21st Century POWER PARTNERSHIP
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Flexible Coal

Evolution from Baseload to Peaking Plant

The experience cited in this paper is from a generating station with multiple units located in North America referred to here as the CGS plant. For commercial reasons, the station has not been identified.

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Summary for Policymakers:
Key Findings from a North American Coal Generating Station (CGS)

Twenty-first century power systems, with higher penetration levels of low-carbon energy, smart grids, and other emerging technologies, will favor resources that have low marginal costs and provide system flexibility (e.g., the ability to cycle on and off to follow changes in variable renewable energy plant output). Questions remain about both the fate of coal plants in this scenario and whether they can cost-effectively continue to operate if they cycle routinely.

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The experience from the CGS plant demonstrates that coal plants can become flexible resources. This flexibility—namely the ability to cycle on and off and run at lower output (below 40% of capacity)—requires limited hardware modifications but extensive modifications to operational practice. Cycling does damage the plant and impact its life expectancy compared to baseload operations. Nevertheless, strategic modifications, proactive inspections and training programs, among other operational changes to accommodate cycling, can minimize the extent of damage and optimize the cost of maintenance.

CGS's cycling, but not necessarily the associated price tag, is replicable. Context—namely, power market opportunities and composition of the generation fleet—will help determine for other coal plants the optimal balance between the level of cycling-related forced outages and the level of capital investment required to minimize those outages. Replicating CGS's experience elsewhere will likely require a higher acceptance of forced outages than regulators and plant operators are accustomed to; however, an increase in strategic maintenance can minimize the impact on outage rates.

Many power systems the world over are being reshaped by new economic and political landscapes, which have resulted in increased investments in renewable energy, distributed energy technologies, and natural gas. This transformation will likely yield a substantial reduction in coal-generated electricity. For example, to reduce greenhouse gas emissions, Ontario, Canada is phasing out the use of coal by the end of 2014.

As power systems undertake this transition, questions remain about the fate of coal plants and how their operations may change in systems with increasing penetration levels of variable renewable energy, such as wind and solar. Future power systems may need more flexible generation resources. These resources can be characterized by the ability to cycle on and off and run at low minimum loads to complement variations in output from high penetration levels of renewable energy.

Coal plants are perceived to be unable to sustain extended periods of cycling—however, some coal plants, including the one featured in this case study, have been cycling for decades. CGS has at times cycled on and off as many as four times a day to meet morning and afternoon peak demand (see "Attributes of Flexibility" sidebar). It is one of a few coal plants worldwide to accomplish this level of flexibility. Yet, it was originally intended to run as a baseload unit, rarely to be turned down or off.

Attributes of Flexibility at CGS

- Start up and shut down on the same day, even twice daily (e.g., run from 5:00 a.m. to 10:00 a.m. and again from 4:00 p.m. to 8:00 p.m.)
- Load follow and run at minimum generation levels: from 480 megawatt (MW) max net capacity per unit to 90-MW net, and even to 60-MW net (for up to 6 hours) with gas support
- Provide automatic generation control (until recently when the feature was retired)
- Operate at sliding pressure, from 8 to 9 megapascals, which increases efficiency and flexibility at part loads

Although CGS's need for flexibility predates the rise of renewable energy, the experiences at CGS illustrate how older baseload coal units could be incentivized and modified to complement peak power demand in a system with significant low-variable cost natural gas and renewable energy. It must also be noted that CGS had some initial design advantages in terms of the boiler design and availability of gas igniters that supported its operational regime.

This case study reviews 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 plants and helps policymakers better understand how to formulate policy and make investment decisions in the transformation toward low-carbon power systems.

After considering the historical context for CGS's flexibility, this document reviews the technical details of cycling: the problems that can emerge from operating the plants as intermediate and peaking plants, and modifications to the plant and operating systems that enabled the coal plant to achieve this flexibility. It concludes with reviews of the implications for costs and emissions, and the extent to which these changes could be replicated.

Historical Context for Flexibility at the CGS Plant

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

After a competitive market was introduced in the early 2000s, the plant was operated for longer periods at full plant output. But, 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 represents the accumulated latent damage from the cycling CGS performed in the 1990s.[1]

The competitive market created the incentive for CGS units to continue to be able to operate flexibly, for example, that they be able to two-shift and operate at reduced output below intended minimum load. In this market context, decisions to modify the plant, replace parts, and lower EFOR were evaluated piecemeal, based on profit potential (e.g., expected peak demand, prices, and potential order of the plant within the market dispatch). Cycling with fewer generating hours increases equipment wear and tear, which reduces a plant's cost competitiveness, which for CGS reduced the ability of its owner to justify plant modifications and projects. Although the market allows expected start-up costs to be included with a bid, these costs are part of the dispatch optimization. Therefore, if start-up costs are bid too high, the CGS units will not be dispatched. Management knew of the impact, but did not determine the actual wear and tear related costs from the cycling at CGS.

[1]Typical EFOR for a baseload coal plant is 6.4% (Vuorinen 2007, based on NERC statistics). Other reliability measures for plants in use globally are the equivalent availability factor, the unit capability factor, and the unplanned capability loss factor.

Cycling at CGS—Technical Details

Impact of Cycling and Operating at Minimum Load Levels

The coal units at the CGS plant were designed to run at full output and start cold only a few times a year. However, each coal unit has experienced an average of 1,760 starts, including 523 cold starts (see "Starts" table on next page) throughout its lifetime. The overarching impact of this type of cycling is thermal fatigue; large temperature swings, for example, from cold feedwater entering the boiler on start-up and from steam heating up, create fluctuating thermal stresses within single components and between components when materials heat up at different rates (for example, welds). Other typical impacts of cycling and operating at low loads include:

- Stresses on components and turbine shells resulting from changing pressures
- Wear and tear on the auxiliary equipment that is only used during cycling
- Corrosion caused by oxygen entering the system (e.g., during start-up), and changes to water quality and chemistry, resulting from, for example, falling pH
- Condensation from cooling steam, which in turn can cause corrosion of parts, leakage of water, and an increased need for drainage.

SUMMARY FOR POLICYMAKERS: IMPACT OF CYCLING

The primary impact of cycling is the wear and failure of equipment parts due to large temperature swings that occur when a plant starts up. The impacts from cycling can take several years to show up as damage or forced outages. Damages from cycling at the CGS plant largely aligned with industry experiences.

Average Number of Starts at CGS over Course of Plant Life

Cold (7–8 hours to sync):	523
Warm (4 hours to sync):	422
Hot (1.5 - 2 hours to sync):	814
Total	**1,759**

These impacts can cause equipment components, particularly in the boiler, to fatigue and fail. The equipment failure in turn leads to increased outage rates, increased operations and maintenance (O&M) costs, additional wear and tear from the increased O&M, and more extensive and sophisticated training and inspection and evaluation programs (EPRI 2001). The damage from cycling is not immediate—for example, components may fail and EFOR may rise a few years after significant cycling.

Specific experiences from cycling at the CGS plant include:

- **Failures of boiler tubes** caused by cyclic fatigue, corrosion fatigue and pitting.
- **Cracking in dissimilar metal welds, headers and valves,** and other thick-walled components due to rapid changes in steam temperature.
- **Cracking of generator rotors** due to the movement between the rotor and casing during "barring" (the use of slow turns to keep rotors from being left in one position too long during turning gear operation); the rubbing creates copper dusting, which can also cause ground faults in the rotor.
- **Oxidation,** for example, from exposure to air on start-up and draining; oxides in boiler tubes can dislodge due to thermal changes. *See photo for an example of foreign object damage on turbine fin "96."*
- **Corrosion of turbine parts,** not only from oxides (see above) but also from wet steam that occurs on start-up, during low-load operations, and during poor layup conditions when the plant is dried. This was not a significant issue at CGS.
- **Incidence of condenser problems** that occur, for example, when thin tubes crack from thermal stresses at start-up and shutdown; two-shifting requires condensers to be blown down, i.e., water must be drained from equipment to remove mineral build up from condensate. At the CGS plant, the high number of blow downs with its significant water throughput caused wear and tear and copper to be leaked into the adjacent lake. Eventually, the condenser was retubed at CGS.
- **Migration of turbine blade root locking shims** associated with frequent cycling.
- **Rewedge frequency** on stator increased with increased cycling.

Photo by Debra Lew, NREL

Modifications to the CGS Plant and Operations to Minimize Cycling Impacts

The CGS plant owner made a host of physical modifications to equipment to prevent and address impacts from cycling and low load operations, but the owner estimates that once the physical changes were in place, 90% of future savings in costs came from adjustments to operating procedures. For example, establishing procedures and training on boiler ramp rates has been especially effective. Controlled ramp rates help minimize thermal fatigue, and continual reinforcement of its importance through training helps ensure that ramp rate procedures are followed.

Another example of effective modifications to operating procedures is high-energy piping inspections, the value of which is not always appreciated at other coal plants. The inspection program at the CGS plant reviews all the failure mechanisms that can occur (e.g., aspects of thermal and corrosion fatigue), and the program 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 major ones. All need to be addressed to anticipate and minimize forced outages.

Operating Procedures

To meet the flexibility requirements, CGS operators experimented with different operational procedures over the years. Some of the modifications to operating procedures included:

- **Forced cooling:** The owner of CGS experimented with accelerated forced cooling for the boiler, which would enable the owner to more quickly shut down the unit to repair a boiler tube and be back online in two days. Despite maintaining temperature changes within equipment specification, after a year of implementing accelerated forced cooling, the units recorded a noticeable increase in corrosion and cyclic fatigue failures. As soon as the owner returned to natural cooling, the failure rate decreased. This was a learning experience for the plant operators, since force cooling the boiler resulted in a rapid rate of temperature change causing increased damage. Hence, shut-down procedures now call for keeping 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 installed thermocouples to examine temperature differentials between the header and water, and switched from intermittent to trickle feed. The boiler manufacturer recommends maintaining the differential at less than 37.8°C (100°F) (B&W 1994), but the owner takes further precautions and keeps the temperature difference at less than 30°C.
- **Layup procedures:** The owner established and follows layup procedures that vary based on how long the unit will be off (e.g., drain while hot for short outages; use nitrogen blankets for long outages). These procedures reduce boiler tube failures and other effects of corrosion fatigue.
- **Pressure part management:** The owner established a pressure part management program, which entails reviewing every pressure component and establishing causes for degradation and failure.
- **Other changes to boiler operating procedures:** These included a boiler metal temperature monitoring program; 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:** As with its actions to reduce damage to boilers, the owner established training and monitoring procedures, with associated monitoring equipment, to limit ramp rates and to monitor temperature changes to heavy wall fittings, headers, and the casing to the main steam line.

SUMMARY FOR POLICYMAKERS: MODIFICATIONS TO OPERATING PROCEDURES

Changes to plant operating procedures have been critical to enabling CGS to cost-effectively cycle on and off. Controlling the rise in temperatures on plant start-up and temperature drops on shutdown and having rigorous inspection programs for major and minor components have limited the damage from cycling. Training programs to reinforce the skills needed to monitor the impacts of cycling have also been central to the plant owner's strategy. Once the physical modifications were in place, approximately 90% of the plant's subsequent savings came from changes to operating procedures.

- **Water chemistry maintenance:** To reduce corrosion, proper water chemistry must be maintained to protect surfaces that oxidize. Because water chemistry varies with cycling, the owner maintains chemistry staff onsite at all hours. The owner also established a Chemistry Managed System (following ISO Standards).
- **Environmental controls:** The owner created maintenance procedures for environmental controls to manage impacts of cycling.
- **Breaker maintenance:** The owner modified its maintenance and inspection program for low and medium voltage breakers.
- **Overall monitoring programs:** The owner conducted a "gap review" in 2012, in which it compared reports from the Centre for Energy Advancement through Technological Innovation, the Electric Power Research Institute (EPRI), and Structural Integrity on best practices associated with cycling with CGS's equipment status and mitigating actions.

SUMMARY FOR POLICYMAKERS: PHYSICAL MODIFICATIONS

Physical changes to the plant have also been critical to the CGS plant's cycling. These changes have focused on actions that improve drainage and thermal resiliency, and reduce opportunities for corrosion.

Decisions on whether and when to replace parts or modify components have been made on a case-by-case basis. In other words, the plant owner analyzed whether wholesale power market opportunities in the coming year justified the cost of replacing a part and reducing the forced outage rate.

Physical Modifications

CGS also made many physical modifications to the boilers, pulverizers, turbines, rotors, and condensers, including modifications to:

- **Boiler:**
  - Added a metal overlay to water walls to minimize oxidation
  - Modified buckstays (would now cost approximately $1 million–$1.5 million per unit, including asbestos handling and cost of cutting)
  - Replaced some metal fold expansion joints with fabric joints
  - Cut back tie bars on membrane walls to avoid corner tube failures
  - Cut back membranes in various areas to reduce start-up stresses
  - Replaced flow elements in the feed pump recirculation valves
  - Replaced dissimilar metal welds (approximately $1 million–$1.5 million for major header)
  - Strategically replaced corner tubes ($200,000 per corner; $175,000 for upper corner tubes; total $4 million)
- **Pulverizers:** Converted the water deluge system to steam inert ($2 million–$3 million); fixed gearboxes ($300,000–$500,000)
- **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:** Sacrificially plugged tubes at the top of the condenser due to low loads and water impingement; also installed stainless steel air removals and retubed the existing admiralty brass on several units ($6 million–$8 million/unit).

To determine when to make modifications, the plant owner annually assessed peak capacity requirements for the market, the role of the thermal fleet, the likely dispatch order of individual units, and the costs to reduce EFOR per unit. Based on this information, the owner conducted targeted O&M, prioritizing units with better EFOR costs to bring down rates. The owner did not maintain EFOR rates at a uniform level; the decision not to do so was mediated by larger market factors.

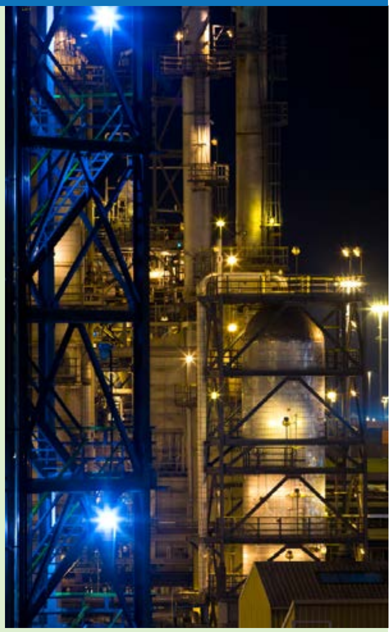
The owner was not able to enact all best practices to prevent cycling damage. For example, during the early 1990s when cycling increased, market conditions and relative requirements for the asset did not allow for major O&M and capital expenditures. Also, the owner has been unable to justify the costs of other industry best practices for cycling, such as utilizing heating steam from auxiliary boilers, bypass systems, and cross-connection between units (for more information on best practices, see EPRI 2001 and Kumar 2012).

Recent EFOR Rates

2002	14%
2003	20%
2004	33%
2005	25.5%
2006	22%
2007–2009	16–17%
2010	9%
2012	20.5%

Decreasing Minimum Generating Levels

Minimizing generation levels can allow plants to stay online during periods of low energy prices, such as at night, and minimize the need for and impacts of cycling. The CGS plant owner must also sometimes run its plant for non-market reasons, namely to keep heat in the building. The owner experimented with reducing output below 90-MW net (19% net rating), an already significantly low generating level for most utilities, which typically limit minimum generation levels to 40%-50% of rated capacity. To generate 50-MW gross, 35-MW net for 2–6 hours, the owner monitored temperatures and conducted tests on the turbine to establish limiting factors. The test run was successful. It was discovered that, while there might be some efficiency loss from keeping all boiler drains open, the turbine was the limiting factor at lower loads. Some of the likely sources of problems—such as turbine blades fluttering, economizer misting, or issues of mixed flow—did not materialize, at least to concerning levels. The owner lacked sufficient instrumentation to fully evaluate the impacts of such low operating levels on the boiler. If the owner were to do this long-term, the company would thoroughly evaluate the boiler design at low generating levels and then have a turbine designer evaluate impacts on valves, blade flutter, and other parts and processes.



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Cycling at CGS—Costs and Replicability

Costs to Modify Plant and Operations to Achieve Flexibility

The costs associated with cycling, and modifications made in response, are difficult to isolate. Modifications were made over the course of decades, in response to both cycling and non-cycling wear and tear, to achieve EFOR rates that varied highly by unit and year. Extrapolating cost implications for coal plants generally from the CGS plant to other plants 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 very market- and context-specific, and which vary from year to year.

Studies such as Kumar (2012) evaluate cycling costs by calculating operating, maintenance, and repair costs associated with cycling. The plants in this case study of CGS represent typical operations, in which coal plants are operated and maintained according to baseload requirements. Yet, the CGS plant owner understood that CGS would be cycling significantly and therefore modified operating practices and equipment to minimize the impacts of cycling. Thus, 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, based on the owner's proactive changes to operations and equipment.

Cycling also incurs costs associated with increased emissions rate. The selective catalytic reduction (SCR) system, which controls emissions, must be operated at a minimum plant generating level. But, if the CGS plant needs to cycle below this level, the owner has authority to run the plant without the SCR system. Other emissions impacts occur due to increased fuel use at start-ups, reduced plant efficiency at less than full loads, and reduced effectiveness of pollution-control equipment when flue gas temperatures at start-up are too low to support the chemical reactions needed to remove pollutants (Lew et al. 2013). For example, emissions of nitrogen oxides at the CGS plant increase 10% on start-up due to increased fuel use then. Despite the fact that emissions rates during cycling can be higher than rates during non-cyclic operation, studies such as Lew et al. (2013) show that the avoided emissions from wind and solar far outweigh secondary emissions impacts induced by cycling.

Replicability

The CGS plant has achieved flexibility in cycling over the course of several decades, and the experience has provided valuable information on impacts, recommended modifications to operations and equipment, and relative costs. Nevertheless, 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, which may not be the case in other North American plants, most of which have different designs. For example, CGS's boilers are horizontal and include automated drains. The horizontal design facilitates cycling by improving drainage, which is needed to reduce corrosion fatigue and the time needed to come back online. Good 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 of a "pendant design," which result in water accumulation at the bottom of the U-shape and slow drainage. This design cannot be modified, although a $10 million–$15 million bypass system could be added to control temperatures and reduce tube failure. Automation of the drainage system (on both the boiler and the main steam line) is also critical to reducing failures, and this is absent in most plants. Earlier in a plant's projected lifetime, major retrofits could make economic sense.

Operating distinctions: CGS experiences much higher EFOR rates than are typically accommodated in markets, where coal plants run at baseload. They can manage these high EFOR rates based on the role that these coal units play in their system operations. That said, these plants have lower capacity factors and high startup rates. The CGS plant owner found that EFOR rates could be reduced by being very proactive with inspections and strategic operational modifications. Nevertheless, a trade-off between maintenance costs and EFOR rates remains. Grid operators may need to change how they operate their systems, and coal 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 generation levels. Market areas with capacity payments could alleviate this potential. Another example of an operating distinction is full-time onsite chemistry staff at CGS.

Regulatory distinctions: Operating at low generation levels could be challenging in other regulatory contexts 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.

Conclusions

The transformation of the power sector to greater penetration levels of renewable energy, demand response, and other emerging technologies in many cases requires that an increased proportion of the power generation fleet be flexible. In other words, it must be able to cycle up and down to meet the remaining demand for electricity. At CGS, the plant owner has achieved what few coal 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 affected 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 operations, included features that facilitate cycling. While 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, a calculation that the owner bases on market opportunities. Finally, the coal units will be shut down before the end of their lifecycle, which affects decisions on maintenance. Nevertheless, the ability of other coal plant operators to replicate CGS's flexibility will be instrumental in valuing coal in an increasingly low-carbon energy system.

Glossary

Cycling: Range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down, and operating at part-load (less than full output) (Lew et al. 2013).

Forced Outage: An unplanned component failure (immediate, delayed, postponed, startup failure) or other condition that requires the unit be removed from service immediately, within six hours, or before the end of the next weekend (NERC).

Ramping: Output that varies between full and minimum levels in order to follow changes in generation demand (Although ramp speed is an important element of a flexible power system, CGS generating units did not ramp faster than typical coal plants, and therefore ramp speed was not a focus of this case study).

Start: Starting of a unit that is offline; starts are described as hot, warm, or cold, depending on the temperatures of the metal in the turbine.

Two Shifting: Operational sequence whereby a generating unit is started and shutdown within a 24-hour period. Typically, the shutdown is overnight. Also used as a general term describing more than one shutdown within a 24-hour period (2-shifting or 4-shifting).

Wear and Tear: Wear means the component reaches the end of its natural life through ordinary causes (e.g., corrosion, thermal fatigue), though wear can be accelerated by cycling. Tear refers to an abnormal event that accelerates the life, such as occurs during poor control of operating conditions. Tear can occur during baseload operations, but abnormal events are generally more likely during some cycling modes (Connolly et al. 2011).

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