Summary Report on Coal Plant Dynamic Performance Capability

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Introduction:

Interest in the ability of coal plants to move from baseload operation to a more dynamic dispatch is increasing as competitive markets and the introduction of variable renewable resources provide opportunities to obtain greater economic efficiencies from such operations. This paper was commissioned by the Renewable Northwest Project in an effort to summarize the available public information on flexible coal plant operations. It is our hope that bringing the available information together in an accessible paper will further efforts to accurately assess the effects of a growing dependence on renewable resources on the existing power system.

Overview:

Coal powered electric generation can fluctuate dynamically and increasingly does so in competitive wholesale electric power markets. In such markets, coal units ramp generation levels up or down, operate at low load levels, and experience more frequent shutdown and startup events. For several decades, many coal units have cycled to follow load, and their cyclic performance has challenged some analysts' assumptions based on historical observations of base-loaded coal power plants. Coal power dynamic performance is crucial to model the economic dispatch of generator fleets, especially in markets where variable generation sources such as wind and solar resources serve significant fractions of power system demand. This paper reviews published information on the dynamic performance of coal generation, recognizing the physical and economic consequences accompanying such operation.

The minimum generation level, ramping rates, minimum run time, and minimum down time collectively characterize dynamic performance and varies widely according to plant design.[1] Statistical research examining thousands of coal plants has been undertaken to generalize the limits and costs of dynamic operation. These statistical results are presented with a review of coal engineering design in an effort to contextualize the statistical results and allow for discussion of modifications and costs.

Coal Plant Design:

Coal is burned to heat boilers covering a range of technologies. Beyond the specific boiler technology coal plants share a relatively similar general design diagramed in figure 1. Water is passed through a series of heat exchangers that draw heat from the boiler, producing steam, which later is super-heated to high temperatures and pressures. The steam is released through a throttling valve into staged turbines that convert the steam's heat and pressure into rotational energy to power the electrical generator. After exiting the turbine, the steam is cooled in a condenser and returns to its liquid phase. Before the water is passed back into the boiler, it is pre-heated by steam extracted from the turbines to improve efficiency.

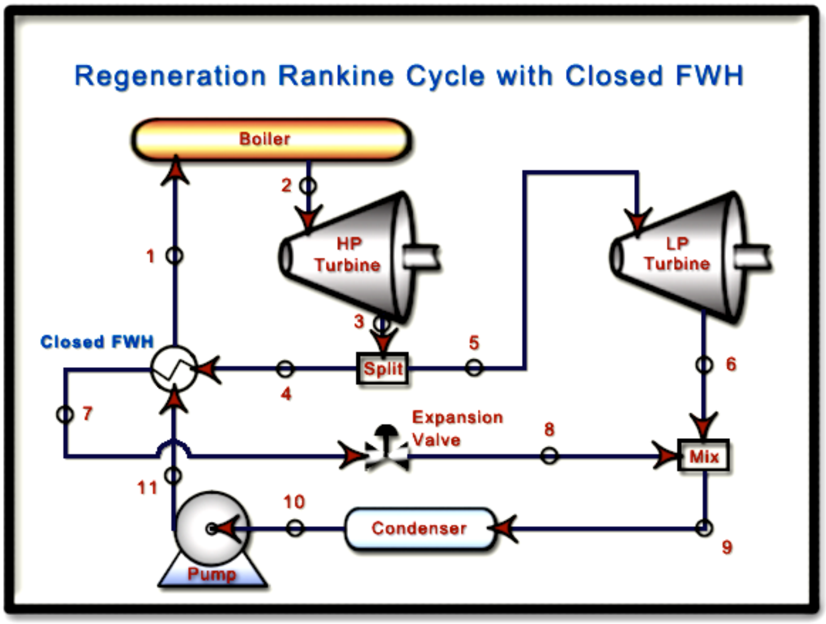

Figure 1: Steam Cycle Diagram. Sourced from LearnThermo Educational Blog.[2]

The thermal energy of coal can be released through direct combustion of pulverized coal, or by burning the products of a gasification process. The overwhelming majority of coal plants use pulverized coal burning boilers, and these plants are further divided into sub-critical, super-critical, ultra super critical, and circulating fluidized bed (CFB) boiler designs.[3] This report will not evaluate the load following performance of gasified coal plants because such few examples exist.

The four pulverized coal-burning boiler technologies are principally distinguished by the pressure and temperature of the steam cycle. Higher temperatures and pressures allow for greater energy extraction and increased plant efficiencies. In the most efficient designs, the working fluid is pumped into the boiler at pressures above water's critical point[*]. Super-critical and ultra super-critical technologies are distinguished from subcritical boiler designs by high boiler fluid pressure. This pressure prevents boiling, but the fluid is heated and passes through the boiler as a mixed phase super-critical fluid. However, metal alloys with the material strength needed to operate at the high pressures and temperatures far beyond water's critical point only became available in the late 1960s. Plant designs that can accommodate the challenges of mixed phase super-critical steam have only proven reliable in the last few decades.[4] For this reason

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[*] Water reaches the critical point when the temperature exceeds 374.15C, and the pressure exceeds 22.12 MPa. At pressures and temperatures above this level, there is no physical distinction between liquid and gaseous water—i.e., the fluid is in a state that is neither distinctly liquid water nor steam.

most coal plants are of the sub-critical design, with the majority of super-critical projects in Europe.[5] Ultra super critical designs represent the most recent generation of advanced materials, and operate at temperatures above 1050°F and pressures above 32 MPa. The handful of existing plants were built in the late 1990s in Europe and Japan. This report expects that ultra super-critical plants will share load following performance with the similar super-critical design. Yet, due to the few plant examples, the report will not attempt to specifically quantify ultra super-critical load following performance.

Boilers are further distinguished by water circulation design, which impacts load following performance. Generally, there are two main types of boilers, drum and once-through. Drum boilers, typical in sub-critical units, introduce water into the boiler's evaporator, pass steam onto the super heater, and re-circulate remaining water back into the evaporator. Drum boilers require thick walled steam drums, with a large thermal mass, to hold the cycle's steam. Super-critical plants are based on a once-through design that does not re-circulate fluid. Without a heavy steam drum, the once-through design has less thermal mass, allowing faster load response and shorter starting times. However, once-trough load response adjusts both fuel firing and steam flow rates introducing stresses not present in drum boilers. Despite the more responsive dynamic performance of a once-through boiler, the durable drum boiler is more suitable for dynamic and two-shift operation.[6] Extensive boiler modification is an impractical retrofit option, and the fundamental design is chosen to be commensurate with operator needs.

Boiler pressure control design strongly affects dynamic operation. Sub-critical boilers are generally kept under constant pressure operation (CPO) maintained by the throttling valve. There is a large temperature and pressure drop across the throttling valve and during steady operation the boiler steam is hotter than the high-pressure (HP) turbine. The throttling valve adjusts under dynamic operation, releasing hotter steam into the relatively cooler HP turbine which induces thermal stress. CPO ramping rates are limited by the temperature gradients acceptable in the HP turbine stage.[7] Variable pressure operation (VPO) overcomes this limit by leaving the throttling valves open and minimizing temperature and pressure drops across the throttling valve. Consequently there are rarely temperature mismatches between boiler steam and the HP turbine under VPO. With an open throttle, boiler pressure and temperature is variable and controlled by the firing rate that subsequently affects turbine power extraction. Variable pressure operation introduces control complexity but increases load following performance and minimizes wear on steam side equipment. Lastly, under hybrid VPO the valves are left almost open but can adjust over a narrow range. Hybrid VPO is a popular performance compromise in plant design offering some pressure control and minimized wear.[8]

Circulating fluidized bed units use entirely different boiler technology. Processed coal is suspended in a particle bed that is fluidized by an oxidant. The circulating bed material creates a uniform heat distribution important for combusting high-ash, low volatile fuels.[9]

The steam cycle of a CFB is nearly identical to that of a pulverized coal plant, with temperatures and pressures close to super-critical designs. There exists little published data of CFB cyclic performance, therefore it is assumed roughly equal to super-critical plants. However this assumption is limited, as CFB cyclic operation will likely incur different costs and stresses than super-critical plants.

Dynamic Operation:

Some electricity markets became much more open and competitive under deregulation. Market economies motivate coal plants to operate flexibly, and some coal plants generate power over dynamic and fluid ranges. Modern coal plants are designed for dynamic response and even some older sub-critical plants, originally designed and built to satisfy base loads, are now operating variably.[10] This operational evolution has been an international phenomenon and coal units throughout both the United States and the world have adjusted their generation as the market has demanded. Additionally, the growing presence of variable wind generation in power systems further motivates dynamic coal plant operation.

Ramping Rates:

Ramping Rate Performance Data:

Coal plants may contribute to meeting a changing net demand by increasing or decreasing generation, but the rate of that change is limited by a set of physical and economic factors. Physically, the enormous thermal mass of the boiler and steam generator attenuate the response to changes in fuel feed rates. Minutes pass before fuel adjustments affect steam mass flows, and hence turbine and generator output. Engineers use an array of alternative techniques allowing coal-units to respond faster. The maximum ramping rate is specific to plant design and is also a function of plant capacity. Generally, coal-fired units become less responsive as they approach minimum generation levels.

This report aggregates publications and specific plant examples to demonstrate feasible ramping rates for sub- and super-critical coal plant capabilities. Table 1 includes published generalized ramping rates according to plant design, Table 2 reviews a 1982 EPRI survey of coal fired dynamic performance[11], and Table 3 includes examples of working coal plants. In general, the ramping limit for super-critical plants is 7% per minute allowing for greater load following performance than sub-critical plants that may increase generation 3% per minute.

Table 1
Design Ramp Rates

Plant Design	Publication	Ramping Rate	Comments
Sub-Critical	Power-Gen World Wide[12]	5% per minute	From 50% to 100% Capacity
Sub-Critical	IMTE AG Power Consulting[13]	3-5%	
Super-Critical	Babcock Power[14]	7% per minute	Typical from 50-90% Capacity
Super-Critical	Power-Gen World Wide[9]	7-8% per minute	From 50% to 100% Capacity
Super-Critical	IMTE AG Power Consulting[10]	7-8% per minute	

Table 2
1982 EPRI Survey Results

Capacity (MW)	Design	Avg. Ramp Rate (% / min)	Max Ramp Rate (% / min)
180	Sub-Critical	1.8	3.6
300	Sub-Critical	2.0	3.1
420	Sub-Critical	1.1	2.9
540	Sub-Critical	1.7	2.8
660	Sub-Critical	1.3	3.7
420	Super-Critical	1.3	4.3
540	Super-Critical	1.1	3.6
660	Super-Critical	1.2	2.0
780	Super-Critical	0.9	3.5
900	Super-Critical	1.0	2.0

Table 3
Selected Individual Plant Ramp Rates

Plant Design	Location	Ramping Rate	Comments
Sub-Critical	Central City, Kentucky, USA[15]	3% per minute	Unit ramp rate improved 300% after simple sensor and control retrofits.
Super-Critical	Yonghung, South Korea[16]	3% per minute 5% per minute	-from 30-50% capacity -Above 50% capacity
Super-Critical	Rostock, Germany[10]	7% per minute	Startup 1994. Two-shifting daily.

The EPRI study, reflected in table 2, is an important resource to quantify dynamic performance limits. In 1982, the EPRI survey thousands of coal plants around the United States and aggregated their findings. Their results represent the average coal plant performance in 1982. Many of those coal plant still operate, and the findings are likely reflective of a dynamic performance floor today. The data also acknowledges the important difference between maximum and average plant ramping rates. Despite plant advertised ramping capabilities, operators often limit performance to lower rates to minimize plant wear.

Ramping Control Schemes:

As the sub-critical plant in Central City, Kentucky demonstrates (Table 3), there is great potential to improve ramping rates in older coal-fired units. Some modifications are more substantial than others, but all implement retrofit technology commonly used to allow coal plants operate more dynamically. Those operations and technologies allowing load following behavior are varied are summarized below.

Steam throttling is the most common method of changing turbine speed. When ramping up, stored energy in the boiler is released to briefly provide a surge of power. During constant pressure operation or hybrid VPO the throttling valve between the boiler and the turbine is partially closed and pressure is highest in the boiler. The throttling valve can open to increase the steam mass flow that passes through the turbine and increasing power output. While this technique is the most traditional form of power control, it results in a continuous loss of plant efficiency.[17] After the throttle is opened steam pressure quickly decreases and fuel must be increased disproportionably to regain the system's original steam pressure. The control scheme adjusts power in seconds. VPO boilers cannot ramp up production with steam throttling as the throttling valve is already open and instead must use other control schemes.

Another common control scheme adjusts the feed water extraction from both the high and low pressure (LP) turbine stages. Most plant designs draw steam from both turbines into the feed-water tanks to pre-heat feed-water before it returns to the boiler. Pre-heating increases plant efficiency by requiring less fuel to achieve the operating boiler pressure and temperature. Power output can be increased by closing extraction valves on both the HP and LP turbines, but this power boost comes at a loss in efficiency. The control schemes are called HP pre-heater bypass and condensate throttling with respect to HP turbine and LP turbine steam valve closure.[18] Both control schemes create a greater mass flow across the turbines, increasing power. While turbine throttling increases power in seconds, extraction control schemes act over minutes.[19]

Throttling, extraction, and firing adjustments can be optimized by automated control. Many steam plants, especially older systems designed for base loads, are not equipped to manage control schemes in concert. One of the most cost effective retrofits for increasing a steam plant's load following performance is to install the monitoring equipment and computer control allowing for automated dynamic control of the traditional control schemes. The Kentucky sub-critical plant listed in Table 3 was retrofitted with simple sensors and automated responses that improved plant ramp rates by 300%. Automated optimization processes achieve load following performance standards previously considered impossible.[20]

Innovative dynamic control schemes have been developed further in the last decade. For example, it is possible to dynamically control steam generation by adjusting the position of the fireball within the boiler. For both once-through and drum boilers, drawing the fireball lower over the evaporator increases steam production and increases plant power. However, because the fireball typically targets the boiler re-heater to increase plant efficiency, lowering the fireball position will decrease plant efficiency.[21] Not all plants are equipped with tilting burners. This is a modest modification that allows for increased load following performance without changing firing rates.

Another innovative control scheme to improve dynamic performance is to adjust the grinding pressure of the coal mill. The coal mill holds a certain volume of coal and power output can be increased by raising the hydraulic pressure of the mill to deliver coal faster to the boiler, increasing generation over several minutes.[22] Because the coal feed to the mill cannot be accelerated as quickly, the mill acts as an energy storage device whose coal volume initially decreases with increased hydraulic pressure, then stabilizes once the coal feeder accelerates, then refills once the load ramp ends.

Minimum Generation

A plant's minimum generation is one of the most significant parameters for dynamic performance.[23] Low minimum generation allows a dispatcher to satisfy an attenuated load without disrupting more profitable units or forcing a coal plant into a damaging shut down and starting expensive peaking units. Operating at low generation is associated with several negative impacts including poor power control, poor environmental control performance, problematic air-flow limitations, and increased heat rates (lower efficiency.)[24] Furthermore, at low load boiler burners lose flame stability and costly supplementary firing may be required. Minimum generation is defined as the lowest safe and reliable plant operation without use of supplementary firing units, and for coal units is typically 35-40% of full load capacity. [25]

Many coal plants now routinely operated near minimum generation were originally designed for high efficiencies at full load. Those design priorities resulted in poor low generation performance and minimum operating levels which, in many cases, were unknown.[26] Minimum generation level and performance can be dramatically improved with relatively simple modifications. Plant operators around the USA have investigated this potential and a survey conducted by The Electric Power Research Institute in 1998 demonstrated that while minimum load potential is unique to each plant it can be significantly decreased for all older sub-critical steam plants. A portion of the survey is listed in Table 4.[27] For every plant listed some cost effective combination of unit master control, feed-water and boiler control, and/or turbine enhancement retrofits enabled significant reduction in plant minimum load.

Table 4
Example Improvements in Minimum Load Retrofits

Size (MW)	Current Minimum Load	Potential Minimum Load
254	35%	24%
267	34%	22%
65	23%	8%
446	28%	22%
258	52%	35%
880	40%	28%
524	46%	38%
70	43%	21%

Minimum generation levels on coal units can also be economically implemented by reprogramming the automated master control. Conventional automated control schemes are designed to provide responsive control within the unit's normal operating capacities. However, the boiler and steam-side response profiles are significantly disturbed at low operation. At low operation the automated master control scheme can be adapted by upgrading measurement instruments, especially flame detection equipment, and performing plant specific modeling.[28] By sliding into tailored control algorithms, coal units can operate at far lower capacities without jeopardizing reliability.

Minimum Run and Down Time

Generally, coal plants are shut down infrequently and operated for relatively long periods of time. Long duration operational windows avoid the damaging thermal and pressure stresses that develop during startup and shutdown. It takes a long time for a plant to heat up or cool down, and the accompanying transitional thermal gradients cause uneven thermal expansion in equipment, inducing stress. To avoid potentially catastrophic damage, plant designers impose minimum run times and minimum down times for plant operation to allow sufficient time for the plant to reach thermal equilibrium.

Equipment manufacturers provide additional operational guidance by recommending minimum startup times. Plants that go offline are only allowed to be restarted after passing its established minimum down-time. Minimum down times may be adjusted depending on the amount of time that the plant had been offline. The longer the plant has been offline, the cooler the equipment has grown, the longer it takes to reheat without incurring more damage. Generally minimum down times are divided into hot, warm and cold starts as defined in the following Table 5.[29]

Table 5

Hot, Warm, and Cold Start Definitions

	Time Since Shutdown	Metal Temperature
Hot Start	< 8 hours	> 400 °C
Warm Start	< 48 hours	> 200 °C
Cold Start	> 48 hours	< 200 °C

Available data describing coal unit minimum down times vary widely. Much of the variation stems from different operational definitions of hot, warm, and cold starts and whether those times reflect equipment limitations or average operating procedures. This study was unable to parse the conflicting definitions from publicly available data. The data reprinted in Table 6, supports the generalization that coal plants require approximately 12 hours to cold start, 4 hours to warm start, and 1 hour to hot start.

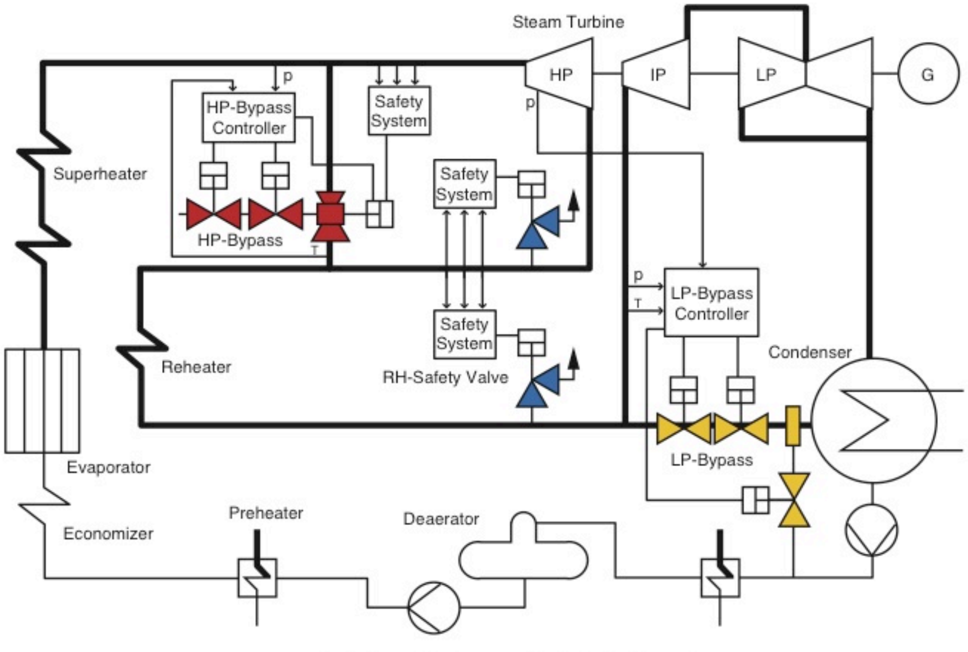
Table 6

Available Data on Minimum Down and Run Times

Publication	Unit Size & Type	Minimum Down Time	Minimum Run Time	Synchronization Start Time	Full Load Start Time	Start Class
IEEE Transactions on Power Apparatus and Systems[30]	180 MW Drum	-	-	3.7 hrs	8.0 hrs	Warm Start
“	300 MW Drum	-	-	6.2 hrs	10.0 hrs	Warm Start
“	420 MW Drum	-	-	2.4 hrs	4.7 hrs	Warm Start
“	660 MW Drum	-	-	2.4 hrs	4.9 hrs	Warm Start
“	660 MW Once- Thr	-	-	11.0 hrs	15.0 hrs	Warm Start
“	780 MW Once-Thr	-	-	2.5 hrs	5.0 hrs	Warm Start
OMMI[31]	500 MW, Unspec	-	-	0.6 hr	1hr	Hot Start
NWPP[32]	Generalized	12 hrs	24 hrs	-	-	-
University of Singapore[33]	250 MW, Unspec	6 hrs	3 hrs	-	-	-
KTH[34]	123.5MW, Unspec	24 hrs	24 hrs	-	-	-
“	284 MW, Unspec	12 hrs	12 hrs	-	-	-
IEEE Transactions on Power Systems[35]	Generalized	5 hrs	-	5 hrs	-	-
APPRO[36]	500 MW, Unspec	-	4 hrs	-	-	-

The limits of minimum run time, minimum down time, and synchronization time have been pushed by two-shift operation. Two-shifting units operate from 10 to 15 hours during predicted times of high load and are shut down overnight.[37] Many plants, regardless of their original design, have adopted two-shift operation to meet the demands of competitive markets. Studies of two-shifting operation have suggested that the original equipment manufacturer guidelines are very conservative and their suggested minimum down times can generally be halved allowing for two-shift schedules.[38] Experience developed over the last few decades has produced plant designs and startup and shutdown procedures which minimize the thermal stresses of two-shifting allowing heavy cycling while mitigating and controlling plant damage.[39,40]

A turbine bypass valve system is the most crucial technology allowing for quicker run, down, and synchronization times. Modern plants regularly implement turbine bypass in plant design and other plants retrofits have included turbine bypass installation. As diagramed in Figure 2, a turbine bypass provides controllable conduits for steam to pass through the steam cycle without passing through the HP and/or LP turbines. Bypass valves effectively remove the thermal dependence of the boiler on the turbine. They allow steam to pass around the HP turbine or LP turbine and proceed directly to the condenser. The boiler may then change temperatures freely and bypass valves control the rate of steam temperature change in the turbine. Turbines are very sensitive to thermal stresses and bypass valves allow these stresses to be mitigated during start up and shutdown. Turbine bypass valves are especially important for two-shift operation, but all modern coal plants designed for dynamic operation rely on bypass valves to start quickly.



Typical coal fired supercritical plant schematic

Figure 2: Sourced From CCI/Sulzer Valves[41]

Damage Due to Dynamic Operation:

Start Up Costs

The paper has, so far, reviewed the dynamic capabilities of coal power plants. Despite these capabilities, most plants typically operate well below performance limits. Dynamic operation can be very damaging to plant equipment, and plant operators act conservatively to limit these costs. Whenever generating units are turned on, off or ramped down to low load operation, the boiler, steam lines, and turbine undergo major stress associated with changing temperatures and pressures. However the resulting wear and tear is difficult to measure as it only becomes evident during maintenance and equipment replacement. Many utilities and operators do not know the costs imposed by dynamic operation.[42,43] To effectively measure plant costs, analysis can produce specific signature plant data that estimates the resulting strain on power plant components. This information is crucial in order to dispatch fossil fleets economically.

Creep-fatigue interaction contributes to component failures. Creep and fatigue are material processes describing material deformation. Creep is the gradual deformation resulting from constant stresses and forces. Fatigue is structural damage resulting from repeating periodic stress.[44] Both material failure modes have unique deformation profiles, but when acting in unison can produce synergistic effects leading to premature failure. The ferritic steel used in power plants has a high tolerance for creep and fatigue stresses independently, but after reaching 50% of its life creep damage, the metal can only withstand 10% of its fatigue stress tolerance.[45] Normal power plant operation constantly exposes equipment to creep damage but dynamic operation introduces fatigue stress resulting in creep-fatigue interaction can heavily damage equipment, decrease lifetimes of critical components, and increase forced outage rates. The nature of creep-fatigue interaction makes cycling particularly damaging for older plants that have already reached the last half of their material creep lifetime and are thus especially sensitive to fatigue loads.[46]

Plant efficiency is also impinged by dynamic operation. The same damage introduced by thermal gradients also fouls heat exchangers making, them less effective at passing heat from the boiler to steam tubes.[47] More fuel is then required to create the same amount of power. The gradual reduction in plant efficiency accompanying dynamic operation incurs significant costs over the course of the plant lifetime.

The operation and maintenance costs of dynamic operation are distributed disproportionately throughout the lifetime of the plant. However, O&M costs have been found to be heavily correlated with the number of plant starts.[48] Justified by the correlation, cycling lifetime O&M costs are folded into start up costs of each coal unit and can be integrated into economic dispatch scheduling.[49] The estimated start up costs vary widely and are influenced strongly by plant design and capacity.

APTEC and several other engineering consulting firms suggest that start up costs have been dramatically underestimated by utilities that have put themselves at financial risk as a result.[50] In response, agencies such as the EPRI and OMMI performed statistical analyses of thousands of coal plant O&M expenditures and correlated those costs to many variables including start ups. These statistical analyses use multiple regressions whose resulting function estimates start-up costs based on a range of variables including, capacity, boiler design, capacity factor, and the previous year's O&M costs.[51] More generalized figures were also published, with the caveat of diminished accuracy. This data and EPRI regression estimating costs as a function of plant capacity are reprinted in Table 7 and Figure 3 respectively. The statistical generalizations roughly agreed with APTEC's estimates.

Table 7
Results of Statistical Analsyis of O&M Costs

Publication	Event	Cost per Event ($2009)
EPRI[52]	Cold Start	$90,000
	Warm Start	$5400
	Hot Start	$4600
	Cycle > 60%	$1800
OMMI[53]	Cold Start	$80,000
	Warm Start	$5000
	Hot Start	$4200
IEEE Power Systems[54]	Hot Start	$7500
APTEC[55]	"Cycle"	$15000 - $100,000

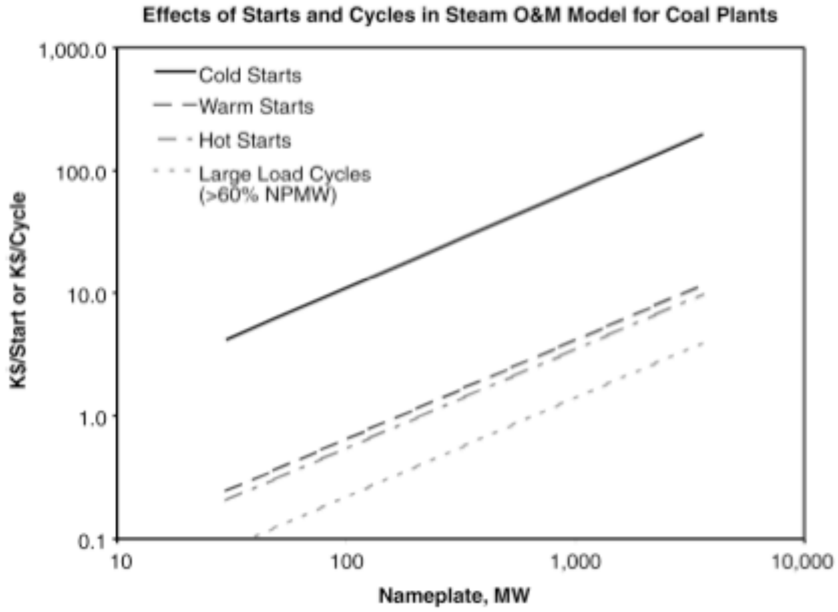


Figure 3: Steam O&M Costs per Start/Cycle. Sourced from EPRI.[56]

As the APTEC data indicates, cycling cost estimations vary widely and are dependent on many elements which require plant specific analysis to be more precise. Within the same publication APTEC authors suggest that 50% errors in the estimation can be tolerated. However, the authors stress that start up cost estimations that are much too low can be very economically damaging, while estimations that run much too high are relatively less so.[57]

Damage Mitigation

Any coal unit can be operated dynamically, yet modulating steam plants introduces stress to the plant that in many cases the unit is not designed for. However, a growing body of international evidence has shown that coal-fired units may be operated dynamically without dramatically lessening the plant's operational lifetime.

Two 680 MW coal fired units in China have been cycling heavily for over fifteen years, with daily two-shift operation. The plant was designed for cyclic capabilities and is equipped with a turbine bypass system that the plant operators cite as providing the plant's cyclic durability. Over the plant's lifetime, significant operational experience has been gained and the engineers have concluded that the plant "convincingly affirmed that large coal-fired generating units can perform extensive two-shift operation without requiring replacement of major components of boilers or turbines."[58]

Other studies find higher costs attributable to dynamic operation, but also acknowledge the potential to mitigate them. Along with the report from China, two EPRI studies lend credence to the idea that costs can be managed. In 2003 the study *Feasibility of Wear* *and Tear Sensors for Flexible Plant Operations* researched how sensor installations could inform control schemes to diminish cyclic damage. The study determined that new sensor technologies and software control applications could, in a cost effective manner, "enable most fossil-fueled plants to make the transition form base-loaded operations to flexible operations without any significant events or significant increases in undesirable effects."[59] An unrelated EPRI study in 2004 studied the potential to reduce boiler damage resulting from cyclic operation. Their conclusions echo the previous research effort and suggest that by conducting specific plant analysis and implementing tailored operational changes or retrofits, "many cycling-induced boiler failure mechanisms… can be eliminated, minimized, or controlled."[60]

Summary

Many coal plant operators are experiencing higher economic efficiencies than are available from operating their units strictly as baseload facilities. Coal power plants covering a range of designs and vintages are operating as more dynamically dispatchable units. Retrofitting existing units can improve the flexibility of existing coal plants and mitigate expected increased O&M costs and unit outages. Flexible dispatch of coal plants allows plant operators to take advantage of greater overall power system optimization as well as lower overall emissions by making more efficient use of available renewable energy.

Unfortunately, there is no one-size-fits-all solution to improving the dynamic operation of coal plants. One experienced European plant operator responded to our inquiries:

> *I think there is only one way to improve the dynamic performance of fossil fired power plants: Hard work carried out by control engineers. These engineers will have to analyse the various control algorithms of the boiler and turbine side to find the "load flexibility bottle necks". Some of these bottle necks can be solved by control optimization, but many of the bottle necks will probably require some new hardware. It is my experience that each power plant is acting different and it is thus not possible a forehand to pinpoint where the bottle necks are. The most crucial problems are normally related to the balance between firing and feed water. But it can still be the coal mill control, the feed pump control, the combustion air flow or temperature control, the furnace pressure control or…*

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