STAFF PAPER

THERMAL EFFICIENCY OF GAS-FIRED GENERATION IN CALIFORNIA

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ABSTRACT

This staff paper describes general trends in natural gas-fired generation in California from 2001 through 2010. Over this 10-year period, California's gas-fired generation has seen thermal efficiency improvements of more than 17 percent. The successful development of new combined cycle plants since 2001 is the primary reason for the decline in California's systemwide heat rate.

Keywords: Combined cycle, heat rate, gas-fired generation, thermal efficiency

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Discussion

This staff paper describes general trends in natural gas-fired generation in California from 2001 through 2010. [1]

Over this 10-year period, California's gas-fired generation has seen realized thermal efficiency improvements of more than 17 percent. [2] An increase in generation from newer combined cycle plants and a reduced dependence on generation from aging power plants are the primary factors. If the cogeneration component is removed from this comparison, the efficiency gain in gas-fired efficiency over the past 10 years has been greater than 24 percent.[3]

As shown in **Table 1** the average heat rate of all forms of gas-fired generation declined from 10,330 to 8,566 British thermal units per kilowatt hour (Btu/kWh) from 2001 to 2010.

Table 1: California Natural Gas-Fired Heat Rates for 2001 – 2010 (Btu/kWh)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Gas	10,330	10,254	9,873	9,674	9,494	9,094	8,818	8,858	8,748	8,566

Source: QFER CEC-1304 Power Plant Data Reporting.

The natural gas power plants examined in this paper are grouped into five categories based on a combination of duty cycles, vintage of the generator unit, and technology type.

Peaker plants are those identified as having a peaking duty cycle role; these generating units are called upon to meet peak demand loads for a few hours on short notice. This is the only category grouped solely by its duty cycle. These plants typically use a fast-ramping, simple cycle combustion turbine and usually are restricted in their total hours of operation annually. There were 34 peaker plants identified in 2001; by 2010, the number of peaker plants had grown to 68.

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1 This study is not intended to address the impacts on the statewide system inertia that is occurring due to the changeover from aging steam turbines to newer combined cycle plants and the growth in renewable generation. System inertia refers to the rotating mass of electrical generation and is a measure of an electrical system's ability to absorb fluctuations in frequency. Generally, the lower the system's inertia, the more susceptible the electrical system is to disruptions and outages. In this context, inertia is a measure of a system's resistance to stoppages.

2 2010 Heat Rate = 8,566 Btu/kWh
2001 Heat Rate = 10,330 Btu/kWh
Percentage Change in Heat Rate = (10,330 – 8,566) / 10,330 = 17.1%

3 2010 Weighted Average Aging + New CC Heat Rate = 7,504 Btu/kWh
2001 Weighted Average Aging + New CC Heat Rate = 9,927 Btu/kWh
Percentage Change in Heat Rate = (9,927 – 7,504) / 9,927 = 24.4%

Aging power plants are those plants built before 1980 and composed almost exclusively of steam turbines that use once-through-cooling technology. Due to air quality and environmental concerns, aging power plants are being phased out or repowered with cleaner, more efficient combined cycle turbine technology. The number of aging power plants has fallen from 27 to 22 as of 2010.

The *new combined cycle* category consists of those generating units constructed since 2000 with a total plant capacity of 100 megawatts (MW) or more. A combined cycle plant has a steam turbine that is integrated with at least one combustion turbine. Its higher fuel efficiency results from the ability to use the waste heat from the combustion turbine to produce steam for the steam turbine. These newer combined cycle plants produce electricity with better heat rates than either stand-alone combustion turbines or steam turbines. In 2001 there were only 5 combined cycles with this new technology; by 2010, California had 30 new combined cycle plants.

The *cogeneration* category consists of a mix of combustion turbines, combined cycle units, and steam turbines; they typically have a relatively high heat rate. Cogeneration plants, commonly referred to as combined heat and power or CHP plants, produce (1) heat for an onsite or nearby dedicated thermal host, and (2) electricity for onsite industrial use or for wholesale injections to the high voltage grid. Heat rates measure the conversion of chemical energy in natural gas to electrical energy but do not incorporate a credit for the beneficial industrial use of waste steam. The number of cogeneration plants has remained relatively constant from 2001 through 2010: 145 and 150, respectively. The majority of cogeneration plants in California are under 50 MW in size, often in the 1-10 MW range.

The remaining natural gas power plants fall into the *other* category. These are older units built before 2000 that are not considered to be peakers, cogeneration, or aging. There are about 20 plants are in this category for each year studied.

This data has been compiled based on the attributes of the individual generating units within each power plant. Accordingly, it is possible that a power plant (or generating station) may have individual units that fit the definitions of different categories. For example, a power plant may have units considered aging and other units that are peakers. In this study, the generating units are placed into a single category while the plant site within which they reside within falls into multiple categories. As such, all data categories are mutually exclusive, and no unit is double-counted.

Table 2 summarizes in-state natural gas-fired electric generation in 2010 with breakouts for five categories of natural gas-based generation.

Table 2: California Natural Gas-Fired Power Plants Summary Statistics for 2010

	Capacity (MW)	Share	GWh	Share	Capacity Factor	Heat Rate (Btu/KWh) (1)
Total Gas	46,295	100.0%	112,922	100.0%	27.8%	8,566
New CCs [2]	16,196	35.0%	71,373	63.2%	50.3%	7,176
Aging Plants [3]	16,748	36.2%	6,219	5.5%	4.2%	11,269
Peaker Plants [4]	4,331	9.4%	848	0.8%	2.2%	11,202
Cogeneration [5]	5,992	12.9%	31,175	27.6%	59.4%	11,161
Other [6]	3,029	6.5%	3,307	2.9%	12.5%	8,367

Source: QFER CEC-1304 Power Plant Data Reporting.

1. All Btu's in this paper are in HHV.
2. Combined cycle plants 100 MW and larger built since 2000.
3. Power plants identified as aging were built before the 1980s.
4. Peaker plants are identified as operating less than 10 percent of the time, used primarily to meet peak load conditions.
5. Includes combined heat and power plants using both combined cycle and simple cycle technologies.
6. Includes all remaining natural gas plants not falling into any of the above-identified categories, such as internal combustion generators and plants built in the 1980s and 1990s.

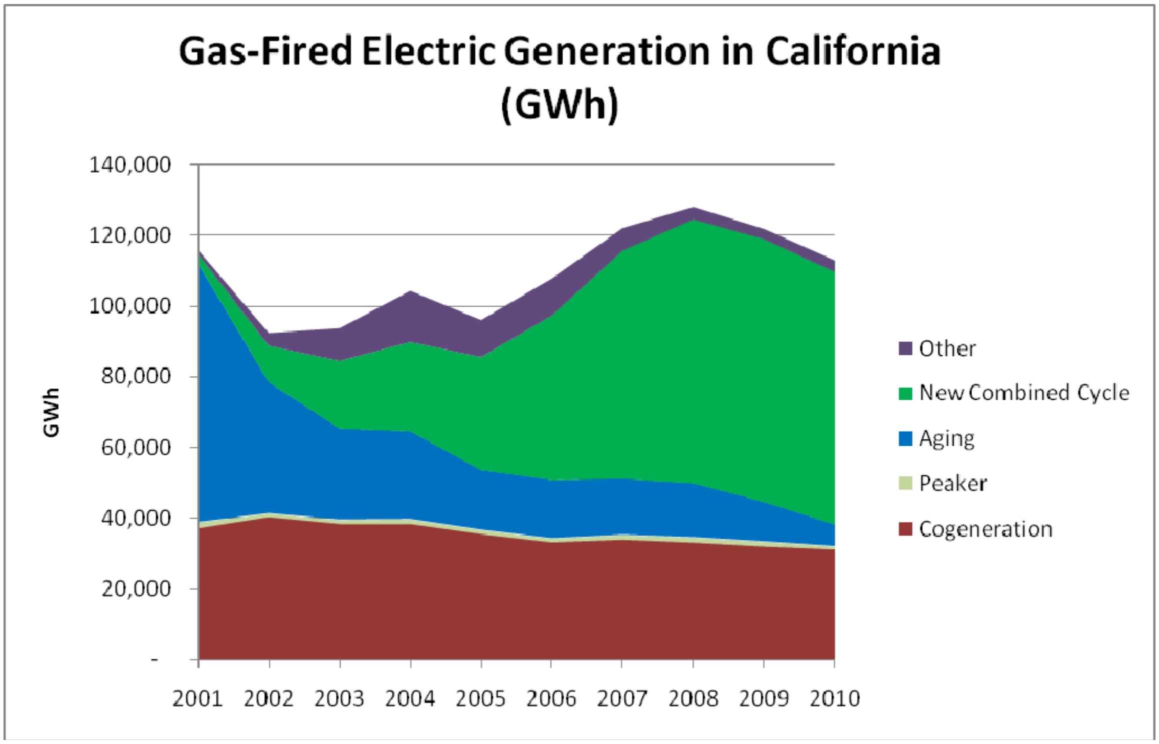
By capacity, roughly 35 percent of the fleet consists of combined cycle units built since the energy crisis. However, these new combined cycle plants provided 63 percent of the energy from all gas-fired generation categories in 2010. These combined cycle units operate at an average capacity factor of 50 percent with an average heat rate of 7,176 Btu/kWh (in higher heating value terms or HHV).

In contrast, the group of aging power plants comprise 36 percent of all gas-fired capacity but contribute only 5.5 percent of all electric generation from natural gas. By 2010, these aging plants (more than 35 years old) operated at a 4 percent capacity factor and had an average heat rate of 11,269 Btu/kWh.

As shown in **Figure 1**, the sharp decline in generation from aging power plants after 2001 began a trend that continued throughout the decade as more new combined cycle plants came on-line. Total amounts of gas-fired generation were particularly high in 2001 because of extreme drought affecting California and Pacific Northwest hydro generation. Total amounts of gas-fired generation increased markedly after 2005 as the California economy grew, particularly during 2007 and 2008, two dry hydropower years in California. Generation from aging plants held flat during the recent drought but continued to diminish as the recession took hold in 2009 and 2010.[4]

4 Between 2001 and 2010, the level of coal-fired electricity imported from out-of-state sources dropped from 23,700 GWh to 13,100 GWh. This drop in coal imports has been made-up largely with increases in gas-fired generation. This implies that the total systemwide heat rate improvement is

Figure 1: Total Gas-Fired Electric Generation



Source: QFER CEC-1304 Power Plant Data Reporting.

Combining the total energy produced by source shown in **Figure 1** with the measured heat rates reported in **Table 2** allows researchers to calculate a combined average heat rate for California's natural gas-fired generation. **Figure 2** shows how aggregate average heat rates for gas-fired generation in California have improved over the last decade. This trend has been consistent, and the efficiency gains have been cumulative. As may be judged by the slope of the trend line in **Figure 2**, the greatest efficiency gains occurred from 2002 to 2003, and from 2005 through 2007 when the majority of new combined cycle plants began commercial service. Gains in power plant efficiency as measured by heat rates result in direct reductions in greenhouse gas (GHG) emissions. The heat rate is directly proportional to GHG emissions.

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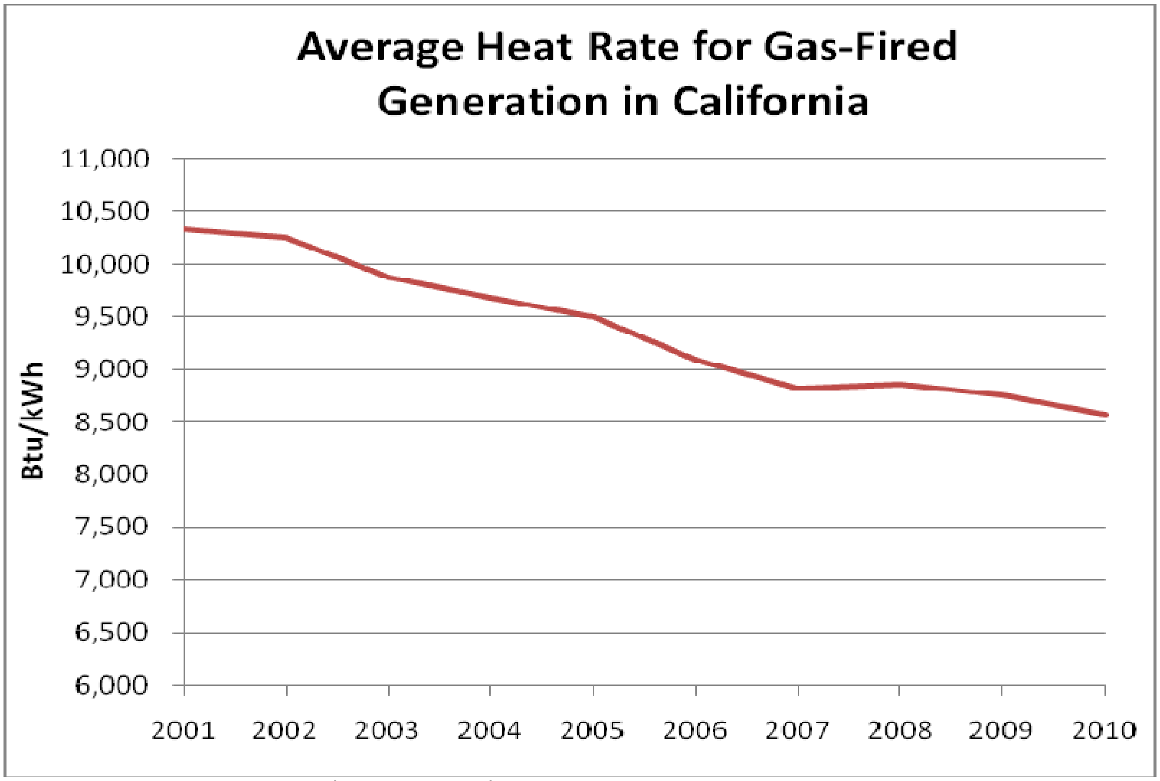
larger than the improvements in gas-fired generation alone. It is, however, beyond the scope of this paper to attempt to estimate the total system heat rate improvement from these combined effects.

Figure 2: Gas-Fired Heat Rates for Electric Generation



Source: QFER CEC-1304 Power Plant Data Reporting.

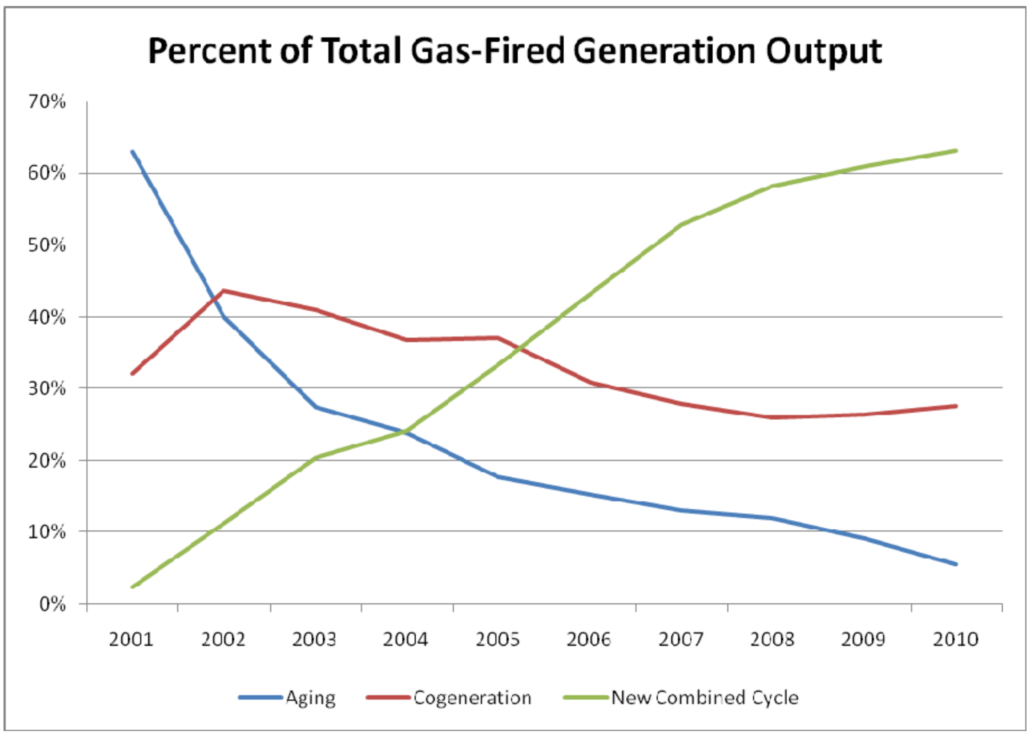
The successful development of new combined cycle plants since 2001 is the primary reason for the decline in California's systemwide heat rate. California can continue to benefit from improved systemwide generating efficiency by adding new combined cycle plants. The average heat rate for new combined cycle plants in 2010 was 7,176 Btu/kWh, and the long-run limit on combined cycle efficiency is generally held to be about 6,300 Btu/kWh. Under real-world operating conditions 6,600 – 6,700 Btu/kWh on average might be seen from these resources, thus further reducing the system heat rate that was 8,566 Btu/kWh in 2010.

There are several factors, however, that will mitigate against such reductions. The gas plant fleet is increasingly going to be tasked with ramping generation up and down over a wider range of conditions, as well as cycling on and off daily to compensate for new intermittent resource generation supply and availability. Adding this functionality to new gas-fired generation comes at the cost of efficiency in two areas. The full load heat rates of such resources are often higher than for recently built combined cycles that are designed and intended to be operated at fixed levels of output. In addition, the operation of these resources at partial load, while not prohibitively inefficient, does result in a relative loss of efficiency (for example, a higher heat rate).

Additionally, the development of carbon sequestration technologies (*zero-carbon gas*) will occur only with high onsite generation station loads (self-service or *parasitic* loads). The energy required for carbon sequestration will reduce amounts of net generation for load, thus, increasing the net heat rate of any such facility.

In terms of GHG emissions, efficiency improvements offer a direct reduction in GHGs. Newer combined cycle plants have helped contribute to this reduction. As shown in both **Figure 3** and **Table 3**, power generated by newer combined cycle plants over the past 10 years has come very close to completely replacing (or displacing) the total output from aging power plants. In 2001, aging power plants generated 73,131 GWh, while newer combined cycle plants generated only 2,730 GWh. Fast forward to 2010, and the newer combined cycle gas plants generated 71,373 GWh, while aging plants generated 6,219 GWh — a near-complete reversal in roles.

Figure 3: Trends in Gas-Fired Output by Plant Type



Source: QFER CEC-1304 Power Plant Data Reporting.

Table 4 confirms the changeover to newer combined cycle plants with a large reduction in fuel usage over the past 10 years. Total aging and new combined cycle plant fuel usage from 2001 to 2010 was reduced by 171 million MMBtu from 753 million to 582 million MMBtu, a reduction of 24 percent over 10 years. The corresponding change in the combined heat rate of both aging and newer combined cycle plants improved from 9,927 to 7,504 Btu/kWh over 10 years.[5] See **Table 5** for more details on heat rates by power plant type.

The increased reliance on newer combined cycle generation suggests that the method in which balancing authorities schedule power on the system has changed over the past 10 years. The dispatching of the various system resources (power plants) is beyond the scope of this report as the data is considered confidential by each balancing authority.

Table 3: Power Generation from California's Natural Gas-Fired Power Plants (GWh)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Gas	115,930	92,395	93,719	104,337	96,062	107,833	122,127	128,076	121,845	112,923
New CCs	2,730	10,319	19,112	25,265	31,930	46,527	64,575	74,628	74,319	71,373
Aging (Total)	73,131	37,096	25,783	24,818	16,928	16,505	15,849	15,305	11,196	6,219
Aging: OTC	*66,488*	*33,494*	*23,506*	*23,301*	*14,924*	*14,609*	*14,424*	*13,600*	*10,454*	*5,762*
Aging: Non-OTC	*6,643*	*3,602*	*2,277*	*1,517*	*2,004*	*1,896*	*1,425*	*1,705*	*742*	*457*
Peakers	1,655	928	1,080	1,297	1,129	1,053	1,299	1,444	1,358	848
Cogeneration	37,218	40,409	38,478	38,442	35,568	33,233	34,008	33,155	32,031	31,175
Other	1,196	3,642	9,266	14,515	10,507	10,515	6,397	3,543	2,941	3,307

Source: QFER CEC-1304 Power Plant Data Reporting.

5 2001 Fuel Use by New CCs + Aging Plants = (19 + 734) = 753 million MMBtu
2001 Generation by New CCs + Aging Plants = (2,730 + 73,131) = 75,861 GWh
2001 Heat Rate = (753 * 1,000,000) / 75,861 = 9,927 Btu/kWh
2010 Fuel Use by New CCs + Aging Plants = (512 + 70) = 582 million MMBtu
2010 Generation by New CCs + Aging Plants = (71,373 + 6,219) = 77,592 GWh
2010 Heat Rate = (582 * 1,000,000) / 77,592 = 7,504 Btu/kWh

Table 4: Fuel Use by California's Natural Gas-Fired Power Plants (Million MMBtu)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Gas	1,198	947	925	1,009	912	981	1,077	1,135	1,066	967
New CCs	19	74	139	183	231	337	464	536	535	512
Aging (Total)	734	388	279	270	181	176	165	173	130	70
Aging: OTC	*669*	*350*	*253*	*250*	*158*	*154*	*148*	*154*	*120*	*64*
Aging: Non-OTC	*65*	*38*	*26*	*20*	*23*	*22*	*17*	*19*	*10*	*6*
Peakers	21	10	12	14	13	12	14	15	15	10
Cogeneration	410	448	425	436	405	377	383	380	361	348
Other	13	28	70	107	82	79	51	30	25	28

Source: QFER CEC-1304 Power Plant Data Reporting.

Table 5: Heat Rates for California's Natural Gas-Fired Power Plants (Btu/kWh)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Gas	10,330	10,254	9,873	9,674	9,494	9,094	8,818	8,858	8,748	8,566
New CCs	6,974	7,150	7,271	7,226	7,248	7,242	7,181	7,181	7,193	7,176
Aging (Total)	10,037	10,465	10,825	10,863	10,717	10,681	10,411	11,334	11,591	11,269
Aging: OTC	*10,064*	*10,441*	*10,762*	*10,731*	*10,613*	*10,542*	*10,275*	*11,301*	*11,498*	*11,152*
Aging: Non-OTC	*9,763*	*10,694*	*11,454*	*12,877*	*11,488*	*11,742*	*11,781*	*11,590*	*12,894*	*12,742*
Peakers	12,529	10,873	11,287	11,129	11,147	11,027	11,020	10,662	10,898	11,202
Cogeneration	11,027	11,081	11,054	11,336	11,387	11,354	11,268	11,449	11,280	11,161
Other	11,180	7,556	7,527	7,369	7,764	7,466	7,922	8,499	8,658	8,367

Source: QFER CEC-1304 Power Plant Data Reporting.

For cogeneration plants, fuel usage rates and the corresponding GHG emission rates have remained relatively flat over this 10-year time frame. California's cogeneration plants operate at high capacity factors (59 percent) and at relatively high heat rates (11,161 Btu/kWh for 2010). Over the past 10 years, the heat rate of CHP plants has consistently been above 11,000 Btu/kWh. However, given that these plants are also producing a useful thermal output (heat), it is difficult to assess any efficiency gains related to the useful output of both steam and heat. Thermal quality requirements for industrial applications may impose limitations on achievable electrical efficiency. Conceptually, GHG reductions through efficiency gains within this category are possible if a cogeneration plant loses its thermal host and increases net generation for offsite load, or if it repowers with modern turbines.

Conclusion

California has experienced a significant improvement in the thermal efficiency of its in-state natural gas power plants over the last 10 years. From 2001 to 2010, thermal efficiency has improved 17 percent. This improvement in efficiency is due to the increased reliance upon combined cycle power plants, which are operating at a 50 percent capacity factor. By contrast, aging power plants operate at a 4 percent capacity factor. This thermal efficiency improvement of the state's portfolio of natural gas plants offers a direct reduction in GHGs.