in lowering the risks associated with investing in (and thus improving) new technologies. One risk-reducing mechanism is government assumption of liability. Another is government-backed financing, which lowers borrowing costs. The 2009 U.S. economic stimulus, for example, provided more than $2.5 billion to finance clean-energy loan guarantees—funds that were leveraged into about $16 billion in investment projects (Synder, 2012). Still another model is direct financing—something that is easier, perhaps, in countries where governments own the firms that deploy new technologies and have control over banks and other sources of capital. We return to this topic in our case study on China.

A perennial challenge in the deployment of new technology is managing the risks associated with deploying pre-competitive and unproven technologies; while many different forms of risk management techniques have emerged, most share the common feature that the government assumes (or assigns, such as to consumers or to regulated enterprises) the extra risk associated with novel technologies.

4. Case Study: Why Can China Build Power Plants Much Cheaper?

Asian nations, particular China, are leading the way in building most of world's new power plants at a much faster speed and at much cheaper costs. Today, for example, most of the world's most efficient (supercritical and ultra-supercritical) coal-fired power plants, are being built in China (Nalbandian, 2008). The cost to build an ultra-supercritical power plant in China is less than one third of building the similar one in the United States (see figure 2). Onshore wind turbines are built in China for half the cost typical in the west, and compared with some high cost countries (e.g., Switzerland) the Chinese cost is a lot lower (figure 2). Although famous for its massive coal fleet, China overtook the United States in 2010 as the world leader in accumulative wind power installed capacity with a total capacity of 62.4 GW by the end of 2011, more than one fourth of the global wind capacity (World Wind Energy Association, 2012). China is also a leader in manufacture of some renewable technologies—notably solar modules, where China (and Taiwan's) market share has sharply risen as they have driven down costs and prices (see Figure 11).

Figure 11: Average Retail Module Price Sold in the U.S. and China & Taiwan Market Share of Global Shipments of PV Cells/Modules



Data sources: NPD Solarbuzz (2012) and Mints et al. (2011).

An explanation for the very low capital costs in China is found by looking at all four of the factors we examined earlier: learning, commodity prices, labor and policy.

Learning requires building and experience. Some of the lower cost in China may simply reflect huge economies of scale—and thus rapid riding down learning curves—that come from a large domestic market and (where domestic demand is relatively small, such as in solar) an export oriented manufacturing system. China's large wind capacity has grown to its current 62 GW from just 1.3 GW in 2005. In nuclear power, 25 out of a world total of 61 are under construction in China—by contrast, just one is under construction in the United States (World

Nuclear Association, 2012). The total Chinese nuclear capacity (40 GW in 2011) is expected to increase five- or six-fold to top 70 GW by 2020 (China Daily, 2012).

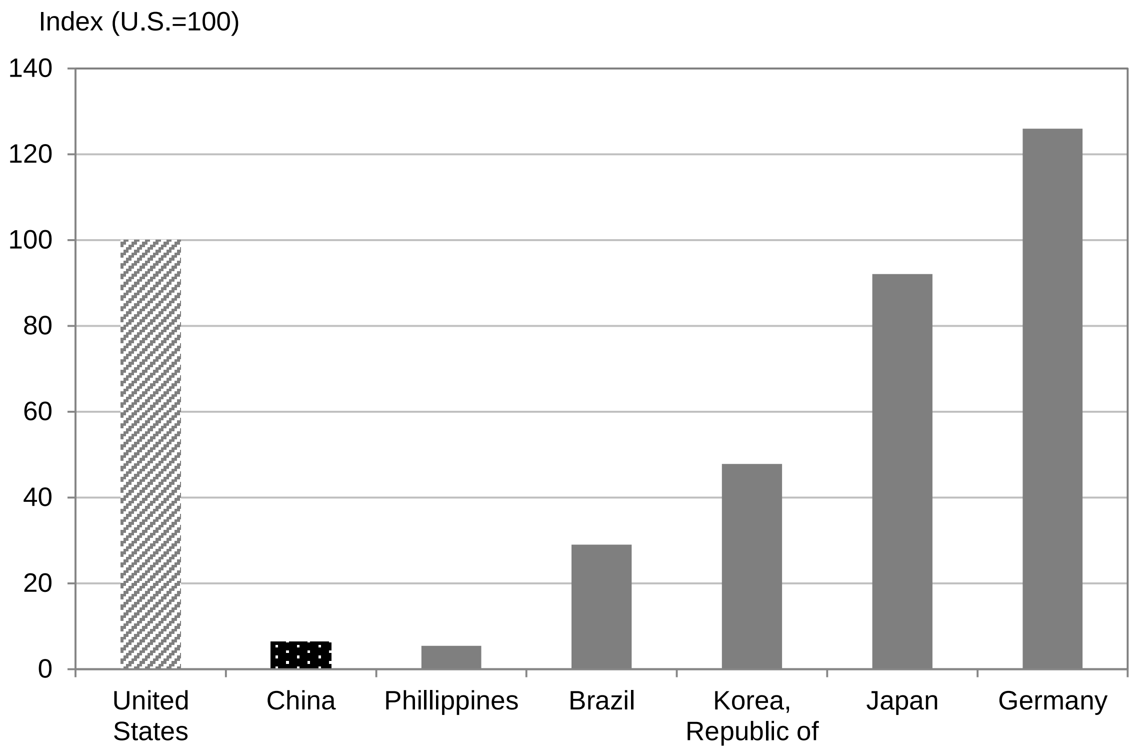
Of the four factors we have considered, the only one that appears *not* to play a major role in China is commodity prices. Perhaps a decade (or more) earlier, central administration of the Chinese economy could help explain why producers faced often lower prices for strategic materials—such as steel and concrete—when compared with their western counterparts. As a gradual transition to a market economy, China implemented a dual price system Since February 1985, permitting producer goods exchange at two different prices: a state-set price, for centrally rationed supplies, and a higher free-market price (Naughton, 1996). Today, except for only a few, almost all commodity prices in China conform to international prices (Streifel, 2006). In fact, China has become the most important player in international commodity markets and international prices will depend very much on the pace of demand in China and its status as a net importer or exporter (Streifel, 2006).

The heart of "the China Price"—in general, which means 30% to 50% lower cost for manufacturing products when compared with the U.S. or anywhere else—is widely believed to be the country's much cheaper labor costs (Engardio et al., 2004). While there has been extensive analysis of the "China price" for manufacturing, there has been a few studies looking at differences in large-scale engineering projects (e.g. Yang, 2011), where the "the China Price" we argue is not only benefited from its lower labor costs, but more critically promoted by its regulatory environment.

As measured in U.S. dollars, in 2010 Chinese hourly labor compensation costs in manufacturing were roughly 6 percent of those in the United States, slightly surpassing those of some developing countries like the Philippines, but still significantly lagged behind those of other countries like Brazil (see Figure 12). The average manufacturing wage in China in 2010 is still only about $2 an hour (CBS, 2011), compared with $35 in the United States (U.S. Bureau of Labor Statistics, 2011), though the wage is expected to much higher up to about $5 in the eastern part of China (Powell, 2011).

China's hourly cost advantage, while still significant, is shrinking rapidly. The real wages for manufacturing workers in China have grown nearly 12% per year (see Figure 10). Harder to parse are the trends for highly skilled professionals where there is a large pool of workers who can work in conditions where their western peers will not (e.g.,12-hour days, on weekends, willing to live in sheds close to projects, etc.). Today, China produces far more number of first university degrees in natural science and engineering (NS&E), compared to the United States and also the largest number of doctoral degrees in engineering, rising four-fold from approximately 4,000 in 2001 to over 15,000 in 2008, compared to 8,000 in the United States and 4,000 in Japan in the same year (NSF, 2012).

Figure 12: Index of Hourly Compensation Cost in Manufacturing, Selected Countries, 2010



Note: Direct comparisons are difficult due to differences in statistical techniques and the need for corrections due to labor quality.

Source: Data for China is from China Labor Statistics Yearbook 2011. Data for other countries are from U.S. Bureau of Labor Statistics (2011).

Finally, we look at the role of policy. China's regulatory environment is enormously favorable for large construction projects. Its system of "state capitalism"—which is a political system that "tries to meld the powers of the state with the powers of capitalism, depends on government to pick winners and promote economic growth, and also uses capitalist tools such as listing state-owned companies on the stock market and embracing globalization (The Economist, 2012)"—are particularly well suited to large, financially risky engineering activities for three reasons.

First, industry is dominated by state-owned enterprises (SOEs), which account for 80% of the value of the stock market in China. Energy and utilities, in particular, are the two industrial sectors that SOEs have the most influential footprints (The Economist, 2012). As in many other settings where SOEs operate with soft budget constraints, well-managed SOEs (which are the norm in China) are often better able to manage risks (and shift them to government) while absorbing the benefits of learning (Victor et al., 2012).

Second is the role of state-controlled finance, notably from Chinese policy banks that have largely financed the buildup of new power plants through almost-zero interest debt, which provides a significant cost advantage over those builders in economic systems where the state plays a more distant role. Cheap or free public finance does not necessarily affect overnight costs—such as bare erected cost (see Figure 6)—but it can lower risks that are inherent in such projects and reduce costs for some forms of procurement. The most notable example is the Chinese Development Bank (CDB), one of the three Chinese policy banks. Originally operated as an arm of the Chinese central government, CDB is now a joint stock company with limited liability that reports to China's national cabinet on certain policy issues and it is the only bank in China whose governor is a full minister. This allows the Chinese government to direct funds to activities that the government is keen to support—including infrastructure, which has garnered massive investment as the central economy has tried to promote economic growth and has been worried that adequate electric power supply could be an impediment to growth. It is reported that CDB had $687.8 billion in loans on its books at the end of 2010, more than twice as much as the World Bank (Bloomberg, 2011a). The CDB raises most of its money via long-term bonds and with an implicit state guarantee, which makes it easier, cheaper, and a lot less risky for utility builders to obtain financing. Such advantages are not unique to China, and they often arise when state-backed firms raise debt—such as state-backed oil companies (e.g., Pemex)

(Victor et al., 2012) or state-backed Tennessee Valley Authority, which recently raised long-term debt at an interest rate of 1.875% (Flessner, D, 2012).

One strategic focal point of CDB nowadays is to finance emerging industries, which includes solar power and other forms of clean energy. It was reported, for example, that in 2010 alone CDB reached an agreement on providing $30 billion in low-cost loans and credits to the top five Chinese solar panel manufacturers, with $8.9 billion to LDK Solar alone, the largest Chinese solar player (Mercom Capital Group, 2011). It is believed that the huge almost-zero interest debt funded by Chinese policy banks at least help Chinese solar companies achieve economies of scale, drop the price of solar at an astonishing pace, and therefore dominate the solar market (Lacey, 2011). This advantage, which is rooted in the relationship between the Chinese state and its state-dominated banking system, is also the source of growing trade conflicts—notably with the U.S.

Third, the Chinese state—as with essentially all governments that are funding new energy sources—has offered massive subsidies. It has offered reduced corporate income tax (CIT), significant reduction in value added tax (VAT), other tax incentives, and feed-in tariffs and subsidies to operators of renewable energy projects to compensate for their costs. A reduced CIT rate of 15%, for example, is given for advanced and advanced and new technology enterprises including solar and wind, compared to a regular rate of 33%. Chinese wind farms are also eligible for a 50% VAT rebate and VAT has been reduced from 17% to 8.5% (Zhang et al., 2011). In July 2011, a national feed-in tariff for solar projects, 1.00 or 1.15 RMB/kWh (about $0.15 to $0.18 per kWh) depending on the construction time, was announced to form its domestic solar market (NDRC, 2011). The feed-in tariff for wind projects now ranges from 0.51 RMB/kWh to 0.61 RMB/kWh or $0.08/kWh to $0.10/kWh depending on a region's wind resources (Zhang et al., 2011). To stimulate its distributed/rooftop solar PV, for example, the

China government launched in 2009 the "Solar Roofs Plan" and the "Golden Sun Project." As the end of 2010, the "Solar Roofs Plan" approved 210 projects and covered 181 MW of approved PV capacity with a total cost to the Chinese government of RMB 2.4 billion (or roughly 380 million) and the "Golden Sun Project" approved 314 projects involving over 630 MW of installed capacity with a total construction costs associated with the projects to be roughly RMB 20 billion (or roughly $2.9 billion) (Wang, 2011).

A small fraction of the subsidies that have benefitted China's industry have come from overseas—notably through the Clean Development Mechanism (CDM) that allows polluters in the EU to offset carbon emissions at home by investing in clean energy abroad. It is estimated that about one in five of China's renewable energy projects have been the beneficiaries of the Europe's cap and trade program (Kraeme, 2012). As of March 6, 2012, China had 1,843 CDM projects registered at the UN, about half of the world total, and expected average annual carbon credits from the registered projects reach 336 million with a value ranging from 3 to 10 billion euro depending on price of carbon credits. About 80 percent of these CDM projects involve hydro and wind power projects (UNFCCC, 2012). It is estimated that emissions reduction revenues make up 20 percent of their income wind and small hydropower projects (Lan, 2012).

5. Implications and Conclusions

We have argued that the assumed cost of building power plants is a variable that deserves much more attention by analysts working with tools such as integrated assessment models. Typically, such models assume that capital costs will be largely fixed except for new technologies (often renewables) where costs will decline with experience. Yet our review shows that costs for existing, mature technologies are, in fact, highly variable around the world and it is plausible that that variability will remain high far into the future.

While there has been much scholarly attention to “learning,” three other factors also play major roles in determining capital costs: the price of commodities (e.g., steel), labor, and a country’s business and regulatory context. (This last factor includes environmental regulation, subsidies and other incentives, and the broader context that how government and business interact.) The price of commodity materials, though widely believed to be important, only plays a minimal role in the overall costs. For mature technologies, labor costs are usually the single largest contributor to total cost. In a nuclear plant built in a typical western country, labor is 90% of the total cost. Along with labor costs, regulatory contexts probably largely explain the large differences across countries. Yet regulatory and policy issues are often ignored or hard to include in coarse models that are designed to examine engineering rather than institutions.

Studies such as the one here have many implications for policy. One is that some of the most consequential policies are those that, traditionally, have not been a central focus of energy policy analysts. For example, given the central role of labor costs it is plausible that changes in the structure of labor markets—such as initiatives to make those markets more competitive and to allow migration of skilled labor—could have a much larger impact on future costs of energy technologies than most of the other factors we commonly study. Similarly, policies that affect the ability of firms to manage risks associated with large capital projects—for example, the presence of soft budget constraints and state-backed financing typical of many state-owned enterprises, including the large energy firms in China—can have a massive impact on the structure of the energy system.

This essay suggests that large-scale energy models might devote more attention to the existing and plausible future variability in capital costs. For example, they might adopt scenarios that explore the possibility of large changes in costs over time—even in mature technologies—due to changes in labor markets, industrial organization and regulation. While the rise in labor costs points to a future where capital costs for plants is rising, it is possible that costs could come way down—partly from labor-saving innovations in robotics and other fields, which have barely made a dent in the power plant industry, and partly from pre-assembly of major components overseas, particularly from low cost Asian countries like China and Korea.

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