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A centurial history of technological change and learning curves for pulverized coal-fired utility boilers

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Abstract

Recent study of the history of technological change has provided better understanding of the driving forces for technological innovation, as well as quantitative estimates of historical rates of technical change. Although such results are widely used in long-term energy models to estimate future costs over time periods of up to a century, most studies of technological learning for major energy technologies are based on historical trends over time periods not longer than 20–30 years (often because of data limitations). Relatively few studies quantify longer-term (century-scale) trends. This study helps fill that gap by reviewing the history of pulverized-coal (PC) power plants, with a specific focus on the technological progress of PC boiler technology over the last century. Historical data for U.S. plants are used to develop long-term experience curves for the overall thermal efficiency of PC power plants, as well as the capital cost of PC boilers and non-fuel operating and maintenance (O&M) costs of PC plants. Despite a technology plateau experienced by PC power plants two decades ago, recent developments indicate that such plants will continue to improve and remain a competitive and important part of power generation technology portfolios.

Keywords: Pulverized-coal boilers; Experience curve; Thermal efficiency; Coal-fired power plant; Learning-by-doing; Technological change; Steam plant; Steam turbine; Electricity

1. Introduction

The importance of technological innovation and its contributions to increased productivity, lower production costs, and economic growth are widely recognized [1–3]. Studies have characterized the historical pattern of cost reductions associated with increased level of production in a variety of industries—a phenomenon commonly called learning-by-doing [3–5]. In most cases, cumulative output or capacity is used as a measure of experience to quantify overall cost reductions resulting from economies of scale, learning-by-doing, capital deepening [6], and expenditures for research and development [7], as well as other factors that influence cost trends (e.g., changes in market structure, organizational forgetting, variations in knowledge transferability, and government regulations) [8–11]. Endogenous models of technical change are increasingly used in large-scale integrated assessment models, typically in the form of an "experience curve" (also called a learning curve) that relates changes in specific investment cost to the cumulative installed capacity of the technology. While there are substantial uncertainties in the use of experience curves to project future technology costs and implications [12,13], the growing use of experience curves in large-scale energy models represents a significant methodological advance over the more common assumption of an exogenously specified cost reduction that is independent of other factors.

For energy technologies, most experience curves used in large-scale models are based on technologies with observed time scales of not longer than about 30 years [14–16]; yet, such curves are commonly used to project energy technology cost reductions over periods of 50–100 years [17–21]. Because relatively few of today's technologies have been in use for longer than half a century, and because

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systematic data on early deployment and cost trends are extremely scarce, few studies have examined the validity of technology experience curves over long periods of time. Thus, case studies that examine historical cost trends of specific technologies over much longer time scales can be of significant value in guiding and bounding experience curve assumptions used to project long-term costs and performance as a technology evolves through different phases and market conditions.

The current study focuses on the pulverized-coal (PC) boiler, one of the few major energy technologies in use for over a century and which is still re-inventing itself. The Energy Information Administration projects that total worldwide installed coal-fired generating capacity will approach 2000 GW by 2030, up from 1119 GW in 2003 [22]. More than 61% of the projected new generating capacity is expected to be in China (546 GW), followed by the U.S. (16.7%, 147 GW) and India (10.7%, 94 GW) [22]. The boiler is the heart of a PC power plant, burning fuel to provide the steam that drives turbines to generate electricity. Technology improvements in PC boilers and in other plant components have yielded significant economies of scale along with improvements in efficiency, reliability, and environmental performance of the overall power plant. This has contributed to significant cost reductions since the introduction of PC plant technology [23]. However, because of the growing (and changing) complexity and requirements of a coal-fired power plant, a deeper understanding of the nature and rate of technology innovation requires focusing on major plant components. Thus, the main purpose of this study is to apply the experience curve approach to the PC boiler, which accounts for most of the total plant cost. To provide context for this analysis, however, Section 2 of this paper reviews the history of coal-fired power plants and quantifies overall trends in improvement of PC plant efficiency. Section 3 then discusses improvements in boiler technology that provide the basis for the experience curves of boiler capital cost and non-fuel operating and maintenance (O&M) cost developed in Section 4. Potential applications of these findings are then summarized in Section 5.

2. Overall trends for PC plants

Improvements in electricity generation technology over the past century have been made in many different areas, including boilers, turbines, generators, and transmission–distribution systems. Overall, the average price (in year-2000 dollars) of electricity for final consumers in the U.S. fell from over 420 cents per kilowatt-hour (kW h) in 1900 to about 10 cents per kW h in the late 1980s, and less than 7 cents per kW h in 1990–2000 [24]. Fig. 1 shows the cumulative installed capacity of pulverized coal-fired plants in the world from 1921 to 2004 [25].[1] The world's annual capacity peaked around early 1970 to late 1980 and subsequently declined after 1990. In the U.S., change in annual capacity spiked in the 1950s, decreased in the 1960s, peaked in the early 1970s and the early 1980s, and gradually subsided to only a few installations per year after 1990. By 2003, the cumulative installed capacity of U.S. coal-fired power plants reached 337 GW.

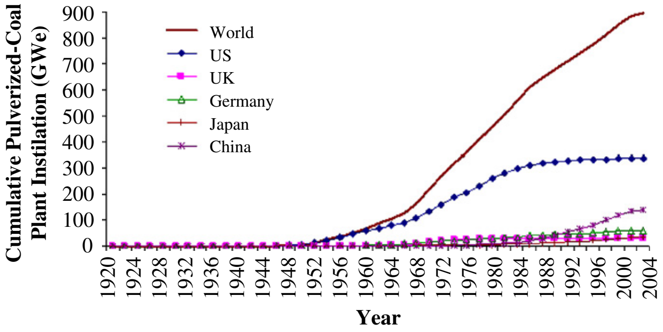

Fig. 1. Worldwide cumulative capacity of PC coal-fired plants. Source: [25,26].

PC technologies in the U.S. played an important role in the world market, especially prior to the 1970s. From 1925 to 1955, the worldwide production of electricity grew from 200 to 1200 TWh, with the U.S. accounting for more than 50% of total production, followed by Germany, the former Soviet Union, and the United Kingdom. From the 1950s to the 1970s, the world's electric power equipment industry was dominated by two American companies, General Electric and Westinghouse, followed by rapidly growing Japanese groups, mainly Hitachi, Mitsubishi, and Toshiba, next to ABB (European). The U.S. manufacturers had not only a large domestic market but also a substantial world market. But with growing international competition, U.S. exports of electric power equipment fell from 32% to 20% of the world market from 1955 to 1969 [27]. Today, the major suppliers of PC boilers include ABB (17%), Babcock and Wilcox (17%), Shanghai Boiler Works Company Ltd. (6%), Foster Wheeler (5.8%), and Rafako S.A. (5.8%), which collectively account for more than 50% of the total market share [25].

2.1. Trends in PC plant thermal efficiency

In the U.S., the maximum thermal efficiency of PC power plants (based on higher heating value, HHV) improved from 8% in 1900 to 40% in 1960 (Eddystone, PA). Much of this improvement was due to advances in boiler technology. Since late 1980, however, the maximum thermal efficiency of new plants has declined to between 37% and 38%, while the average thermal efficiency of PC

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[1] The CoalPower5 data published by the IEA Clean Coal Centre [25] is used in our analysis as it provides detailed plant-level information on the world's coal-fired power plants. The CoalPower5 database recorded the

(*footnote continued*)
total *cumulative* capacity in 2004 is 875.5 GW, lower than the *existing* worldwide installed coal-fired electricity generating capacity of 1119 GW reported by the International Energy Outlook [22].

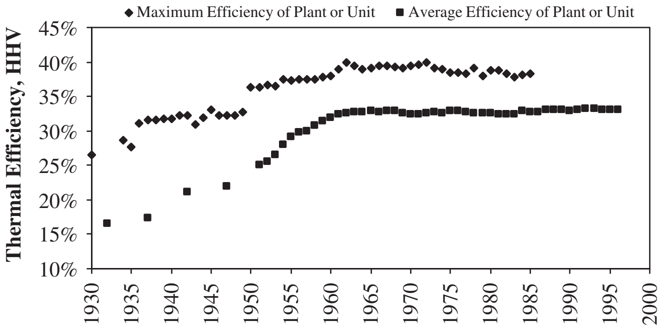

Fig. 2. Annual maximum and annual average thermal efficiency of new PC coal-fired power plants in the U.S., 1930–1995. Source: [24].

plants in the U.S. has remained in the range of 33–34% (Fig. 2). The decline in new plant performance was due to the demise of higher-efficiency supercritical coal units, which were first introduced in the early 1960s and comprised 63% of new installations from 1970 to 1974. By the early 1980s, however, supercritical boiler technology was essentially abandoned in the U.S. (Fig. 3, right), with subsequent new plants reverting to less efficient subcritical units. That trend has been attributed to two major factors: a much smaller demand for new power plant capacity beginning in the late 1970s, which favored the construction of smaller plants (where supercritical technology is less cost-effective); and the low reliability and poor operating performance of the supercritical fleet, which led to high maintenance and replacement power costs[2] [24,28]. While the majority of new PC boilers installed worldwide since 1990 have been subcritical units employing 2400 psi/1000 °F/1000 °F (166 bar/538 °C/538 °C) drum boilers [29], supercritical boiler technology, operating at higher temperature and pressure, continued to be developed in Europe and Asia (primarily Japan). More recently, several “ultra-supercritical” boilers—with even higher temperature and pressure—were built in Europe and Japan, where higher coal prices justified the higher cost of these more efficient plants (Fig. 3, left) [29,30]. Today, supercritical units are again being considered for new power plant projects in the U.S. and Canada [29,31,32].

In the 1990s, more efficient PC plants using supercritical boiler technology achieved net plant efficiencies of 42–44% in Japan, Germany, Denmark, Netherlands, and most recently China [33,34]. Fig. 4 shows the recent progress in PC plant efficiency, achieved via higher steam pressure and temperature, double reheat, and other design changes, albeit with an increase in capital cost [34]. Other studies note that advances in materials and process components could allow ultra-supercritical boilers to achieve still higher efficiency within a decade [29,30,33].

2.2. Experience curve for PC plant thermal efficiency

A typical experience curve has the form of $Y = ax^b$, where Y is the estimated average cost per unit for the xth unit of product; a is the unit cost of the first unit; and b ($b<0$) is a parametric constant. The learning rate (LR) is defined as the fractional reduction in unit cost for every doubling of cumulative output, and is thus equal to $(1-2^{-b})$. The progress ratio, PR, is defined as the fraction of initial cost after a doubling of output, which equals (1-LR), that is, 2^{-b}. In a linear-linear scale graph, the experience curve exhibits steep cost reductions at the beginning and slower cost improvements toward the end, reflecting that as technology becomes mature, the improvement in cost becomes smaller in absolute terms. In a log–log space, the curve is a straight line representing a constant rate of cost reduction associated with increased production. Detailed reviews on the histories, applications, and uncertainties of the experience curve can be found in the literature [13,14,37,38].

In Fig. 5, a log–log experience curve of the form explained above is fitted to the maximum thermal efficiency of PC plants built in the U.S. between 1920 and 1985, and worldwide between 1985 and 2005. The x-axis depicts experience using worldwide cumulative installed capacity of PC plants (in GW). This reflects the international nature of technological learning in the world market for PC plants and boilers, as described later in this paper. The data suggest a progress ratio of 1.033 between 1920 and 2002, i.e., overall plant efficiency improves by 3.3% for every doubling of cumulative installed capacity. The thermal efficiency plateau for U.S. plants beginning in the 1970s is apparent in this graph. Subsequent technology improvements, mainly supercritical and ultra-supercritical boilers developed in Europe and Japan, overcame the plateau and extended the learning curve to a higher level. The experience curve implies that if the rate of improvement continues, the maximum thermal efficiency of *commercially viable* PC plants will reach 43.9% when the cumulative capacity is 2000 GW (projected to be reached by 2030). This level of thermal efficiency already has been achieved by many state-of-the-art plants, as detailed in Fig. 4. It remains to be seen, however, whether state-of-the-art supercritical and ultra-supercritical boilers will become widely deployed worldwide. If we fit an experience curve to only the “best” plants and ignore the plateau effect, then a higher progress ratio of 1.038 is obtained (Fig. 5, dotted line). This implies that if we only consider the rate of improvement of the *best commercially viable* PC plants, the maximum thermal efficiency of such plants would have reached 44.4% today and 46.4% once cumulative capacity reaches 2000 GW. These efficiency values are in line with actual developments today. One study suggests it is now technologically feasible to increase the thermal efficiency of a PC plant to as high as 48–51% by 2020 and 49–53% by 2050, due to advanced materials and overall improvements of the plant [33].

However, the rate of improvement in commercial PC plant efficiency reflects not only advances in power plant

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[2] Part of the reason is that supercritical-coal boilers, at least in the 1970s, did not operate well on U.S. coal with high sulfur and active sodium. This is a major issue that European or Japanese supercritical units have not had to address.

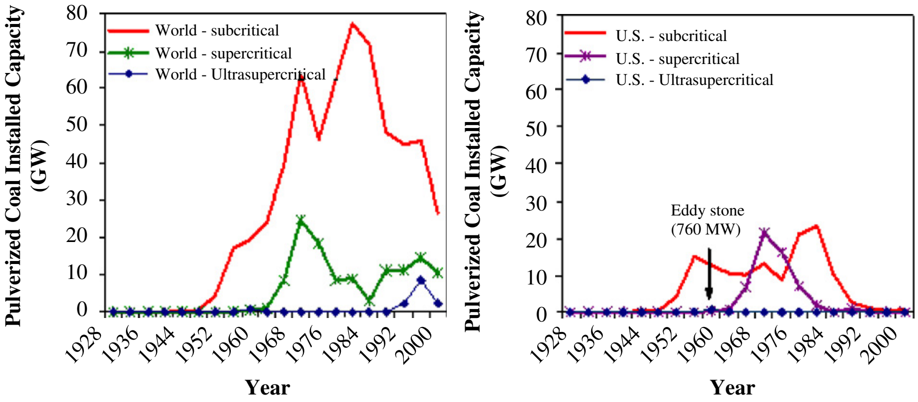

Fig. 3. World (left) and U.S. (right) PC coal-fired plants' annual installed capacity (in GW/year) by type of boiler. Source: [25].

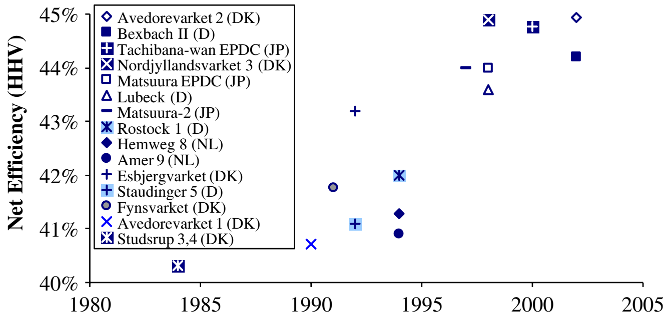

Fig. 4. Recent progress in plant efficiency of PC coal-fired power plants in European countries and Japan. Source: [25,35,36].

technology but also the economic tradeoff between capital cost and fuel cost. That tradeoff tended to slow further deployment of more efficient (but more expensive) technology, especially after 1970. The plateau and decline in thermal efficiency improvements from about 1970 to 1990 also was due in part to new environmental control regulations requiring energy-intensive emission control devices (such as sulfur dioxide scrubbers), which lowered net plant efficiency. As noted earlier, new plant efficiency also declined as utilities abandoned supercritical units in order to increase plant reliability and availability [28,41].

Plotting the percent change in PC plant efficiency as a function of time (Fig. 6) suggests that improvements in PC plant efficiency have not been constant over the last 100 years, but underwent rapid growth over 1940–1960, maturity over 1960–1970, technology plateau (stasis) over 1970–1990 (with some small improvements after 1985), and technology reinvigoration at about 1990. Although these improvements were the result of advances in many plant components, improvements in boiler technology were the main driver, as seen later in this paper.

2.3. *Trends in plant-level construction cost*

Several studies comparing historical construction costs for U.S. coal-burning power plants found that real capital cost per kilowatt continued to decline until the early to mid-1960s, stabilized in the late 1960s, then climbed substantially during the 1970s and 1980s [28,42]. Joskow and Rose [28] controlled for scale effects, technological differences, input price changes, major environmental control technologies, and other cross-sectional differences in real construction costs. They found that real cost increases were primarily due to new regulatory requirements such as environmental, health, and safety standards; changes in work rules; and improved design standards. Increased labor costs, increased construction time, and a decline in construction productivity also contributed to higher costs. Similar findings were observed by Wang and Yu [42]. Nonetheless, Joskow and Rose found significant learning effects for architect–engineering firms and utility companies (albeit at different rates) involved in constructing both subcritical and supercritical plants.

Because previous studies of PC plant cost trends have focused on the cost of the overall plant, they incorporate many factors not related to technological learning, and also reflect considerable heterogeneity in overall plant designs [43]. In contrast, in this paper we focus on the historical cost trend only for PC boilers, and estimate the associated experience curves for PC boiler capital cost. We also derive an experience curve for long-term non-fuel O&M costs of the overall PC plant in the absence of available long-term data on boiler-only O&M costs (although boilers are typically the largest contributor to non-fuel O&M costs [44]).

3. Technological progress of coal-fired boilers

Early coal-fired boilers typically employed fixed or moving grates on which chunks of coal were burned to provide the heat needed to generate steam. The introduction of PC technology, in which coal is pulverized into a fine powder and injected into the furnace via burners, substantially increased the surface area of the fuel and improved the speed and efficiency of combustion. Major subsequent advances in PC boiler design came from economies of scale together with the increased steam pressure and temperature

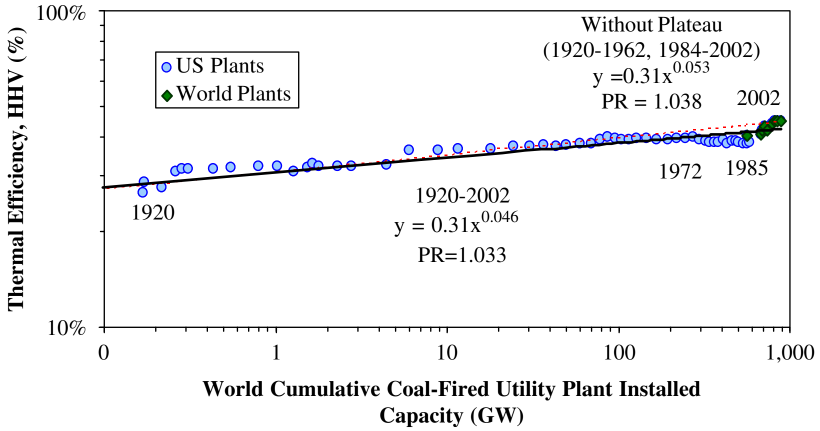

Fig. 5. Thermal efficiency as a function of world cumulative coal-fired utility plant installed capacity, 1920–2002. Source: [24,35,36,39,40].

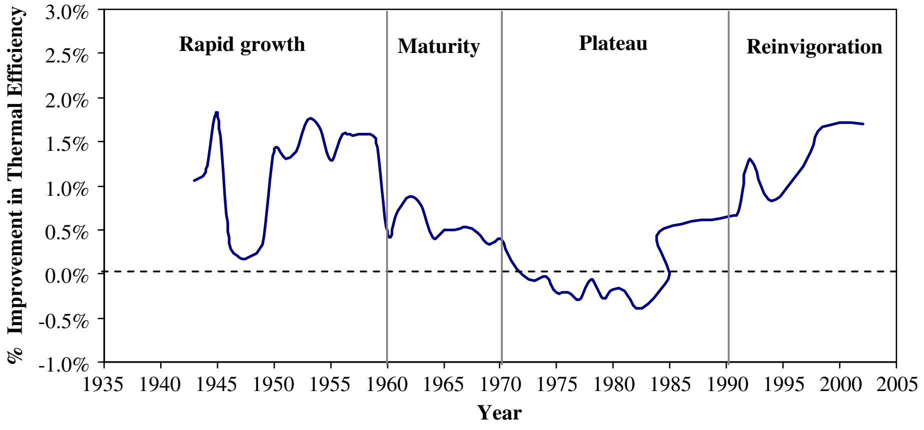

Fig. 6. Improvement (percent change from the previous year, 10-year moving average) in thermal efficiency of coal-fired utility plants over 1935–2002 and corresponding market structural changes.

that became possible with the development of stronger metals (such as "superalloy" steels) and other technology improvements [24]. The resulting increase in boiler efficiency allowed utilities to produce more electricity with less fuel, thereby reducing the capital and O&M costs per unit of product. The following sections elaborate on the technology advancements in PC boiler size, steam temperature, steam pressure, and materials.

3.1. Advances in boiler size

The rapid unit cost reduction of new generating plants prior to the 1970s has been mainly attributed to economies of scale in all power plant components [24,26,28,45], including the generator, turbine, and boiler. In the early 1900s, a 50 MW plant (considered large at that time) housed five 10,000 kW steam turbines and typically required 50–60 boilers to power the turbines [24]. By the 1920s, the introduction of PC, together with improvements in boiler design that raised steam temperatures and boiler output, reduced significantly the number of boilers per plant. The subsequent development of single-boiler, single-turbine systems contributed to more rapid improvements in thermal efficiency and unit cost reductions. Fig. 7 shows how the maximum steam flow of boilers increased 25-fold in 32 years, from 400,000 pounds per hour in 1940 to 10 million pounds per hour in 1972.

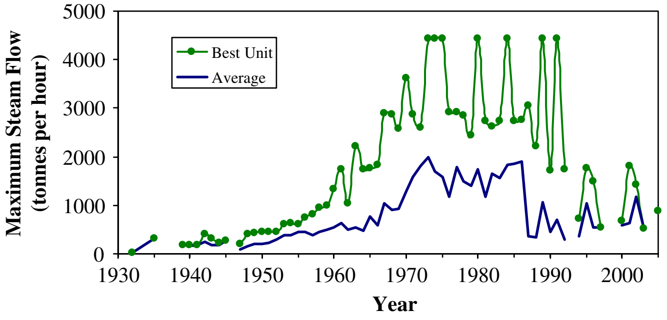

Fig. 7. Maximum continuous steam flow at 100% load (in thousands of pounds per hour) for coal-fired utility boilers. Source: [46].

3.2. Advances in steam temperature and pressure

Advancements in steam temperature and steam pressure have contributed greatly to PC plant efficiency improvements. The maximum steam temperature and pressure increased from about 500 °F (260 °C) and 100 psi (6.9 bar) in 1900 to about 1100 °F (593 °C) and over 4000 psi (276 bar) in the 1950s [24] (Fig. 8). In the early 1960s, the utility industry's move toward larger units was accompanied by widespread adoption of supercritical boilers operating at 1150 °F (621 °C) and 4500 psi (310 bar). Of the nearly 11,000 MW in large units committed by U.S. utilities in 1962 and 1963, 70% were designed for supercritical steam pressure with either single or double reheat [45] (Fig. 3).

During the late 1960s and early 1970s, boiler tubes on supercritical units started to experience metal fatigue and creep, and scale deposits from boiler walls induced greater corrosion and erosion damage in the boiler, turbine nozzles, and other parts of the plant. As a result, the availability of these plants dropped and they became more costly to operate. The inability at that time to improve the metallurgy of boilers and turbines led the utility industry to retreat from supercritical units to the more reliable subcritical units [28,29,45]. Not until roughly 20 years later did utilities in Europe and Japan begin to adopt improved supercritical units (Figs. 4 and 8).

3.3. Advances in materials

In the mid-1930s, metallurgical progress made available superheater tubing and turbine parts that allowed steam temperatures to be raised to 925 °F, thus increasing plant thermal efficiency to 26% [45]. The subsequent development of superalloys that resisted metal fatigue and cracking allowed engineers to design boilers for still higher temperatures and pressures, culminating in the development of supercritical boilers that began service in 1957 [24]. At that time, most engineers believed that the extra cost of special alloys would be compensated by the fuel savings from more efficient supercritical boilers. However, the sustained material problems noted above led to lower availability and higher maintenance costs, which ended the use of supercritical units in the U.S. by the early 1980s. As of 2005, no new supercritical units have been built in the U.S., although several such units are now being planned as a result of the success of units operating in Europe and Japan since the late 1990s. New materials, such as Ni-based superalloys, are expected to increase steam temperature beyond 1400 °F (760 °C) and pressures up to 5000 psi (345 bar), which is expected to increase plant efficiency beyond 45% within a decade [30].

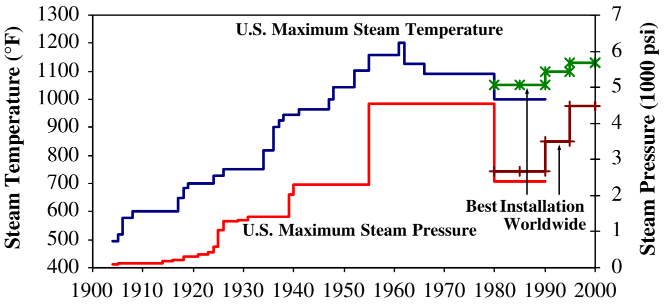

Fig. 8. Best installation PC coal-fired boiler steam temperature and pressure in the U.S. and worldwide (after 1985). Source: modified from Hirsh [24] and McMullan et al. [47].

4. Experience curves for PC boiler capital cost and PC plant non-fuel O&M cost

In this section of the paper, we examine the historical trends in PC boiler capital cost and PC plant non-fuel O&M cost and apply these data to develop experience curves.

4.1. Capital cost trends

To analyze historical trends, cost data are needed with enough detail to quantify PC boiler costs in a systematic manner over a meaningful period of time. While several studies and government agencies (such as the Energy Information Administration of the U.S. Department of Energy) report total power plant costs, very few provide detailed breakdown of costs needed to identify boiler costs. Systematic data for plants constructed prior to about 1980 are even less readily available. We collected data for 12 coal-fired power plants constructed in the U.S. by the Tennessee Valley Authority (TVA) from 1942 to 1973 [48–58], plus one hypothetical plant in a more recent (1999) study by the U.S. Department of Energy [41]. The design characteristics of the TVA coal plants were very similar to those of the best units installed in the U.S. during the same period (Fig. 9). Therefore, we consider the plants used in this analysis to be representative of new U.S. units at each time period. The advantage of the TVA data set is that it provides systematic and detailed plant-by-plant design and cost data over an early 30-year period.

The boiler plant capital cost includes the direct cost of boilers and accessories (which include boiler, draft equipment, boiler plant piping, water feed equipment, coal handling facilities, fuel burning equipment, ash handling equipment, water supply and treating system, raw water system, boiler plant boards, instrumentation, and controls) and indirect costs such as engineering fees, administrative costs, and contingencies. The Handy–Whitman index for steam-generating construction costs [59] was used as the input price deflator to adjust all boiler costs to a common year.[3]

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[3] The Handy–Whitman index is used extensively to adjust for input price changes for electric power plant construction. The index is based upon weighting of different components of a steam-generating plant to reflect changes in input price, design characteristics, labor, materials, and equipment.

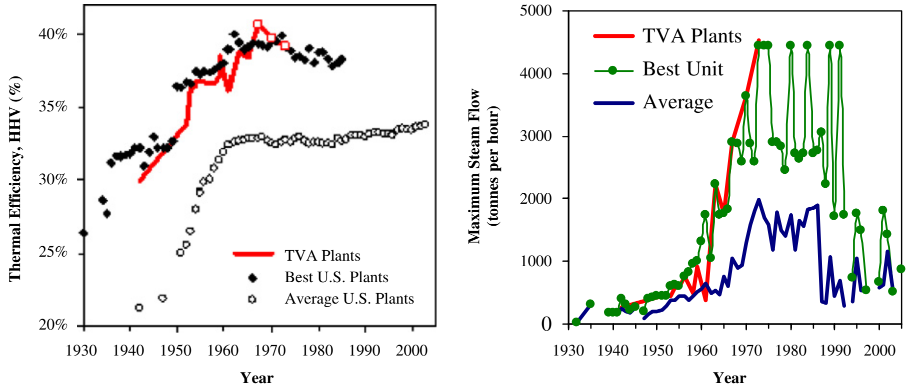

Fig. 9. Thermal efficiency (left) and boiler capacity (right) of 12 TVA plants compared with overall trends in the U.S. The last three data points (square dots) are supercritical units.

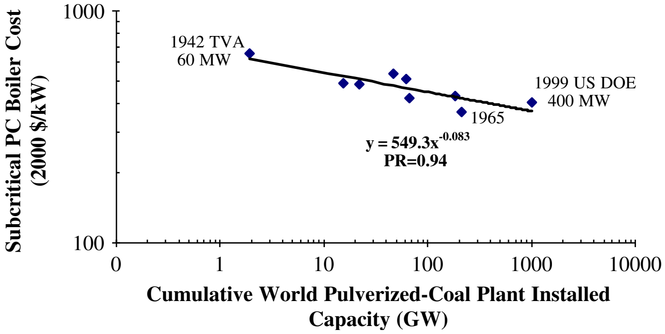

Fig. 10. Historical construction cost of PC boilers (in $/kW) and the learning curve, subcritical boilers.

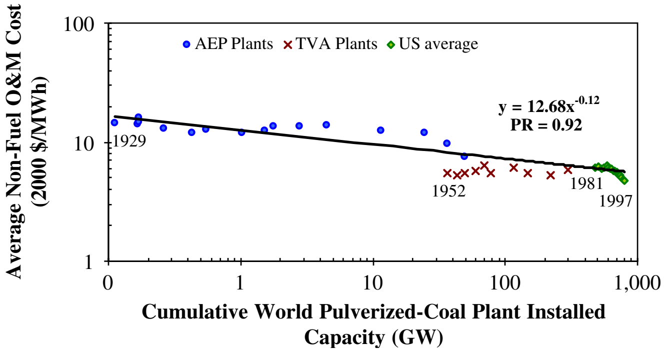

Fig. 11. Average coal steam plant non-fuel O&M cost (adjusted for capacity factor, GDP, and labor cost) for average AEP systems (1929–1958), average TVA plants (1952–1973), and average PC plants in the U.S. (1981–1997). Source: modified from Sporn [45,60] and Beamon and Leckey [44].

To develop an experience curve, the capital cost trends were plotted against the estimated cumulative installed capacity of PC plants worldwide. World capacity was judged to be a better measure of cumulative experience than U.S. capacity alone, in light of the global markets served by major boiler manufacturers. Cumulative world capacity was obtained from the International Energy Agency's Clean Coal Centre CoalPower5 database [25], combined with more extensive data on U.S. capacity from the U.S. Energy Information Administration (EIA) [26] (Fig. 1).

The resulting experience curve is shown in Fig. 10. The overall progress ratio for boiler construction cost during the 60-year period is 94.4%, i.e., an average cost decrease (learning rate) of 5.6% for each doubling of installed capacity. During this period, the size of PC plant boilers increased by nearly 70% while the average efficiency of the overall PC power plant increased from 29.9% to 37.6%. These improvements in economy of scale and overall plant efficiency (attributed in part to improvements in other plant areas) are reflected in the boiler capital cost per unit of net capacity (in $/kW).

4.2. O&M cost trends

Historical declines in the total O&M cost of PC plants prior to 1960 are attributed mainly to the introduction of single-boiler plant designs, automatic controls, and improved instrumentation [45]. Prior to the development of single-boiler, single-turbine plants, stations and workers were required at each pair of boilers, the turbines, the condenser pit, and the electrical switching board. Single-boiler, single-turbine plants made centralized automatic control possible and reduced the number of operators needed at a central control room that controlled all functions from feed of coal to the boiler, to switching of high-voltage output [24,45]. In addition, extensive use of instrumentation and automatic controls allowed better monitoring and recording of actual operating conditions, which reduced operating uncertainties and increased system reliability. Thus, despite increases in wages and the cost of materials and fuel, the average system production costs per kW h at the American Electric Power (AEP) system (one of the largest coal-burning U.S. utility companies) decreased by 9% from 1929 to 1963 in nominal dollars [45]. After adjusting for inflation and labor wage increases, average non-fuel O&M cost decreased by 48% in real terms from 1929 to 1963.

Detailed annual reports on TVA plants' power expenses (Schedules C and H) [60] showed that the reported annual non-fuel O&M cost remained relatively flat between 1942 and 1973, the period of technology stasis (Fig. 11). Average boiler labor cost was more than 10% of the non-fuel O&M in the early 1950s and slightly decreased to around 7–8% in the late 1950s. Fuel expense was around 60–65% of the total O&M cost and the coal price remained relatively constant during this period.

More recently, a study by the EIA confirms the previous observation [45] that the total number of O&M employees for the average large plant in the U.S. has decreased significantly over 1920–1970. It was found that a new, large coal-burning plant in late 1970 required only one-fifth as many employees per megawatt of capacity as did the large plants built from 1920 to about 1950 [61]. Between 1980 and 2000, costs again decreased as U.S. electricity markets underwent significant transformation from integrated power companies (controlling generation, transmission, and distribution) to a more competitive and disaggregated market. An EIA report that examined changes in the operating cost of U.S. fossil–steam power plants from 1981 to 1997 found that the non-fuel O&M cost[4] per kW h for coal plants fell by 32% at existing plants [44]. In 1981, an average 300-MW coal plant had 75 employees. By 1997, the average had fallen to 53 employees, a decline of 32% [44]. Increased plant utilization (a 20% increase from 51% to 61% over the period 1981–1997) also contributed to non-fuel O&M cost reductions between 1981 and 1997. The cost reductions seen in this period are attributed largely to increased competition after deregulation of the utility market.[5] Savings in boiler operation and maintenance contributed most of the reduction in non-fuel O&M cost over 1981–1997 [44], from 43% of the total non-fuel O&M cost in 1981 to less than 34% of the total non-fuel O&M cost in 1997.

Fig. 11 shows experience curves fitted to the total plant non-fuel O&M cost over 1929–1997, adjusted for changes in GDP (using the GDP price deflator), real wages (wage and salary for electric and gas employees [62]), and plant utilization (assuming a constant capacity factor of 50.5%, since cost reductions per kWh due simply to increased utilization are not usually related to technological change). An experience curve fitted to the whole period indicates a progress ratio for overall PC system non-fuel O&M cost to be 92% between 1929 and 1997.

5. Conclusions

Pulverized coal-fired power plants-fired power plants have undergone significant technological change over the past century, and are expected to be an important part of future power generation portfolios [32,63]. Advances in boiler and steam turbine technology, materials of construction, measuring methods, plant design, and system integration all have contributed to sustained improvements in PC plant technology. When only the best commercially viable plants were considered, this study found sustained improvements in the overall thermal efficiency of PC plants over 1940–2005, with an average rate of improvement of 3.8% for every doubling of cumulative worldwide capacity over that period. If this trend continues, the projected thermal efficiency of commercially viable PC coal-fired power plants may reach 46.4% (HHV) when the estimated worldwide installed coal-fired generating capacity is close to 2000 GW, which is estimated to occur by about 2030 [22]. Climate policies and other regulatory actions that encourage efficiency improvements could accelerate this trend [33,63].

For new PC subcritical boilers, the corresponding LR for capital cost reductions (in $/kW) averaged 5.6% over approximately the same period (1942–1999). An experience curve for boiler O&M cost was more difficult to construct, as systematic data are sparse and often ill defined in how they were reported and categorized. Thus, we estimated LRs for non-fuel O&M cost of PC plant to be approximately 8% over 1929–1997, with higher cost reductions during the period of rapid growth over 1929–1963 and the more recent period of utility restructuring over 1981–1997. Besides purely technological developments, myriad factors such as market competition; changes in industry structure [24,44]; and regulations related to health, safety, and the environment also affected rates of technological progress over the past century.

The experience curves presented in this paper thus provide evidence of nearly century-long technological progress and suggest the following sequence of development: rapid growth, maturity, plateau (stasis), and reinvigoration. The resulting experience curves for PC plant thermal efficiency, boiler capital cost, and non-fuel O&M cost offer a quantitative basis for estimating rates of technological change over a long period of time. While not a “guarantee” of future performance, such estimates may be useful for projecting or bounding the potential costs of new or developing technologies similar to those studied here [64]. In particular, the availability of empirically based long-term LRs for major energy technologies provides a useful complement to studies based on shorter periods of time. In this context, the experience curve for thermal efficiency developed in this paper offers an alternative to projections based purely on technological feasibility, and provide an estimate that is bounded in historical reality. The experience curves developed here for capital and O&M costs do not include supercritical or ultra-supercritical boilers, as there are too few in the U.S. for meaningful statistical analysis. Pending the accumulation of additional experience and systematic cost data, future improvements to the experience curve analysis could utilize dummy variables to take into account technology structural

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[4] This includes costs of labor, plant operating supplies (including lubricants, chemicals, other miscellaneous materials, office and other incidental expenses), and maintenance renewal parts and materials [61].

[5] A series of laws, including the Public Utility Regulatory Policies Act of 1978 (PURPA), the Energy Policy Act of 1992 (EPACT), and the Federal Energy Regulatory Commission (FERC) Orders 888 and 889 in 1996, reduced the monopoly power of conventional integrated power companies, increased the number of players, and increased pressure for competition in the electric utility industry. For more information, see [44].

changes reflecting the transition from one technology variant to another. Such methods can be utilized to account for technology structural changes while preserving the accumulated experience and learning from deploying similar technology variants [14]. Future analyses to decompose the driving forces of learning, technological change, and factors influencing the cost reductions of PC boilers also can provide valuable insights for projecting future technology costs.

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