ARTICLE

Same-plant trends in capacity factor and heat rate for US power plants, 2001–2018

Emily Grubert

Georgia Institute of Technology, United States of America

Keywords: committed emissions, natural gas, coal, greenhouse gases, efficiency, capacity factor

Supplementary material for this article is available online

Abstract

This note uses electricity generator level 2001–2018 US capacity, generation, and heat input data to evaluate trends in same-plant capacity factor (how much plants run) and heat rate (how efficiently plants run) as plants age. Based on compound annual growth rates for capacity factor and, for thermal plants, heat rate, and based on the subset of US plants that have been operating since 2010 or earlier, same-plant capacity factors increased slightly, and heat rates decreased slightly, between 2001–2018 (weighted average based on 2018 plant capacity). Trends vary by region, fuel, and plant age. Notably, US natural gas-fired power plants tended to run more, and more efficiently, as they aged, while coal-fired power plants tended to run less, and less efficiently. Potential drivers include relative plant age, policy, financial competitiveness, and an anticipated tendency for plant operators to react to the effects of equipment aging with maintenance, repair, replacement, and optimization. These observations can inform committed emissions-based research, which requires making assumptions about how plant operational characteristics change (or do not) as they age.

Introduction

As of 2018, the United States (US) had nearly 10 000 operational power plants [1], with fossil fuel-fired power plants accounting for about 65% of net generation [2]. Power plants are long-lived infrastructure, often operating for several decades, which motivates investigation of the profile of plants expected to continue to operate well into the future [3]. Given impacts including climate change, air pollution, water use, and environmental injustice [4–6], the future operational profiles of fossil fuel-fired power plants are of particular interest.

The impacts of running existing plants through their retirement, including greenhouse gas (GHG) emissions, are ‘committed’ impacts [7]. Particularly in the context of climate change, understanding committed GHG emissions associated with existing power plants is relevant for informing policy choices, infrastructure planning, and efforts to address environmental injustice. Estimates require making assumptions about the future. For example: is it appropriate to assume that a power plant’s future emissions will match its past emissions? If so, which past emissions?

It is reasonable to assume that a plant’s operational profile might change over time. Fuel dynamics, like water availability for hydroelectric plants or fuel price volatility for natural gas plants, can be a major driver of variability. Overall policy and market dynamics, like electricity prices or competition from other resources, might also influence how often and how efficiently plants run. Other parameters are more directly related to the plant itself. For example, plants might become less efficient as they age, tending to increase emissions; but operators might respond to signs of degradation with repairs or upgrades, tending to decrease emissions. Similarly, plants might run less often as they age due to increasing maintenance needs, tending to decrease emissions, or they might run more often due to lower concern about preventive maintenance as a plant approaches retirement, tending to increase emissions.
Recognizing that factors that can affect power plants’ future operational profiles are numerous and varied, this note presents an empirical investigation of historical trends in US power plant operational parameters relevant for informing committed impact analyses.

Methods

This note asks: how do same-plant capacity factor and heat rate at US power plants change as the plants age, and how does this vary by fuel, region, and plant age? Capacity factor is a measure of how much power plants run, defined as actual generation divided by potential generation: a lower capacity factor correlates with lower absolute emissions, but also lower generation [8]. Heat rate is a measure of power plant efficiency, defined as thermal input divided by thermal content of output: a lower heat rate correlates with a lower rate of emissions per unit of generation [9]. Here, both are evaluated at the plant level over the 2001–2018 time period for which the United States Energy Information Administration (EIA) reports power plant capacity, generation, and fuel consumption for electricity on Forms 906/920/923 [1] and 860 [10].

Plant code, plant name, energy source, prime mover, and operating year were taken from Form 860 at the generator level. Entries were aggregated to the power plant level based on plant code (which might include multiple generating units using different fuels and technologies), in part because of a lack of a unique generator-level identifier associated with generation and capacity data.

The analytical sample is all US power plants with (1) recorded 2018 final data on EIA Forms 860 and 923 [9179 plants with 1196 gigawatts (GW) of 2018 capacity], (2) a listed North American Electric Reliability Corporation (NERC) region (9005 plants, 1191 GW) (figure 1; note that Alaska and Hawaii are included in national but excluded from regional analyses), and 3) at least one unit that has operated since 2010 or earlier with at least one year of positive net generation, given the goal of investigating year-over-year changes (5292 plants, 1018 GW). For the heat rate analysis, the sample was further restricted to thermal power plants using only one fuel type (2794 plants, 730 GW), to ensure that heat rate trends do not reflect fuel switching. Data and calculations can be found in the supplementary data File (SI) is available online at stacks.iop.org/IOPSN/1/024007/mmedia.

Change in capacity factor and heat rate over time are measured as compound annual growth rates (CAGR) at the power plant level, for the portion of 2001–2018 for which EIA has relevant data for a given plant. Averages are capacity-weighted averages based on the reported 2018 capacity of each power plant in the sample used to generate the average. Complete data and calculations are available in the SI, with plant-level analysis on the sheets ‘Capacity Factor’ and ‘Heat Rate’.

In general, data from EIA were assumed to be correct. Data cleaning was limited to the removal of negative capacity factors (often associated with pumped storage hydroelectricity and generators requiring some correction) and thermodynamically impossible heat rates (i.e., those implying ≥100% efficiency). Capacity factors of zero were not removed. Implausible heat rates, such as those reflecting very high (>60%) or very low (<10%) thermal efficiency, were not removed because of the potential for legitimate operational reasons for
unusual readings. For example, very low reported efficiency can reflect nonproductive fuel use for testing, and very high efficiency might be due to use of unpurchased waste heat (e.g., at a refinery) that is not recorded as fuel.

Results and discussion

Capacity factor

Same-plant capacity factors at US power plants rose slightly between 2001–2018, based on a capacity-weighted average. For the 5292 US plants that were operating by 2010 and were still operational in 2018, the capacity-weighted average plant-level capacity factor CAGR is 0.3% (weighted by each plant’s 2018 capacity) and suggests that on average for this analytical period, a given unit of US power generating capacity produced slightly more electricity per year as it aged. This result suggests that a simple assumption that plant output remains constant on average is likely acceptable for general committed emissions estimates: system-wide degradation is not observed.

For higher resolution analyses, note that capacity factor results vary by fuel, region, and plant age during the analytical period. Figure 2 shows that for the NPCC and MRO regions, the capacity-weighted average plant-level capacity factor CAGR is negative. Variability by region could be related to fuel mix. As figure 3 shows, coal plant capacity factors declined on average as the plants aged, while natural gas, wind, and solar capacity factors grew on average as the plants aged. Very high CAGR for wind and solar facilities (figure 3(b)) could be due to extremely low first-year capacity factors for some plants, possibly related to nuances of the way that federal production and investment tax credits motivate owners to begin operations before the end of a given year to secure the tax credit.

This fuel-specific variability relates to regional variability: as figure 4 shows, fuel mixes vary significantly by region.

Figure 5 shows the impact of plant age on capacity factor CAGR. Each point on the chart represents all plants whose capacity-weighted first year of operations across all generators corresponds to the year on the horizontal axis. That is, if a power plant has one 100 MW generator that came online in 1990 and another 100 MW generator that came online in 2000, the plant is in the 1995 cohort in figure 5.

Figure 5 suggests that plants with the oldest and newest generators tend to increase their capacity factors year over year (CAGR is positive). As this analysis defines plant age based on the capacity-weighted operating year, this result could reflect new unit additions: that is, capacity factor might grow quickly in the early years of a given unit’s operations, and very old plants might experience new unit additions more frequently than middle-aged plants. Plants with capacity that is on average 70 to 40 years old show a tendency toward year-over-year capacity factor declines, potentially related to higher maintenance requirements, declining financial competitiveness, or other factors.

Heat rate

Heat rates are evaluated only for thermal plants using a single fuel that were online before 2010, which encompasses 2864 plants (730 GW of capacity). Analysis is restricted to single-fuel plants because heat rate is fuel specific [11], thus excluding 490 thermal plants (166 GW of capacity) with multiple fuels.

Heat rates at US single-fuel thermal power plants decreased over the analytical period, meaning they became more rather than less efficient as they aged. For this sample, weighted based on 2018 operational capacity, the average plant-level heat rate CAGR is −0.2%. Like the capacity factor result, this value is essentially 0, suggesting that committed emissions models can reasonably assume no change in heat rate over time at the fleet level. This result does not mean equipment tends to naturally become more efficient as it ages: the observed decline in heat
rate could reflect operational interventions [11], including plant optimization, removal of inefficient or broken parts from service, and potentially retirements of specific units. Figure 6 shows heat rate trends for thermal plants by region.

As with capacity factor, heat rate observations vary by fuel (figure 7).

Most notably, same-plant efficiency declines at US coal-fired power plants, rises at natural gas plants, and stays stable at nuclear plants during the analysis period. This result could be due to multiple factors. Figure 3 shows that natural gas plants have tended to run more over time, while coal plants have tended to run less: for large thermal generators, efficiency can be higher when plants are running consistently at or near full capacity (rather than turning on and off frequently), so this capacity factor trend could be influencing efficiency. Also,
coal-fired power plants have been more subject to additional environmental controls over time than natural gas-fired power plants, which could contribute to lower net generation efficiency [12].

Figure 8 shows that the oldest plants tend to have either high increases or high decreases in heat rate over time, potentially reflecting both the tendency for equipment to become less efficient as it ages and the tendency for operators to invest in repairs.

This analysis only covers 2001–2018, so plants that have been operating since the 1930s or 1940s have been ‘old’ during the entire analytical period. The newest plants in the sample tend to show declining heat rates over time, potentially reflecting learning and optimization at the plant. Middle-aged plants show essentially no heat rate variability during the period of analysis, which might reflect situations where ongoing optimization and tweaks counter the effects of aging, but conditions have not sufficiently deteriorated to merit major investments.

**Conclusions**

For the 2001–2018 period of available EIA data, US power plants have tended to display slight increases in capacity factor and, for single-fuel thermal plants, slight increases in efficiency as they age. Although this finding suggests that it is reasonable to assume that emissions intensity per unit of output does not change significantly
Figure 7. Plant-level heat rate average CAGR by fuel, weighted by 2018 plant capacity, based on 2001–2018 data.

Figure 8. Plant-level heat rate average CAGR by capacity-weighted operational year, weighted by 2018 plant capacity, based on 2001–2018 data.
as plants age, the average masks an important difference between natural gas and coal plants. That is, capacity factor and efficiency tend to grow as the natural gas plants in this sample age, while the opposite is true for the coal fleet. Drivers might include age during the analytical period, regulatory action, market competition, and mechanical conditions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

ORCID iDs

Emily Grubert  © https://orcid.org/0000-0003-2196-7571

References

[1] EIA 2020 Form EIA-923 detailed data with previous form data (EIA-906/920)
[2] EIA 2020 Electricity data browser—Net generation for all sectors
[3] Grubert E, Stokes-Draut J R, Horvath A and Eisenstein W 2020 Utility-specific projections of electricity sector greenhouse gas emissions: a committed emissions model-based case study of California through 2050 Environ. Res. Lett. (https://doi.org/10.1088/1748-9326/abb7ad)
[4] Huijbregts M A J, Hellweg S, Frischknecht R, Hendriks H W M, Hungerbühler K and Hendriks A J 2010 Cumulative energy demand as predictor for the environmental burden of commodity production Environ. Sci. Technol. 44 2189–96
[5] Tessum C W et al 2019 Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure PNAS 116 6001–6
[6] Grubert E and Sanders K T 2018 Water use in the United States energy system: a national assessment and unit process inventory of water consumption and withdrawals Environ. Sci. Technol. 52 6695–703
[7] Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y and Davis S J 2019 Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target Nature 572 373–7
[8] EIA 2020 What is the difference between electricity generation capacity and electricity generation? https://www.eia.gov/tools/faqs/faq.php?id=101&t=3
[9] EIA 2020 What is the efficiency of different types of power plants? https://www.eia.gov/tools/faqs/faq.php?id=107&t=3
[10] EIA 2020 Form EIA-860 detailed data with previous form data (EIA-860A/860B) https://www.eia.gov/electricity/data/eia860/
[11] EIA 2015 Analysis of Heat Rate Improvement Potential at Coal-Fired Power Plants https://www.eia.gov/analysis/studies/powerplants/heatrate/pdf/heatrate.pdf
[12] Brown M A, Li Y, Massetti E and Lapsa M 2017 US sulfur dioxide emission reductions: shifting factors and a carbon dioxide penalty Electr. J. 30 17–24