Making Coal Flexible:
Getting From Baseload to Peaking Plant

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Power systems in the 21st century—with higher penetration of low-carbon energy, smart grids, and other emerging technologies—will favor resources that have low marginal costs and provide system flexibility (see Figure 1). Such flexibility includes the ability to cycle on and off as well as run at low minimum loads to complement variations in output from high penetration of renewable energy. With a lack of general experience in the industry, questions remain about both the fate of coal-fired power plants in this scenario and whether they can continue to operate cost-effectively if they cycle routinely.

To demonstrate that coal-fired power plants can become flexible resources, we discuss experiences from an actual multi-unit North American coal generating station (CGS).[A,1] This flexibility—namely, the ability to cycle on and off and run at below 40% of capacity—requires limited modifications to hardware, but extensive modifications to operational practice. Cycling *does* damage the plant and impact its life expectancy compared to baseload operations. However, strategic modifications, proactive inspections and training programs, and various operational changes to accommodate cycling can minimize the extent of damage and minimize cycling-related maintenance costs.

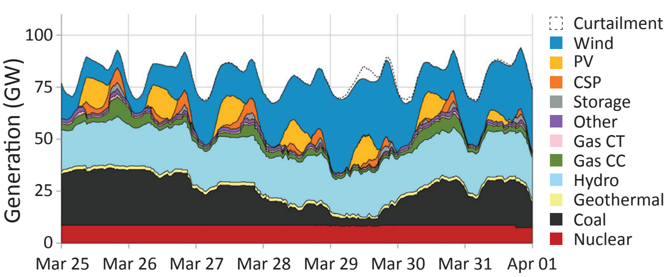

FIGURE 1. Simulated dispatch of generation over one week in a high renewable energy scenario (annual load served by 25% wind, 8% solar photovoltaic).

Notes: PV = solar photovoltaic; CSP = concentrated solar power; CT = combustion turbine; CC = combined cycle

Source: Lew et al., 2013

We have used a case study of this CGS to evaluate how power plants intended to run at baseload can evolve to serve other system needs. The CGS case illustrates the types of changes that may occur in global power systems, especially those with legacy plants. CGS's experiences challenge conventional wisdom about the limitations of coal-fired power plants and help policymakers better understand how to formulate policy and make investment decisions in the transformation toward power systems in a carbon-constrained world.

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A BRIEF HISTORY OF THE CGS PLANT

When it came online in the 1970s, the CGS plant was intended to run at an 80% annual capacity factor. However, the addition of nuclear power soon thereafter displaced coal as the principal source of baseload generation. Consequently, CGS typically ran at 50% annual capacity factor until the early 1990s. To understand the effects of "two-shifting" (i.e., cycling on and off in a day) considerable research was conducted in the 1980s. As a result, plant operations, the steam generator, and supporting equipment were modified.

After a competitive market was introduced in the early 2000s, the CGS plant was operated for longer periods at full plant output—this period was also marked by significant forced outages. For example, in 2004, the equivalent forced outage rate (EFOR)—a measure of a plant's unreliability—was 32%, which represented the accumulated latent damage from the cycling that CGS performed in the 1990s. Typical EFOR for a baseload coal-fired power plant is 6.4%.[2]

The competitive market created the incentive for CGS units to continue to operate flexibly—for example, that they be able to

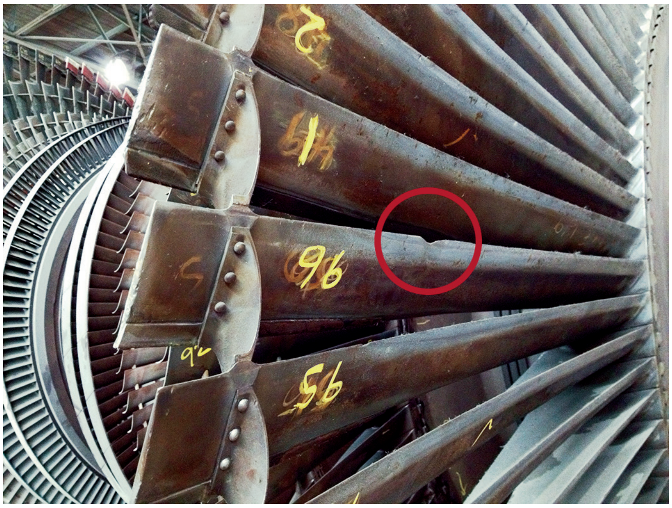

FIGURE 2. Example of large nick in turbine fin (#96) due to impact with dislodged material formed by oxidation (Debra Lew)

two-shift and operate at an output below intended minimum load. Although the two- and sometimes four-shifting created wear and tear and reduced the plant's cost competetiveness, the CGS owners operated the plant in this fashion to compete in the wholesale power market.

EXAMINING THE IMPACT OF CYCLING AT CGS

The CGS coal units were intended to primarily run at full output and start cold only a few times a year. However, each CGS coal-fired unit has experienced an average of 1760 starts, including 523 cold starts throughout its lifetime. The overarching effect of this type of cycling is thermal fatigue. For example, large temperature swings from cold feedwater entering the boiler on start-up and from steam as it is heating create fluctuating thermal stresses within single components and between different components when materials heat at different rates.

Other typical effects of cycling and operating at low loads include:

- Stresses on components and turbine shells resulting from changing pressures
- Wear and tear on auxiliary equipment used only during cycling
- Corrosion caused by oxygen entering the system during start-up and by changes in water quality and chemistry
- Condensation from cooling steam during ramping down and shutting down, which can cause corrosion of parts, water leakage, and an increased need for drainage

These effects (summarized in Table 1) can cause equipment components, particularly in the boiler, to fatigue and fail. In turn, equipment failure leads to increased outages, increased operations and maintenance (O&M) costs, additional wear and tear from the increased O&M, and more extensive and sophisticated training, inspection, and evaluation programs.[3] The damage from cycling is not immediate—for example, components may fail and EFOR may rise a few years after significant cycling.

MODIFYING THE PHYSICAL PLANT AND OPERATING PROCEDURES

Physical Modifications

The CGS plant owner made numerous physical modifications to equipment to prevent and address impacts from cycling and low-load operations. These changes have focused on actions that improve drainage and thermal resiliency and reduce

TABLE 1. Specific experiences from cycling at CGS

Problem	*Impact/Cause*
Failure of boiler tubes	Caused by cyclic fatigue, corrosion fatigue, and pitting
Cracking in dissimilar metal welds, headers, and valves	Due to rapid changes in steam temperature
Cracking of generator rotors	Due to movement between the rotor and casing during "barring" (slow turns to keep rotors from being left in one position too long during turning-gear operation)
Oxidation from exposure to air on start-up and draining	Oxides in boiler tubes can dislodge due to thermal changes and lead to damage downstream, such as the turbine blades (see Figure 2)
Corrosion of turbine parts	From oxides, but also from wet steam that occurs on start-up, during low-load operations, and during poor plant storage conditions when the plant is dried
Condenser problems	Can occur when thin tubes crack from thermal stresses at start-up and shutdown

opportunities for corrosion, as described in Table 2. There were no major capital retrofits to allow additional cycling flexibility.

Decisions on whether and when to replace parts or modify components were made on a case-by-case basis. In other words, the plant owner based such decisions on whether wholesale power market opportunities in the coming year justified the cost of modifications to reduce the forced outage rate.

Operating Procedures

The owner of CGS estimates that once the physical changes were in place, 90% of future cost savings came from modifying operating procedures. For example, establishing procedures and training on boiler ramp rates was especially effective. Controlled ramp rates help minimize thermal fatigue; continual reinforcement of the importance of controlled ramping through training helps ensure that ramp rate procedures are followed.

Another example of effective modifications to operating procedures is high-energy (i.e., high temperature or pressure steam) piping inspections, the value of which is not always appreciated at other coal-fired power plants. The inspection program at CGS covers all the failure mechanisms that can occur (e.g., thermal and corrosion fatigue), and establishes a repair process and a repair program for each failure mechanism. The owner employs many similar inspection programs, for example, for the hanger rods that hold the high-energy piping. These examples illustrate that effective operating procedures require an understanding of *all* components impacted by cycling—not just the major ones. Table 3 describes some of the modifications that were made to CGS's operating procedures to support cycling.

Changes to plant operating procedures were critical to enabling CGS to cycle on and off cost-effectively. Controlling the rise in temperatures during plant start-up and temperature drops on shutdowns as well as having rigorous inspection programs for major and minor components limited the damage from cycling. Training programs to reinforce the skills needed to monitor the impacts of cycling were also central to the CGS owner's strategy.

A LOOK AT COSTS AND EMISSIONS

The costs associated with cycling, and modifications made in response, are difficult to distinguish from normal operation efforts. Modifications were made over the course of decades, in response to both cycling and noncycling wear and tear, to achieve EFOR rates that varied highly by unit and year. Extrapolating cost implications to other coal-fired power plants generally from the experiences at CGS is difficult due to variations in age, design, and history of operations. Moreover, decisions on the scope and timing of modifications depend on business case justifications, which are highly market- and context-driven and could vary from year to year.

Studies of coal-fired power plants, such as Kumar et al.,[5] evaluate cycling costs by calculating operating, maintenance, and repair costs associated with cycling. The plants in this study represent typical operations where coal-fired power plants are operated and maintained according to baseload requirements. However, the CGS plant owner recognized early on that CGS would be cycling significantly and, therefore, modified operating practices and equipment to minimize the impacts of cycling. Thus, because of the owner's proactive changes, the costs to mitigate cycling based on EFOR rates at CGS are likely less than those for other plants with similar cycling and EFOR rates whose owners are not as proactive.

Cycling also incurs costs associated with increased emissions rate. The selective catalytic reduction (SCR) system, which controls some emissions, must be operated at a minimum load. However, if a power plant needs to operate below this level, the owners may have authority to run the plant without the SCR system, as is the case with CGS. Other emissions impacts occur due to increased fuel use at start-ups, reduced plant efficiency at less than full load, and reduced effectiveness

TABLE 2. Examples of physical modifications to support cycling

Boiler	Added a metal overlay to water walls to minimize oxidation, cut back membranes in various areas to reduce start-up stresses, and replaced dissimilar metal welds.
Turbines	Added drains, upgraded the lubrication system, modified vacuum pumps and low-pressure crossover bellows, and inspected the non-return valves, which can be damaged during shutdowns.
Generator Rotors	Insulated and epoxied key parts to reduce rotor cracking from rubbing and established continual tests and checks to monitor trends.
Condenser	Plugged tubes at the top of the condenser that had been damaged as a result of low-load operation and water impingement, reducing overall efficiency; also installed stainless-steel air removals and retubed the existing brass on several units.

TABLE 3. Example modifications to operating procedures to support cycling

Natural cooling	Accelerated forced cooling for the boiler enabled the owner to quickly shut down the unit to repair a boiler tube and be back online in two days. However, after a year of implementing accelerated forced cooling, the units recorded a noticeable increase in corrosion and cyclic fatigue failures. The shutdown procedures are now to keep the boiler shut for the first four hours (natural cooling).
Monitoring economizer inlet headers	Economizer inlet headers can crack from intermittent additions of cold feedwater to the hot inlet header. The plant owner keeps the temperature difference between the header and water at less than 30°C, below the boiler manufacturer recommendations.[4]
Pressure part management	The owner established a pressure-part management program, reviewing every pressure component and establishing causes for degradation and failure.
Other changes to boiler operating procedures	These included a program to monitor boiler metal temperature; a tube replacement and inspection strategy; a thermal and cyclic fatigue inspection and repair program; a fly-ash erosion program to reduce tube failures; and inspection programs for expansion joints, dissimilar metal welds, and flow-accelerated corrosion.
Temperature monitoring for turbine parts	The owner established training and monitoring procedures, with associated monitoring equipment, to limit ramp rates and to monitor temperature changes to thick-walled fittings, headers, and the casing to the main steam line.
Water chemistry maintenance	To reduce corrosion, proper water chemistry must be maintained to protect surfaces that oxidize. Water chemistry varies with cycling, so the owner maintains a chemistry staff onsite and established a Chemistry Managed System (following ISO standards).
Overall monitoring programs	The owner compared reports on best practices associated with cycling with CGS's equipment status and mitigating actions and created an overall plant monitoring program.

of pollution-control equipment when flue gas temperatures at start-up are too low to support the chemical reactions needed.[6] Although emissions rates during cycling can be higher than during noncyclic operation, Lew et al.[6] showed that the avoided emissions from the added wind and solar far outweigh the impacts of cycling-induced emissions.

CAN THE CGS EXPERIENCE BE REPLICATED?

The CGS plant achieved the flexibility to cycle over several decades; this experience has provided valuable information on impacts, recommended modifications to operations and equipment, and relative costs. However, some of the aspects of CGS that improve the plant's flexibility might not easily translate to other contexts.

Physical Distinctions

Some of CGS's original plant designs are conducive to cycling—the owner did not need to conduct major-capital retrofits. For example, CGS's boiler tubes are horizontal, which facilitates cycling by improving drainage; this reduces corrosion fatigue and the time needed to come back online (see Figure 3). Effective operating practice requires drainage of any residual water in the boiler to reduce thermal shocking of tubes in the boiler. In contrast, almost all other boilers in North America are a "pendant design", which results in water accumulating at the bottom of the U-shape and leading to slow drainage. This design cannot be modified, although a $10–15-million bypass system could be added to improve temperature control and reduce tube failure.

Automation of CGS's drainage system, absent in most coal-fired power plants, was also critical to reducing failures. Earlier in plants' projected lifetimes, such major retrofits could be economically feasible.

Operating Distinctions

CGS experiences much higher EFOR rates than typically accommodated in markets where coal-fired power plants run at baseload. The plant owner can manage these high EFOR rates because of the role CGS's coal-fired units play in its system operations. The owner found that EFOR rates could be reduced by being highly proactive with inspections and strategic operational modifications.

However, a trade-off between maintenance costs and EFOR rates exists. Grid operators may need to change how they operate their systems, and coal-fired power plant operators may require a cultural shift to adapt to higher EFORs. This is particularly true because justifying maintenance costs over EFOR rates could become increasingly difficult if the cost per unit of energy generated increases at low load.

Regulatory Distinctions

Operating at low generation levels could be challenging if plants are required to run environmental controls at all output levels. Operating an SCR system requires a minimum generating level that is frequently higher than the low generating levels at which the CGS plant owner is permitted to operate.

FROM BASELOAD TO PEAKING PLANT

At CGS, the plant owner has achieved what few coal-fired power plant operators have been able to do: modify a plant that was intended to run only at baseload into one that can meet peak demands—cycling on and off up to four times a day to meet morning and afternoon electricity demand. Key to the owner's success is changing operational practices: monitoring and managing temperature ramp rates; creating a suite of inspection programs for all impacted equipment (large and small); and continual training to reinforce the skills needed in monitoring and inspections.

The owner's success in cycling has also benefited from factors specific to CGS. The original plant design, although intended for baseload operation, included features that facilitate cycling. Although the cycling features were an advantage for the unit's operating regime, additional modifications and procedural changes were required to improve equipment reliability.

Also, the decades-long practice in cycling has increased the owner's tolerance for rates of forced outages that are higher than those that are typical for plants required for baseload.

The ability of other coal-fired power plant operators to replicate CGS's flexibility will be instrumental in valuing coal in an increasingly low-carbon energy system. Although the CGS unit has certain inherent design features that assist in its operating mode, retrofits and operational modifications to other coal-fired power plants can allow for increased flexible generation across many power systems. Coal-fired power plants can cycle, and if designed and operated appropriately, can provide flexibility, sometimes more significantly than even CGS. There is a cost to cycle and also increased risk of unavailability, but this is true for other types of generation as well.

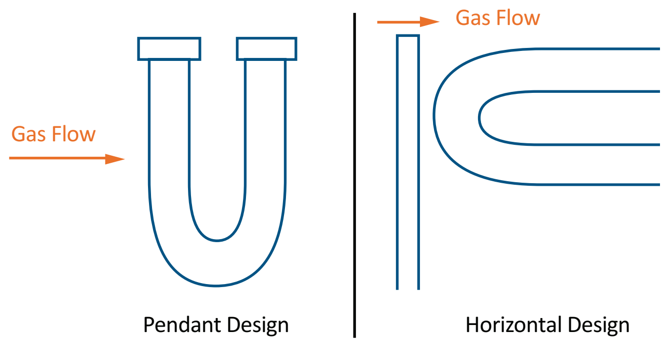

FIGURE 3. CGS has a horizontal, not pendant, boiler design, which facilitates drainage needed to reduce corrosion fatigue and allow the plant to come online faster. The pendant design more easily allows water accumulation. (Graphic: Steve Lefton, Intertek)

NOTES

A. For commercial reasons the CGS is not further identified.

ACKNOWLEDGMENTS

This publication was produced under direction of the 21st Century Power Partnership by the National Renewable Energy Laboratory (NREL) under Interagency Agreement DE-AC36-08GO28308 and Task Nos. WFH1.2010 and 2940.5017.

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