Andover Technology Partners 978-683-9599
Consulting to the Air Pollution Control Industry

CO_2 and NOx Emissions from Natural Gas Combined Cycle and Natural Gas Combustion Turbine Power Plants

Released 2023

Andover Technology Partners
1 Surf Village, Unit B
Manchester-by-the-Sea, MA 01944
phone: (978) 884-5510; e-mail: staudt@AndoverTechnology.com

Andover Technology Partners
1 Surf Village, Unit B, Manchester-by-the-Sea, MA 01944

This is a report that is based upon analysis performed in 2021. It was not released at that time. ATP decided to release this report recently because of its relevance to greenhouse gas emissions and NOx emissions.

As described in more detail herein, all of the analysis in this report is based upon publicly available data.

Contents

Figures

Tables

Executive Summary

The purpose of this effort was to evaluate CO_2 and NOx emissions from natural gas combined cycle (NGCC) plants and natural gas combustion turbine (NGCT) plants and to evaluate the impact of selective catalytic reduction (SCR) on NOx and N_2O emissions.

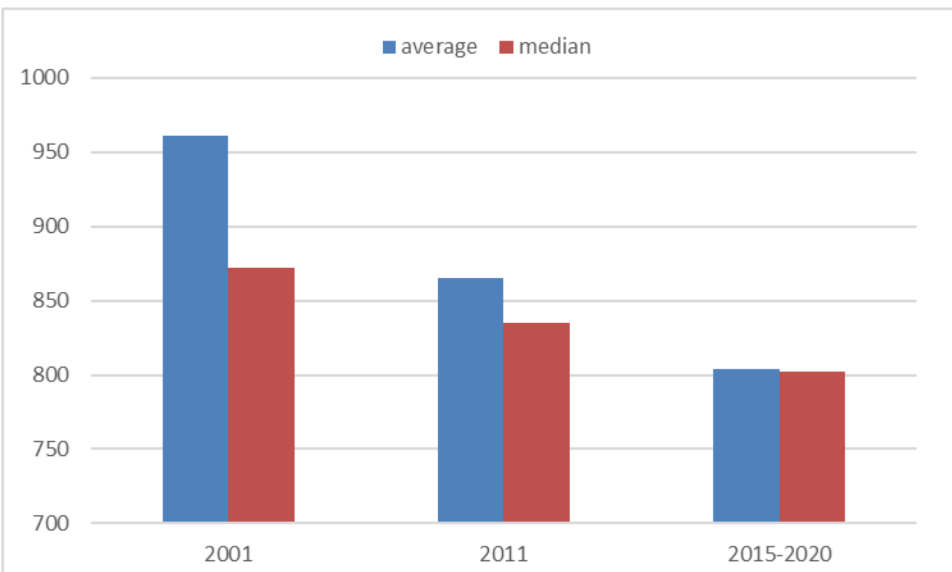
For all emission rates discussed in terms of lb/MWh, the MWh are MWh gross, as taken from US EPA's Air Markets Program Data. All data utilized in this effort are taken from US EPA's Air Markets Program Data for the relevant years or from US Department of Energy's Energy Information Administration (EIA) form 860.

A. Conclusions regarding Natural Gas Combined Cycle (NGCC) Power Plants

1. CO_2 Emissions

CO_2 emission rates have steadily declined for NGCC plants over the past 20 years. Figure ES-1 shows average median 2020 CO_2 emission rates for units placed in service in 2001, 2011, and in the years from 2015 to 2020. As shown there has been a steady decline as NGCC technology has improved. As will be shown later, emission rates for new units often improve in the first few years, meaning that the new units built from 2015-2020 will likely have lower emissions in the future.

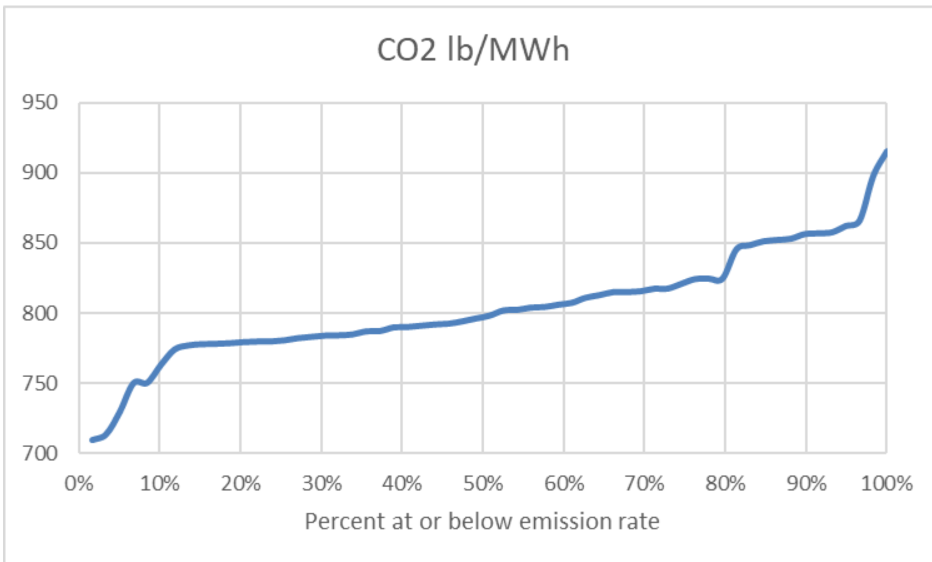
Figure ES-1. Average and median 2020 CO_2 emission rates for NGCC plants based upon year placed in service (lb/MWh).



CO_2 emissions from NGCC plants were examined for the relationship against various operating characteristics. Data was examined for all NGCC plants operating in 2020 as well as for new NGCC units that commenced operation in 2015 or later. It was determined that some units operate as simple cycle units for at least a substantial part of their time, as indicated by much higher CO_2 emission rates than expected for a NGCC unit. Units the generate over about 1.7 million MWh per year typically operate 100% in combined cycle mode while, at lower generation rates, some units operate in simple cycle mode.

It was not unusual for newly constructed units to operate for a year or so largely in simple cycle mode, resulting in a higher emission rate. All newly constructed units (2015 or newer) operating in 2020 in primarily combined cycle mode had emission rate distribution as shown in Figure ES-2. As shown, 90% had and average annual emission rate at or below 856 lb/MWh. 80% had emission rates of about 825 lb/MWh or less. This demonstrates that emission rates below 800 lb/MWh are achieved by at least half of the units.

Figure ES-2. Emission rate distribution for 2020 CO_2 emissions for units installed 2015 – 2020, percent at or below emission rate.



2. NOx Emissions

NOx emissions on NGCC plants have dropped dramatically since 2001. This has been in large part due to advances in both NGCC combustion technology as well as post-combustion NOx reduction technology. Figures ES-3a and 3b shows average 2020 NOx emissions for NGCC plants placed in service in 2001, 2011 and between 2015-2020. Although average 2020 NOx emissions for new units are similar to those placed in service in 2011, median NOx emissions have dropped, indicating that there are fewer high emission units and that emission rates are generally declining

Figure 3a. Average and median 2020 NOx emissions for NGCC plants placed in service in 2001, 2011 and between 2015-2020 (lb/MMBtu)

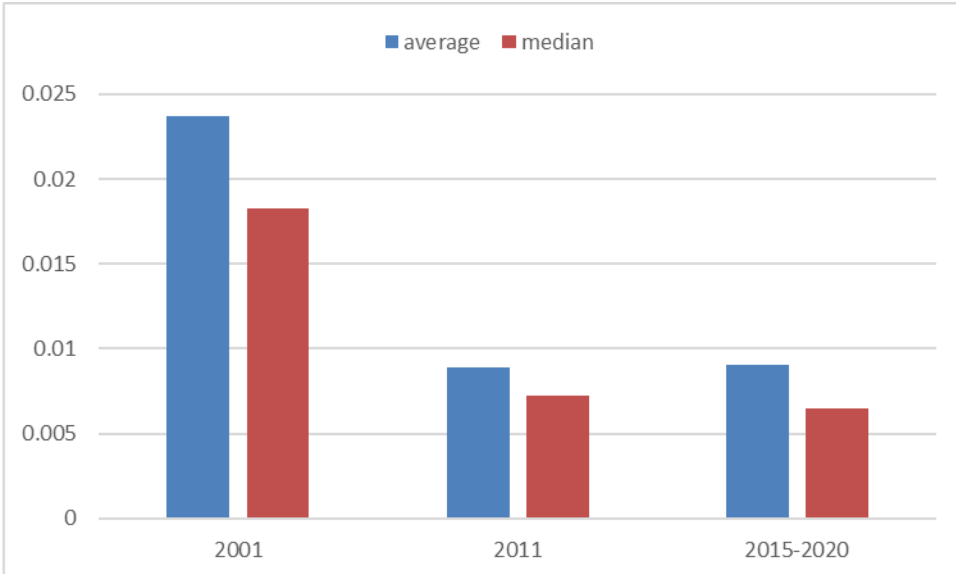
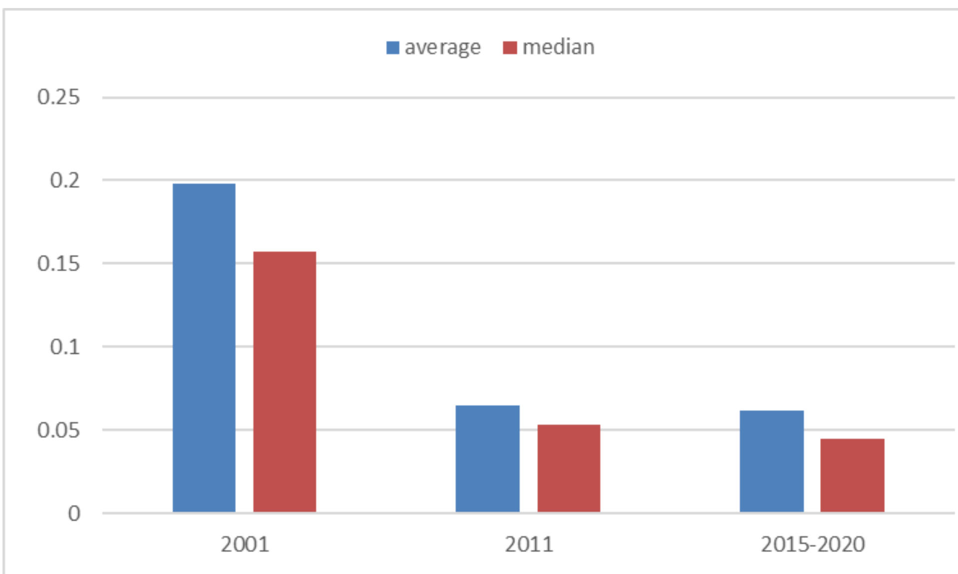


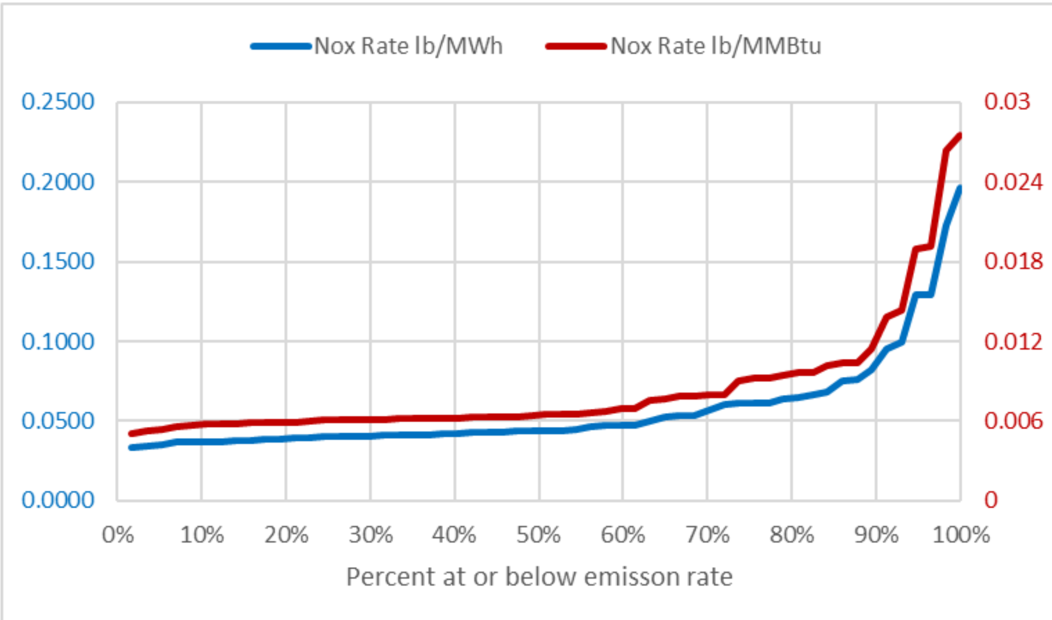
Figure 3b. Average and median 2020 NOx emissions for NGCC plants placed in service in 2001, 2011 and between 2015-2020 (lb/MWh)



NGCC units are commonly equipped with SCR. Only two of the new NGCC units built since 2015 did not have SCR, and these units may have avoided BACT requirements due to specific issues relating to that site.

Figure ES-4 shows 2020 NOx emission rate and the percent at or below the emission rate for those units with SCR (all but the two at Cane Run). The curves of the figure are very flat for most of the units, and start to turn up at around 70% of the units, with the slope growing steeper. As shown, 90% of the units have NOx emission rates at or below 0.082 lb/MWh or 0.0114 lb/MMBtu. It is unclear why the five other units do not achieve lower emissions, or why the slope of the curve increases so steeply above 90% (emissions are much higher) for the remaining five units.

Figure ES-4. Emission rate distribution for 2020 NOx emissions (units with SCR), percent at or below emission rate



3. N_2O emissions

N_2O emissions are a potent greenhouse gas, and N_2O emissions are a concern for any SCR-equipped system. N_2O emissions from diesel engines have received a great deal of attention, and most research on N_2O emissions from SCR systems (and oxidation catalyst systems) have been the focus of research. The main reason is that conditions in diesel exhaust are such that N_2O emissions are expected to be much higher than for gas turbines. A principal reason is that NOx emission concentrations from gas turbines generally tend to be much lower than for diesel engines. There are other factors as well that are described in this document.

In any event, this is an area where more information may become available in the future, and US EPA, DOE and manufacturers should be encouraged to conduct research in this area because of the importance of natural gas power generation.

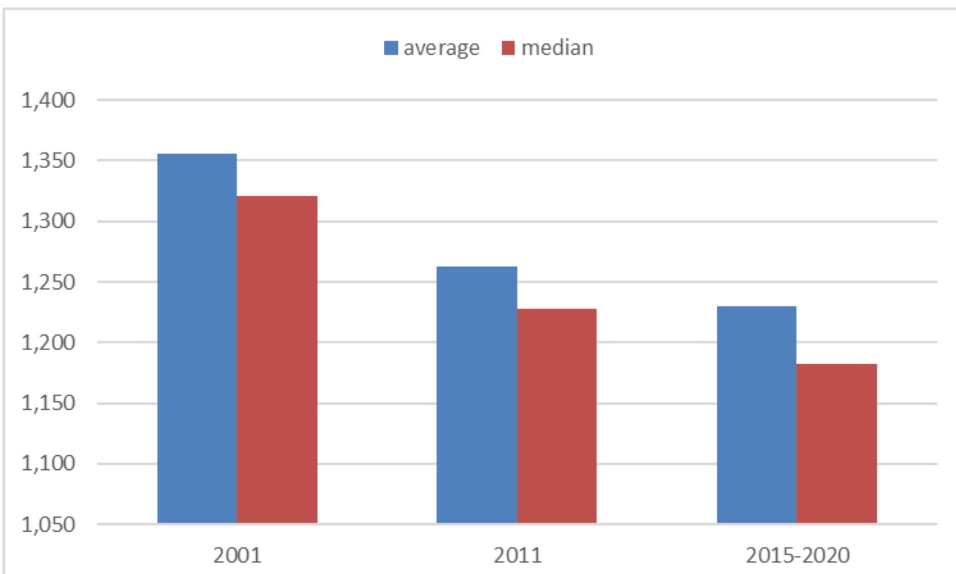
B. Conclusions regarding Natural Gas Combustion Turbine (CT) Power Plants

1. CO_2 Emissions

CO_2 emissions from CT plants was examined for the relationship against various operating characteristics. Data was examined for all CT plants operating in 2020 as well as for new CT units that commenced operation in 2015 or later.

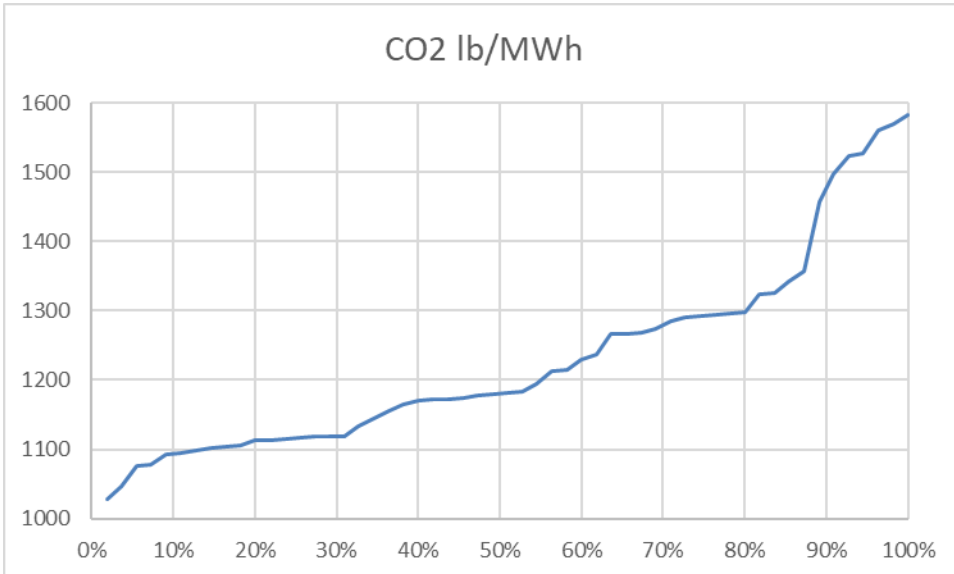
CO_2 emission rates have steadily declined for CT plants over the past 20 years. Figure ES-5 shows average 2020 CO_2 emission rates for units placed in service in 2001, 2011, and in the years from 2015 to 2020. As shown there has been a steady decline as CT technology has improved. As will be shown later, emission rates for new units often improve in the first few years, meaning that the new units built from 2015-2020 may have lower emissions in the future.

Figure ES-5. Average and median 2020 CO_2 emission rates (lb/MWh) for CT plants based upon year placed in service.



The average 2020 CO_2 emission rate for new CT units installed since 2015 is 1230 lb/MWh with a standard deviation of 141 lb/MWh. Figure ES=6 shows the emission rate distribution for the 55 CT units built since 2015. It shows that 80% of all units have emission rates under 1,300 (1,298) lb/MWh and 90% with emission rates below 1,500 (1497) lb/MWh, with the highest emitter at under 1600 (1583) lb/Mwh. However, over 50% of the units achieve rates under 1,200 lb/MWh and over 30% achieve emission rates under 1,120 lb/MWh.

Figure ES-6. Emission rate distribution for 2020 CO2 emissions (CT units) for units built since 2015, percent at or below emission rate



2. NOx Emissions

The NOx emission rates for CT units are very dependent upon whether or not a unit is equipped with SCR. A BACT analysis will normally determine whether or not SCR is installed on a CT plant or whether it is not equipped with SCR, but only combustion controls. Over time, the likelihood of SCR being utilized on a CT plant has increased. Moreover, there were only 13 new electric utility natural gas CTs installed in 2011, seven with SCR and six without. This compares to 222 natural gas CTs in 2001 (the peak year for natural gas CT installations) and 54 over the 2015-2020 period. So, comparisons for 2011 against other years should not be considered precise due to the small number in the sample. In any event, Figures ES-7a and 7b demonstrate that NOx emission rates have dropped a great deal since 2001, largely due to improvements in low NOx combustion technology and more widespread use of SCR.

Figures ES-8 and ES-9 show the NOx emission rate distribution for all natural gas CT units installed since 2015 in terms of lb/MMBtu or lb/MWh, respectively. As expected, the emission rate for units equipped with SCR is well below the emission rate for units without SCR. As these figures show, 61% of those units without SCR and 97% of those units with SCR have emission rates at or below 0.05 lb/MMBtu. On the basis of lb/MWh, all units with SCR and 61% of units without SCR have emission rates at or below 0.50 lb/MWh. These rates are being achieved by CT units even at low average annual operating hour rates.

Figure ES-7a. Average and median 2020 NOx emissions for CT plants placed in service in 2001, 2011 and between 2015-2020 (lb/MMBtu)

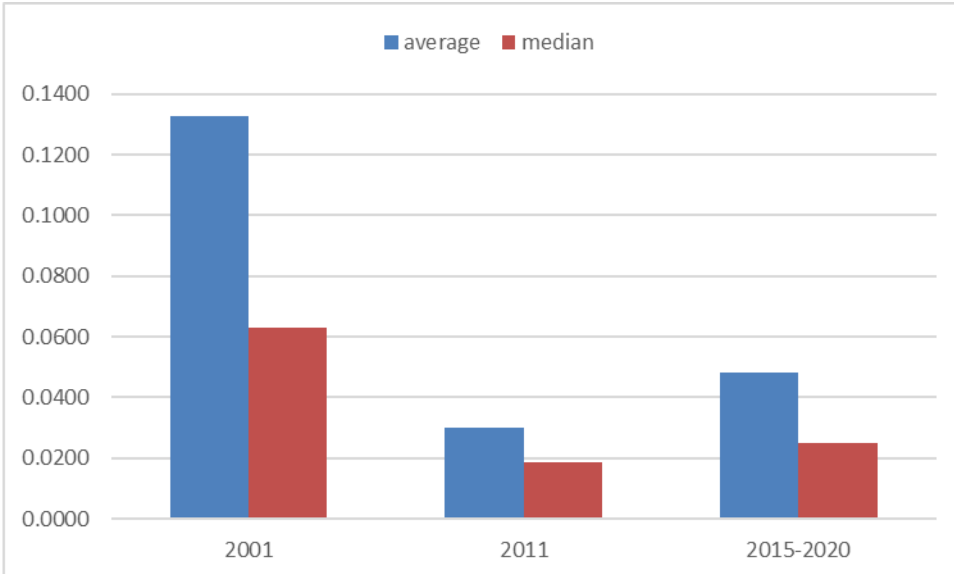


Figure ES-7b. Average and median 2020 NOx emissions for CT plants placed in service in 2001, 2011 and between 2015-2020 (lb/MWh)

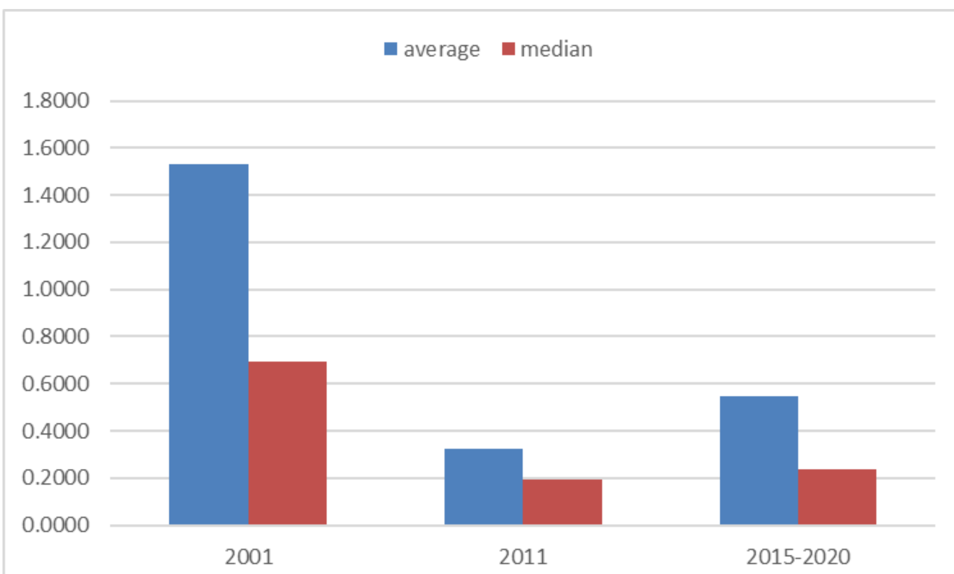


Figure ES-8. Emission rate distribution for 2020 NOx emissions (CT units) for units built since 2015, percent at or below emission rate – all units, lb/MMBtu, without SCR, with SCR

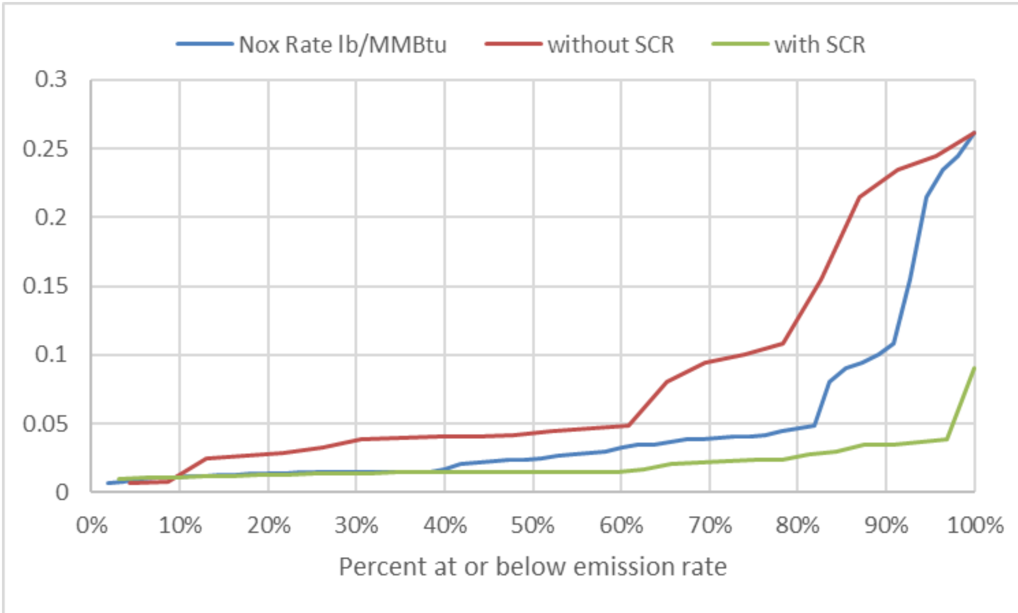
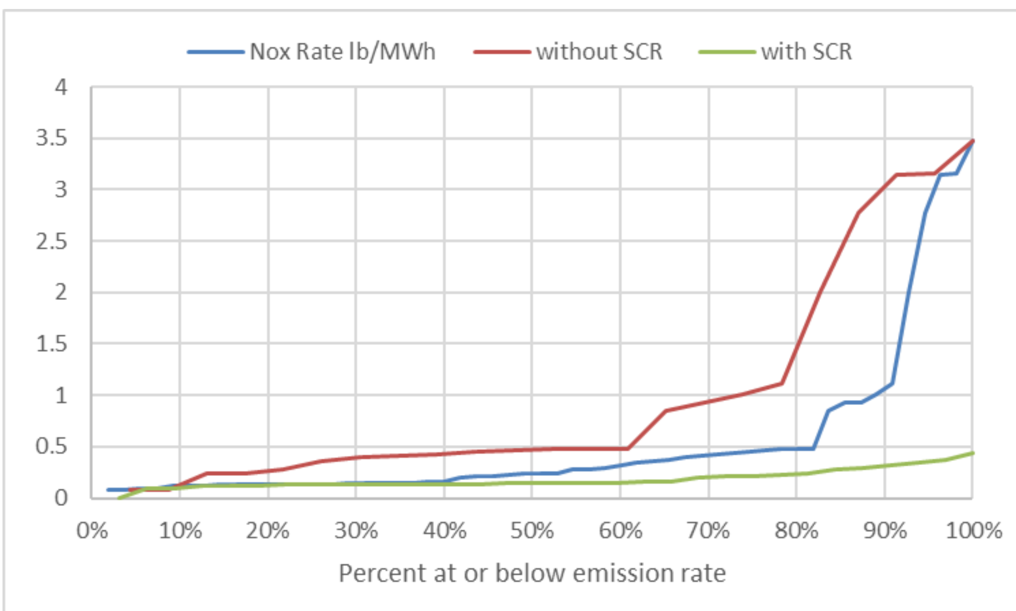


Figure ES-9. Emission rate distribution for 2020 NOx emissions (CT units) for units built since 2015, percent at or below emission rate– all units, lb/MWh without SCR, with SCR



3. N_2O emissions

Although N_2O can be generated from gas turbines equipped with SCR, the information that is available appears to suggest that it will usually be a fairly small amount. This is an area that will require additional attention in the future as more information is gathered.

The attention on N_2O emissions from SCR has been focused on diesel engines due to the high NOx emissions from diesels, and therefore high potential N_2O emissions. However, given the widespread use of natural gas in power generation, it is recommended that research programs be conducted to examine this phenomenon with respect to SCR on NGCC plants and CTs.

I. NGCC Power Plants

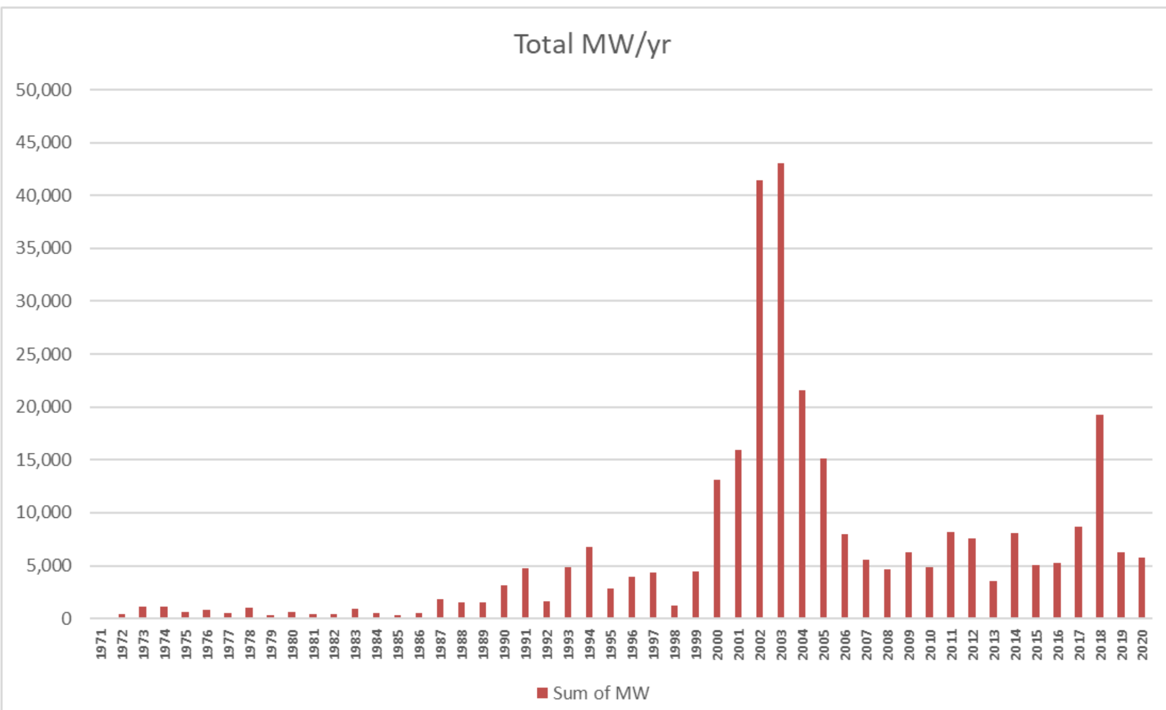
A. Historical installations of NGCC power plants

The history of installations of NGCC power plants is shown in Figure 1. As shown, there was a very large peak in installations in 2002 and 2003, and in 2018 installations were about 19 thousand MW of capacity. Otherwise, in recent years installations have been in the range of 5,000 MW per year.

As Figure 2 shows, average NGCC plant size has increased over the past several decades, with average size of roughly 200 MW in the 1970s to roughly 700 MW today, with some higher. The impact is that these larger turbines may have other differing characteristics. Theoretically, larger turbomachines are more efficient.[1] Also, more recent NGCC plants may have other technological advantages in terms of efficiency or emissions.

While CO_2 emission rates for natural gas power plants are a direct function of the efficiency of the turbine, NOx emission rates depend upon other factors, such as BACT or LAER analysis, and the resulting emission rate that is required. The large majority of NGCC plants have selective catalytic reduction (SCR) systems. But, a very small number do not. This is because a BACT analysis is case-specific, and will differ from one application to the next.

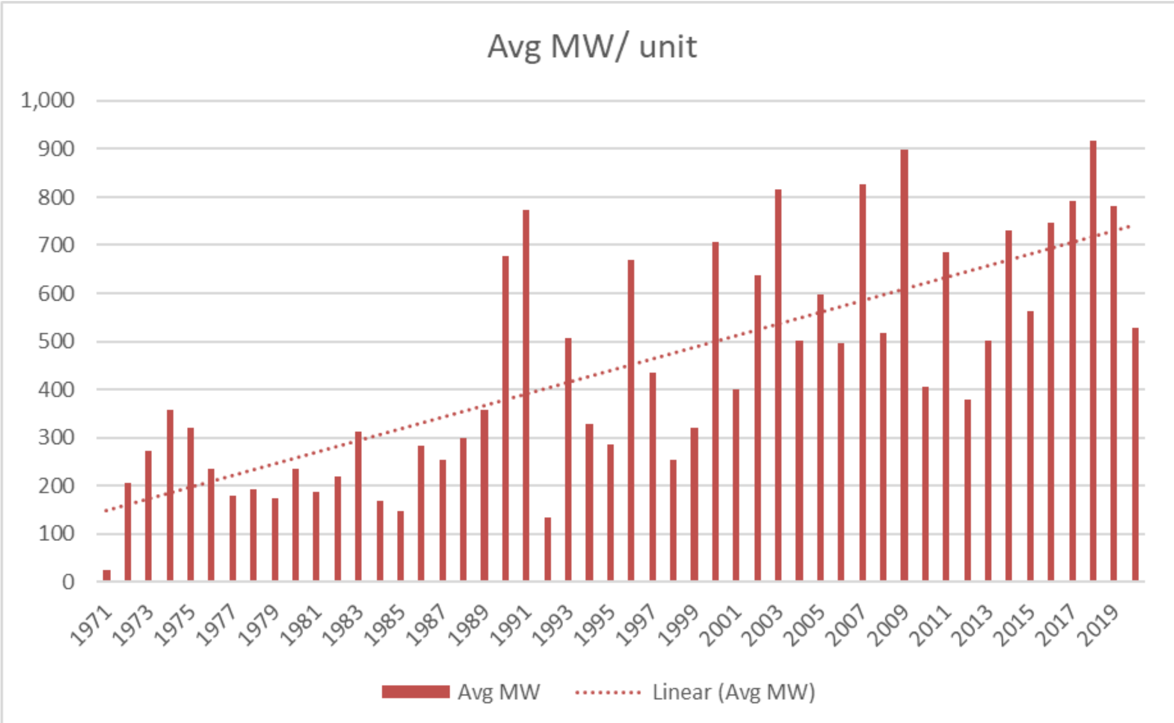
Figure 1. Historical installations of NGCC power plants (nameplate MW installed)[2]



[1] Tip leakage and surface losses per volume flow are lower for larger turbomachines

[2] Developed from EIA Form 860

Figure 2. Average unit size for NGCC plants[3]



B. CO_2 emissions from NGCC power plants

1. Emissions for all units operating in 2020

Figure 3 shows the CO_2 emissions for all NGCC plants reporting into EPA's Air Markets Program data. It shows emissions in 2017 and in 2018. As shown, there is not a great deal of difference between 2017 and 2020 emissions. Importantly, this shows annual emissions rates. The data plots appear to have two loci of points – one with emission rates from under 800 lb/MWh to about 1,000 lb/Mwh and the other from about 1,200 lb/MWh to about 1500 lb/MWh. The reason for these two loci of points is that some of these plants are operating mainly in simple-cycle mode rather than combined cycle mode, and therefore have higher heat rates and emissions rates. Another feature of this figure is that both loci of points drop in value as total generation is increased. This demonstrates that the larger machines that operate the most tend to have the lowest emissions rates. Above about 1.7 million MWh seems to be where simple-cycle operation does not occur. Below that level of generation, some facilities operate in simple cycle mode, while others operate in combined cycle mode, and it is likely that some facilities alternate operation between these two modes.

Figure 4 shows the 2020 CO_2 emission rate data plotted against the maximum rated heat input for the facility, with data from EPA's AMPD. This shows that CO_2 emission rates drop as the unit size increases, which is consistent with larger NGCC plants being more efficient than smaller NGCC plants. Like the data

[3] Ibid

plotted against total generation, there are two loci of points – one consistent with combined cycle operation and the other consistent with simple cycle operation. For those units that are operated in combined cycle mode and are over about 2,000 MMBtu/hr max heat input, the large majority has CO2 emission rates under 900 lb/MWh.

Figure 3. 2020 and 2017 CO_2 average annual emission rate (lb/MWh) for NGCC plants versus gross generation in that year

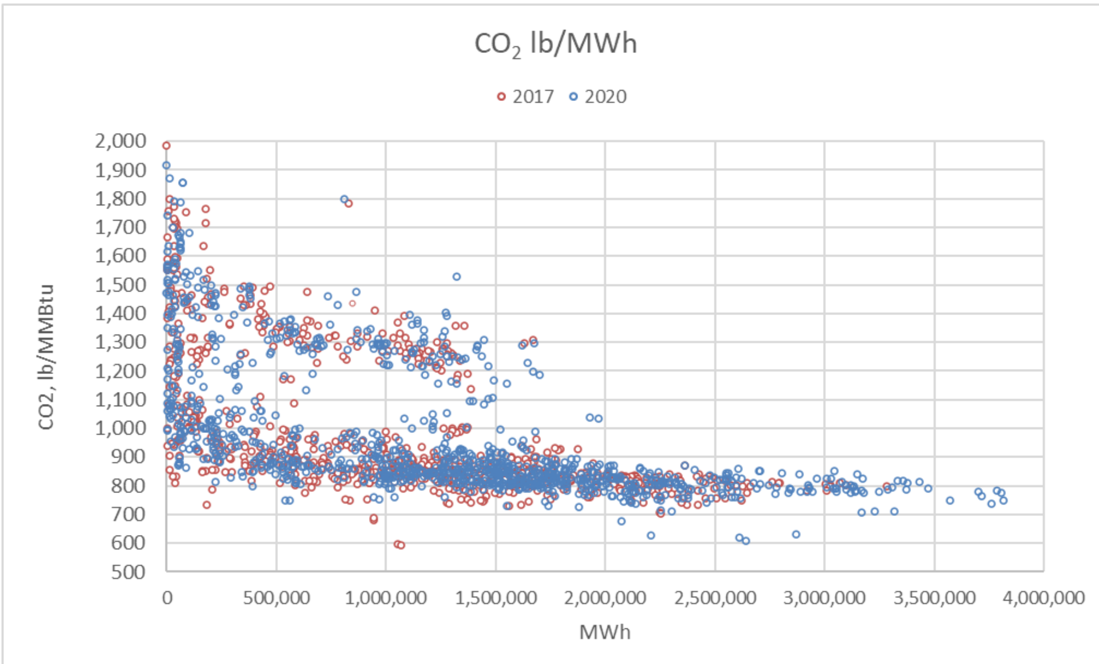
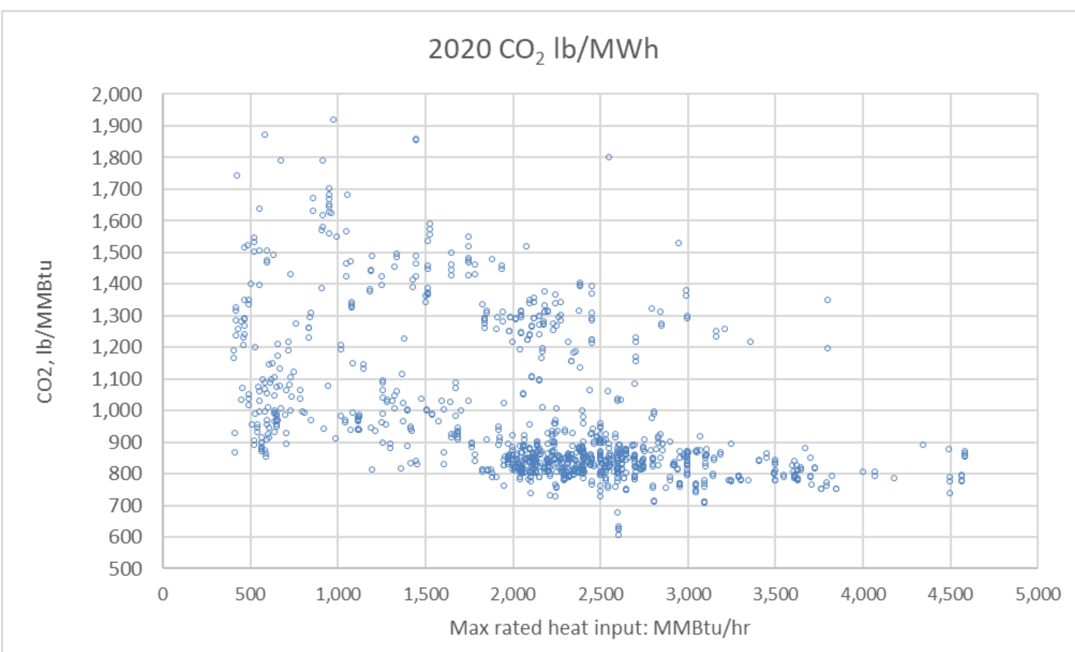


Figure 4. 2020 CO_2 rate versus maximum heat input rate



2. Emissions for new units

While the previous figures include data from all units operating in the given years, facilities that have been installed since 2015 have been examined as well. Figure 5 shows CO_2 emissions data for units installed in 2015 for 2015 and each subsequent year. As shown, while most units installed had CO_2 emission rates below 900 lb/MWh over the entire period of 2015 to 2020, some started at higher emission rates and may have taken a few years to achieve emission rates consistent with what would be expected for a new NGCC plant. Clearly, a few of the facilities took a few years to operate in the NGCC mode rather than the simple cycle mode, as indicated by the reduction of CO_2 emission rates. In fact, Scattergood Generating Station (plant ID 404_4) did not consistently operate in combined cycle mode until 2020. Figures 5 through 9 show similar plots for NGCC plants started in years 2016 through 2019. In a number of situations, the initial years had primarily simple cycle operation that eventually led to consistent combined cycle operation. For Garrison Energy Center (57349_1), a reporting anomaly or error likely accounts for the unexpectedly high CO_2 emission rate.

Figure 5. CO_2 emission rate by year for new units started in 2015

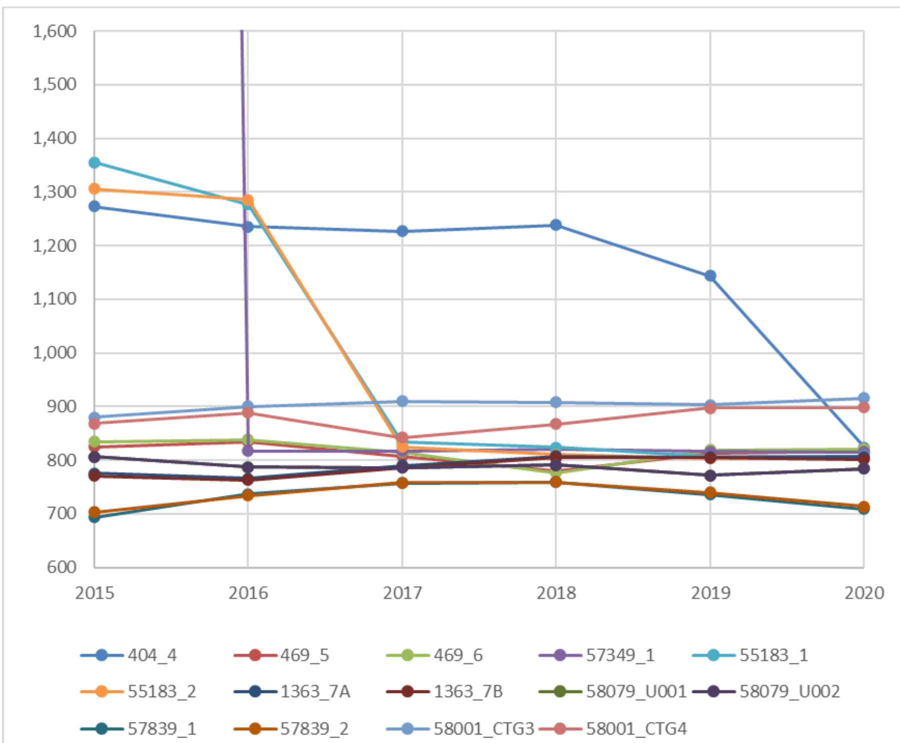


Figure 6. CO_2 emission rate by year for new units started in 2016

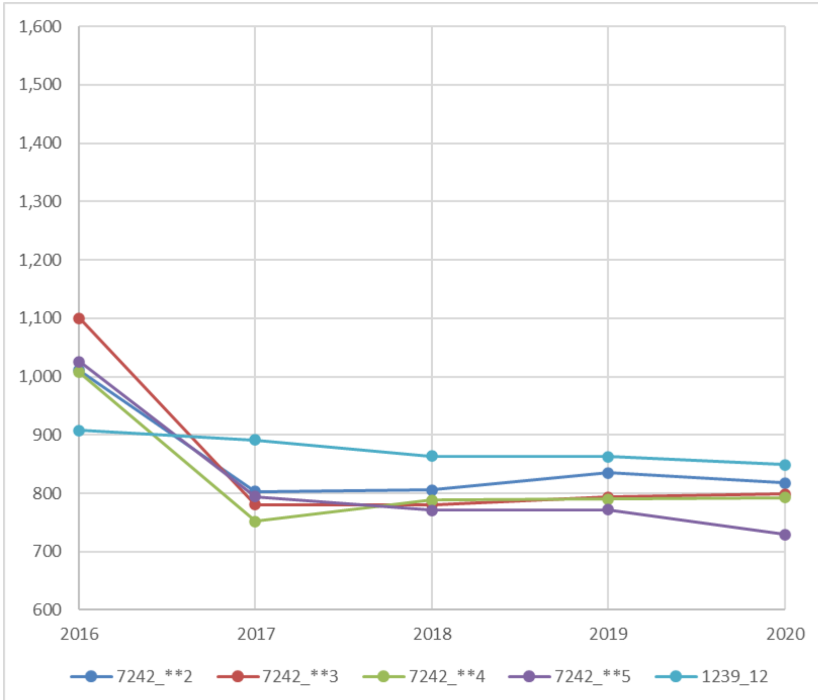


Figure 7. CO_2 emission rate by year for new units started in 2017

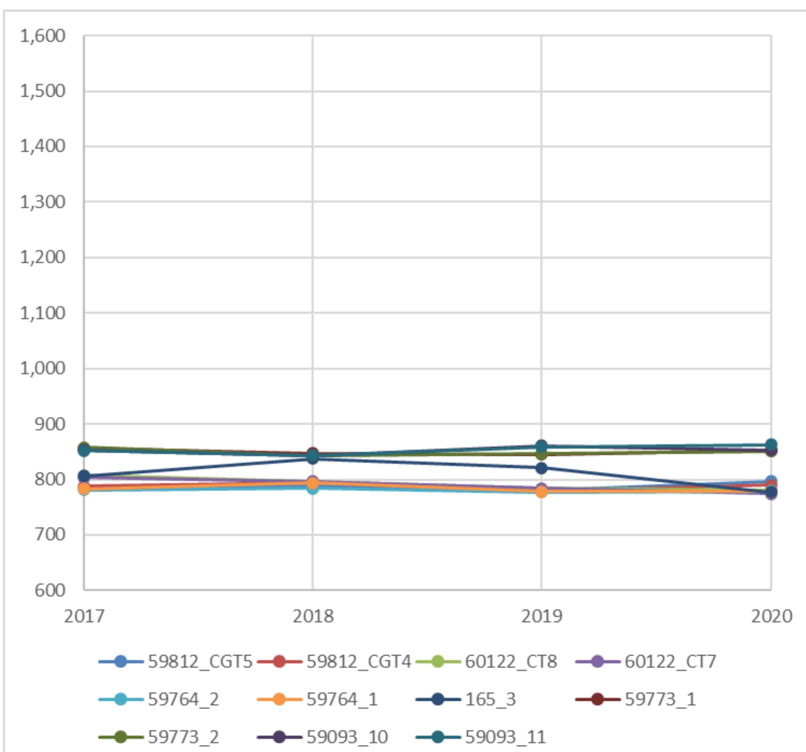


Figure 8. CO_2 emission rate (lb/MWh) by year for new units started in 2018[4]

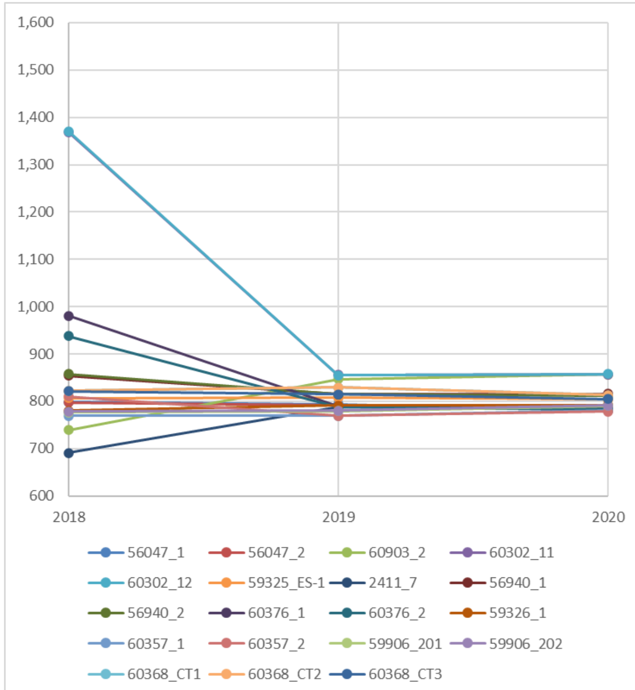
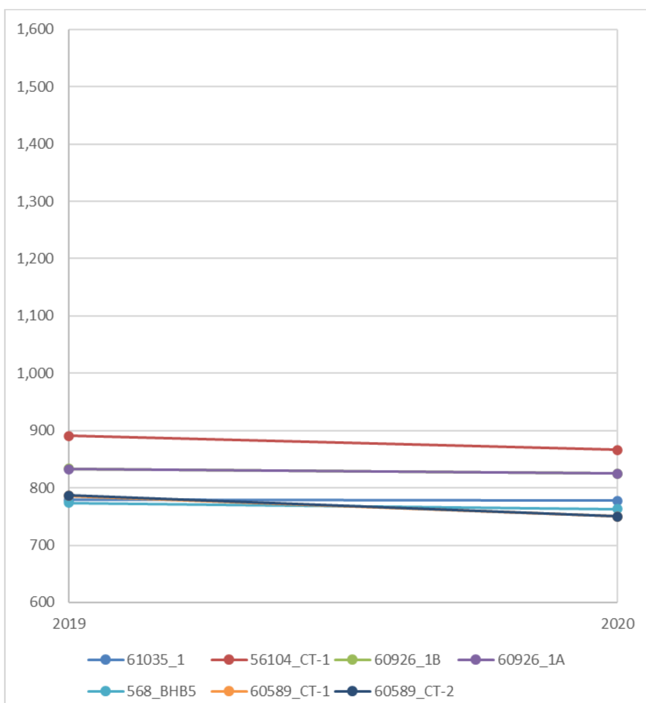


Figure 9. CO_2 emission rate by year for new units started in 2019



[4] Increases in the second year for some unit may be due to a reporting anomaly.

Figures 10 and 11 and 12 show the 2020 annual emission rates for all units that commenced operation in the years 2015 through 2020 plotted against cumulative operating hours, number of years in service, and cumulative MWh, respectively. It is clear that two units started in 2020 only operated for a few hundred hours in simple-cycle mode. Excluding these two units, in every combined cycle case but one, the 2020 CO_2 emission rate was below 900 lb/MWh (and in that case it was 915 lb/MWh).

Excluding the units that were clearly not operating in combined cycle mode, the combined cycle units averaged an emission rate of 804 lb/MWh with a standard deviation of 39 lb/MWh.

Figure 10. 2020 emission rate versus cumulative operating hours for units built since 2015

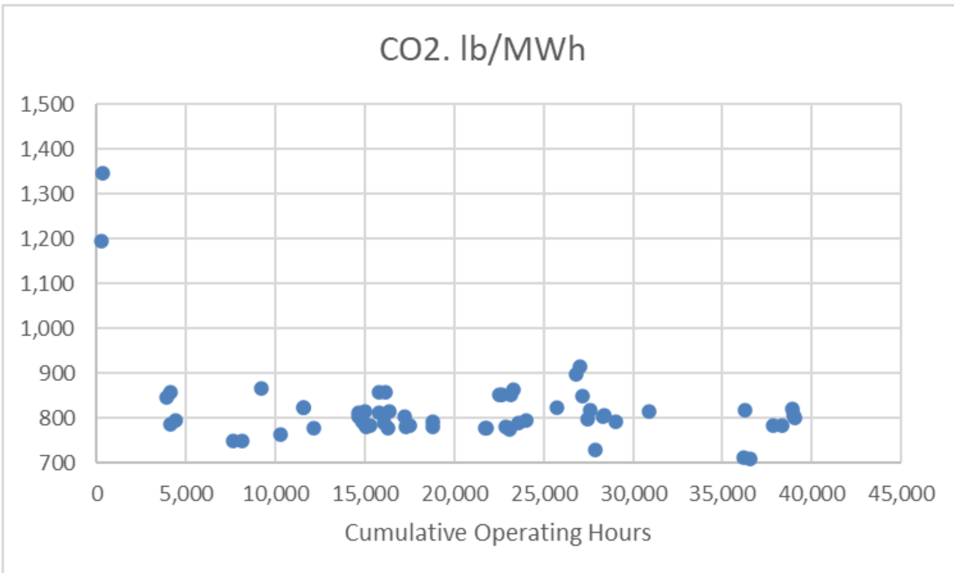


Figure 11. 2020 emission rate versus in service year for units built since 2015

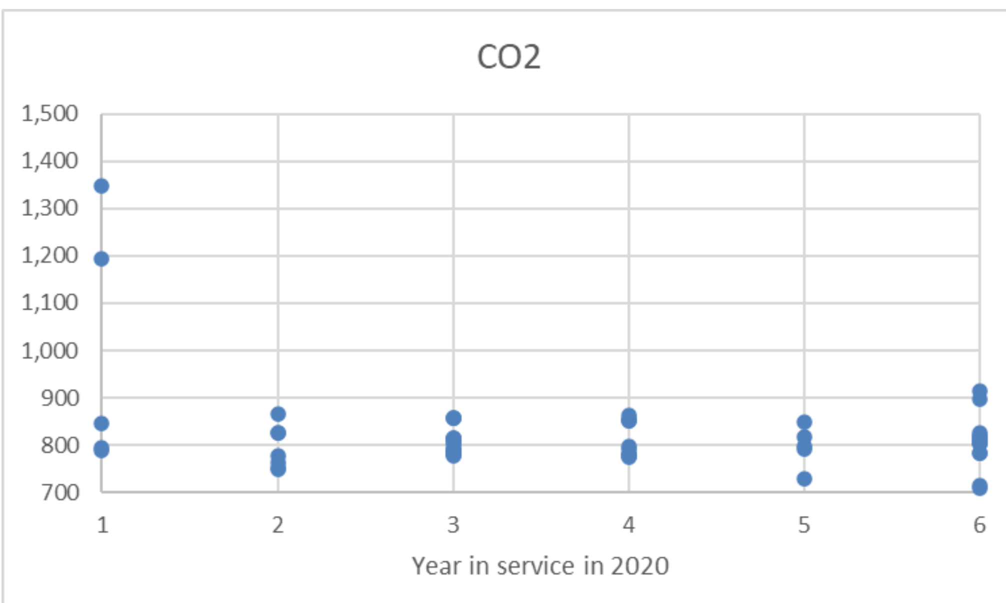
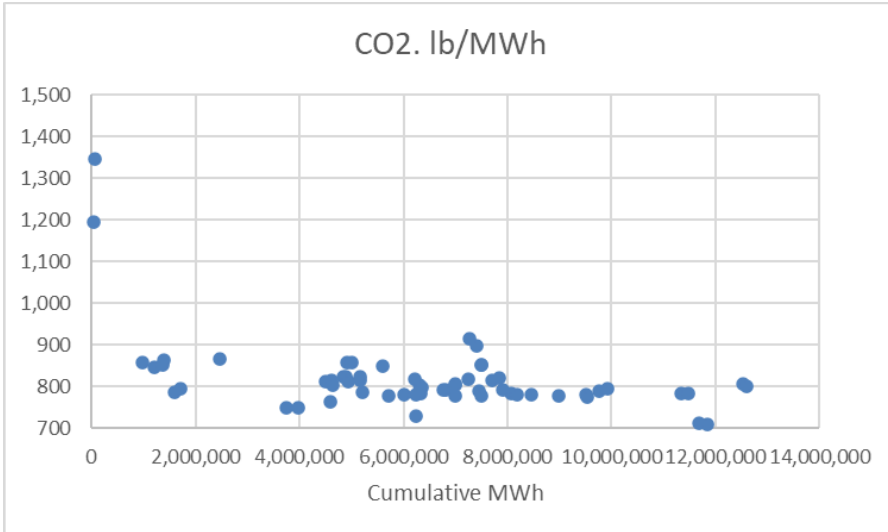
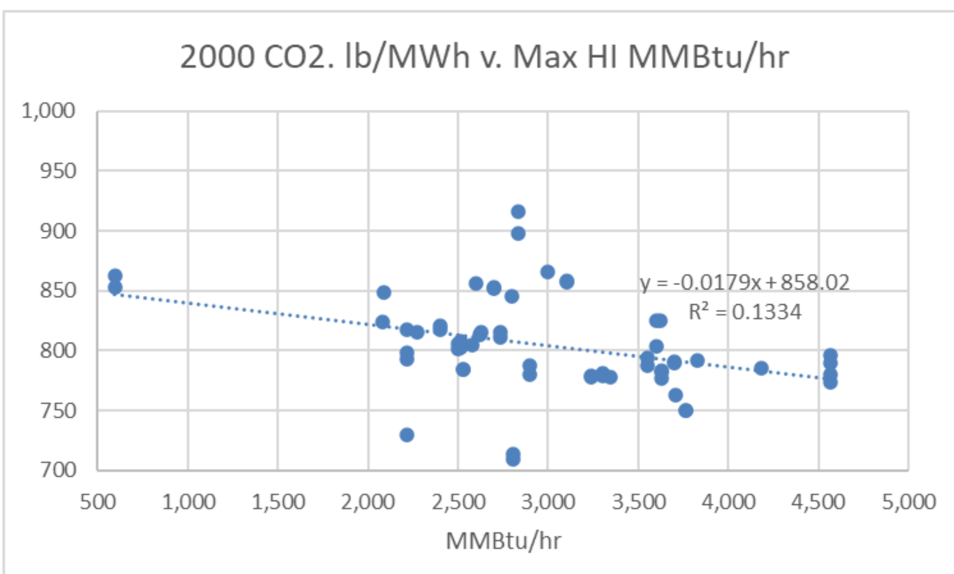


Figure 12. 2020 emission rate versus cumulative MWh for units built since 2015



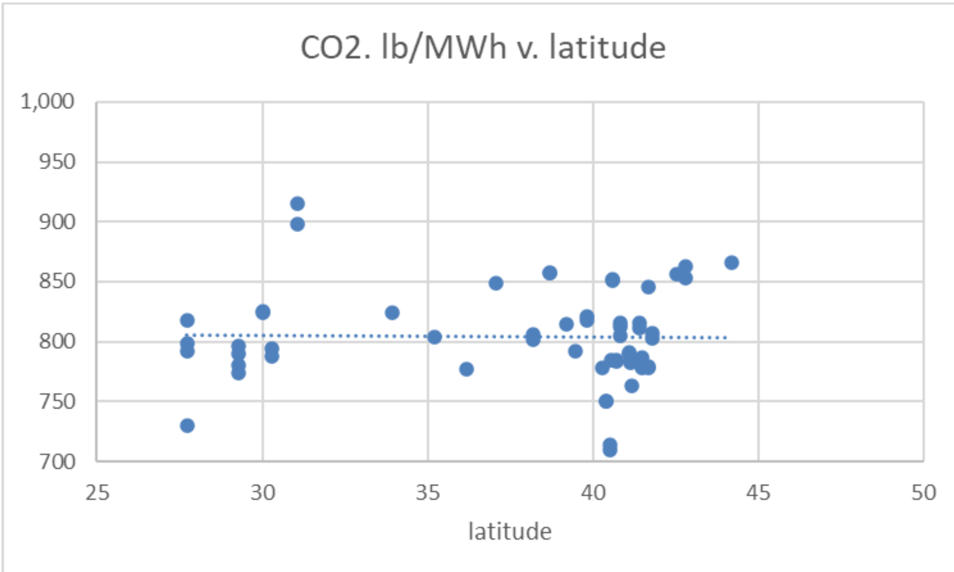
The relationship between CO_2 emission rate and the maximum rated heat input and location was examined for all units with over 1,000 operating hours (excluding the two units installed since 2015 with very few operating hours). Larger combined cycle plants (higher max heat input) had slightly lower CO_2 emission rates than smaller combined cycle plants, as shown in Figure 13. This was a very weak relationship, meaning that other factors play a significant role.

Figure 13. 2020 emission rate versus max heat input for units built since 2015 and over 1,000 cumulative operating hours



The relationship between latitude (as a possible indicator of the temperature of the location) and CO_2 emission rate was also evaluated, and no relationship was found as shown in Figure 14. This is not to say that ambient temperature is not important. It certainly is known to be an important factor with regard to heat rate and CO_2 emission rate. But, this figure shows that factors other than latitude clearly played a much larger role in determining the CO_2 emission rate. Also, latitude alone is not an ideal indicator of ambient temperature.

Figure 14. 2020 emission rate versus latitude for units built since 2015 and over 1,000 cumulative operating hours

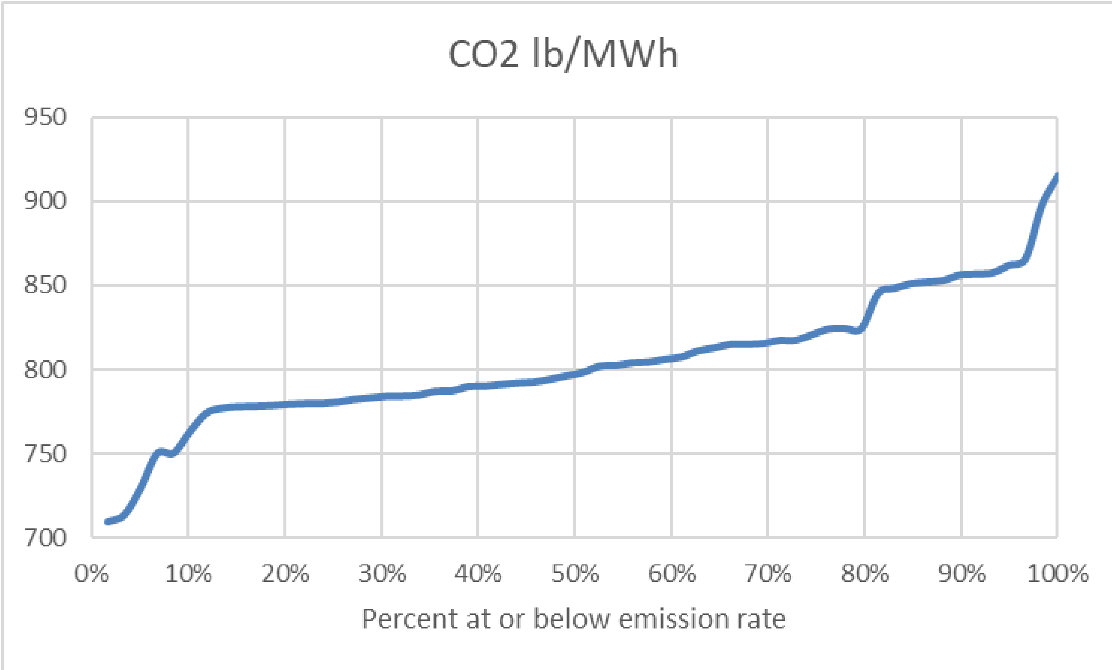


3. Summary of emissions of CO_2 for NGCC plants

Excluding the two units with under 1,000 cumulative operating hours that were clearly not operating in combined cycle mode, the units built since 2015 have an average 2020 emission rate of 804 lb/MWh, with a standard deviation of 39 lb/MWh, with none greater than 916 lb/MWh. Figure 15 shows the 2020 CO_2 emission rate and the percent of new units at or below that emission rate. As shown, 90% of the units have CO_2 emission rates at or below 856 lb/MMBtu. The two units with the highest rates are the Panda Temple plant located in Temple, TX, which is a location that would have a higher ambient temperature than that expected throughout most of the United States.[5] However, there are other new units that are in similarly hot locations in California, Florida, Louisiana and Texas, many of which have CO_2 emission rates of under 800 lb/MWh. It is therefore unclear from the available data why the emission rate of the Panda plants are so high relative to the other plants that are also at hot locations.

[5] Based upon a comparison of the location of Temple, TX to a map of annual average temperature: https://www.climate.gov/news-features/featured-images/what-will-average-us-temperatures-look-future-octobers

Figure 15. Emission rate distribution for 2020 CO_2 emissions, percent at or below emission rate



C. NOx emissions from NGCC power plants

1. Emissions from all units operating in 2020

Figure 16 shows the NOx emissions for all NGCC plants (with emissions under 0.2 lb/MMBtu) reporting into EPA's Air Markets Program data. It shows emissions in 2020 and 2017. Importantly, this shows annual emissions rates. The data plots have two loci of points: one around 0.01 lb/MMBtu and other data that can be much higher. The reason is that some are equipped with SCR and therefore have lower NOx emissions. Another feature of this figure is that each of these loci of points drop in value as total generation is increased. This demonstrates that the larger machines that operate the most tend to have the lowest emissions rates.

Figure 16. NOx emission rates for all units in 2017 and 2020 (only rates under 0.20 lb/MMBtu shown)

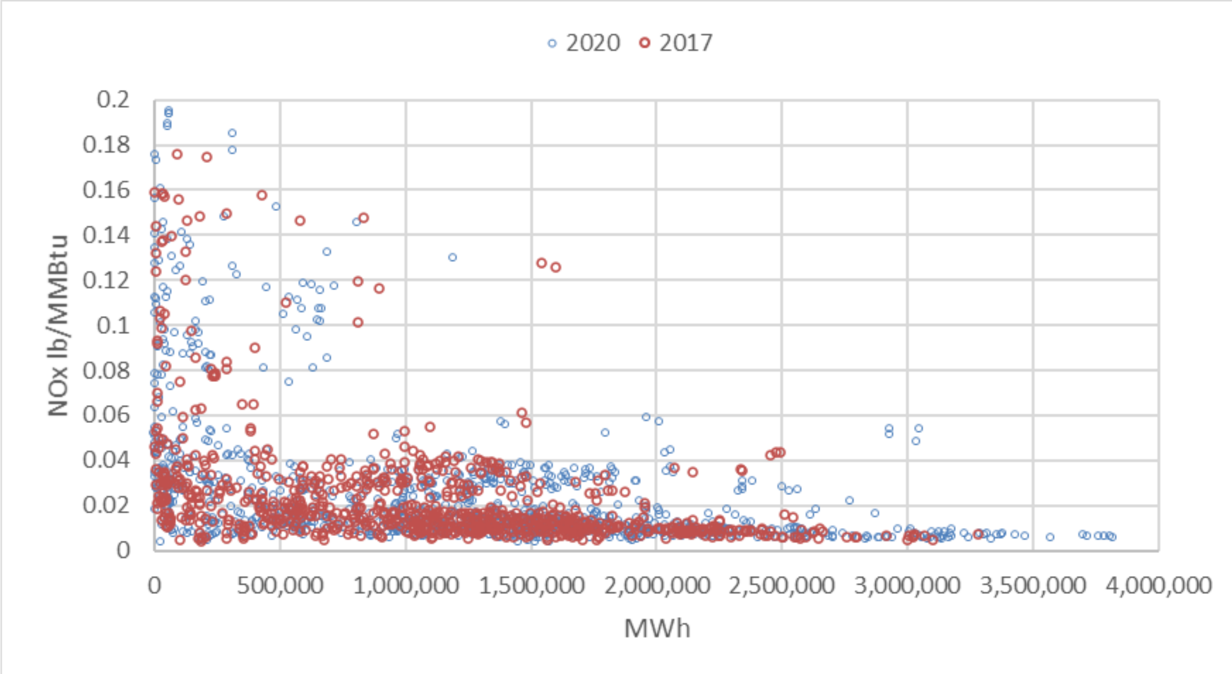
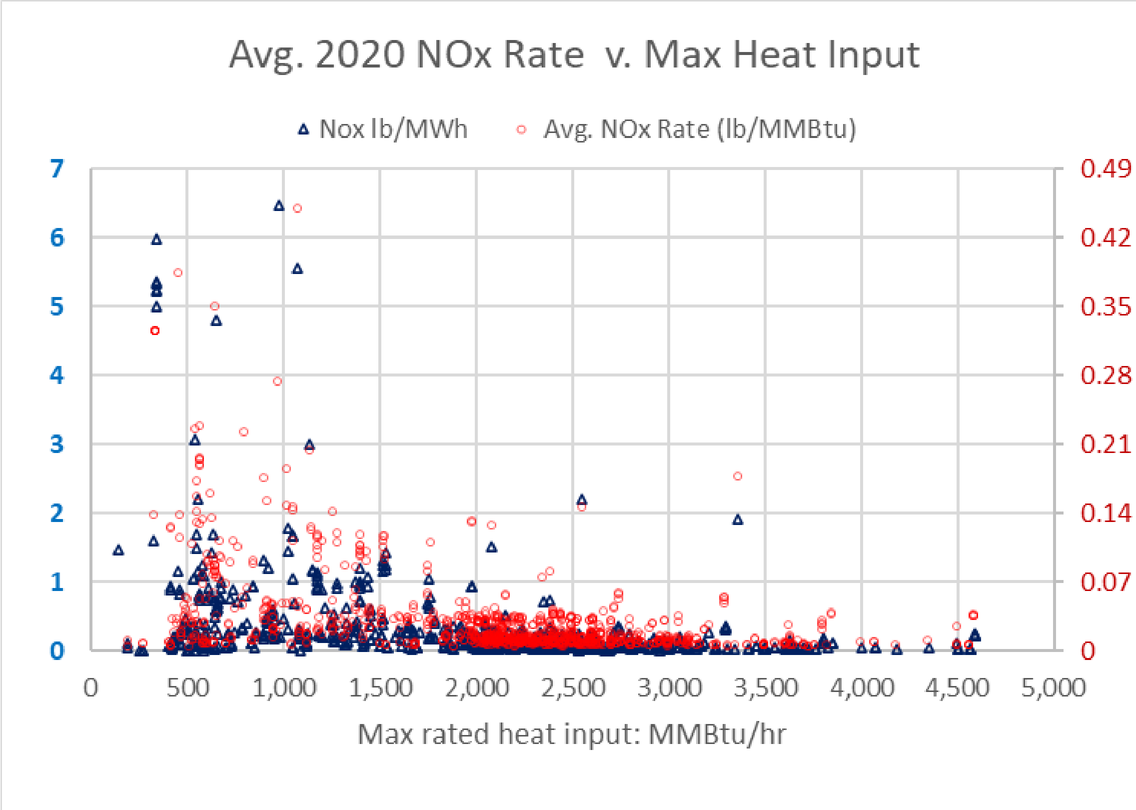


Figure 17 shows the NOx emission rates for all units operated in 2020 versus maximum heat input rate. As shown, larger NGCC plants tend to have lower emission rates. This is at least in part due to larger plants being more likely to be new plants (and therefore subject to stricter limits) and also because they are more likely to be equipped with SCR for NOx control. This figure shows NOx emission rates in terms of both lb/MMBtu and lb/MWh, with both having similar trends.

Figure 17. NOx emission rates for all units in 2020 versus maximum heat input



2. Emissions for new units

Looking only at new units installed since 2015 and considering emission rates of these units and equipment installed, Table 1 shows the average emission rates for different configurations Only two units reported to EPA's AMPD that they did not have SCR, and these were the two units at Cane Run. These units were installed in concert with retirement of coal units at Cane Run, which may have impacted the permit conditions for the installation. [6]

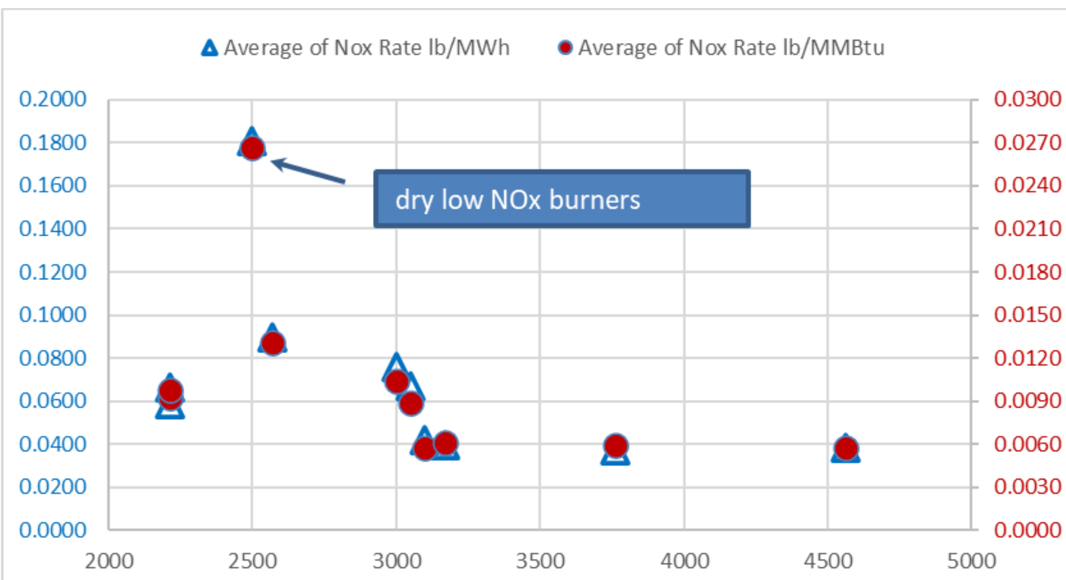
Figure 18 shows the NOx emissions data of Table 1 plotted against maximum heat input. Excluding the units that are only equipped with dry low NOx burners and no SCR, there is a general trend toward lowering NOx emission rate for larger unit sizes.

[6] See: https://www.powermag.com/cane-run-generating-station-unit-7-louisville-kentucky/. Most new NGCC plants have SCR installed due to BACT or LAER requirements. But, since the Cane Run NGCC units were installed in concern with coal plant retirement at the site, there is a chance that BACT may have been avoided under PSD.

Table 1. NOx and CO_2 emissions of new units built since 2015 by NOx control technology

Control Technology	Average of Nox Rate lb/MMBtu	Average of Nox Rate lb/MWh	Average of Max HI, MMBtu/hr	Average of CO2 lb/MWh	Count
No controls indicated	0.0058	0.0418	3100	1,370	2
Ammonia Injection Selective Catalytic Reduction	0.0058	0.0383	4564	796	4
Dry Low NOx Burners	0.0267	0.1806	2500	773	2
Dry Low NOx Burners (Began Jan 14, 2020) Selective Catalytic Reduction (Began Jan 14, 2020)	0.0059	0.0372	3763	786	1
Dry Low NOx Burners Ammonia Injection Selective Catalytic Reduction	0.0104	0.0758	3000	890	1
Dry Low NOx Burners Selective Catalytic Reduction	0.0089	0.0672	3051	1,399	35
Dry Low NOx Burners Water Injection Selective Catalytic Reduction	0.0061	0.0399	3168	790	3
Selective Catalytic Reduction	0.0131	0.0893	2569	886	9
Selective Catalytic Reduction Dry Low NOx Burners	0.0092	0.0589	2215	1,016	2
Selective Catalytic Reduction Dry Low NOx Burners Water Injection	0.0098	0.0666	2215	1,055	2

Figure 18. 2020 average NOx emissions versus maximum heat input (MMBtu/hr)



Figures 19-23 show the average NOx emission rate per year for all units that commenced operation 2015-2019. As shown, in some cases the emission rate was much higher in the first years of operation, and then decreased over time. This is an indication of improved operation of the unit, perhaps more combined -cycle operation (rates are in terms of lb/MWh, which will be impacted by heat rate, and operation of NOx control equipment. Typically, the SCR catalyst is installed within the HRSG, which would not be in operation in simple-cycle mode.

Figure 19. NOx emission rate, lb/MWh, by year for new units started in 2015

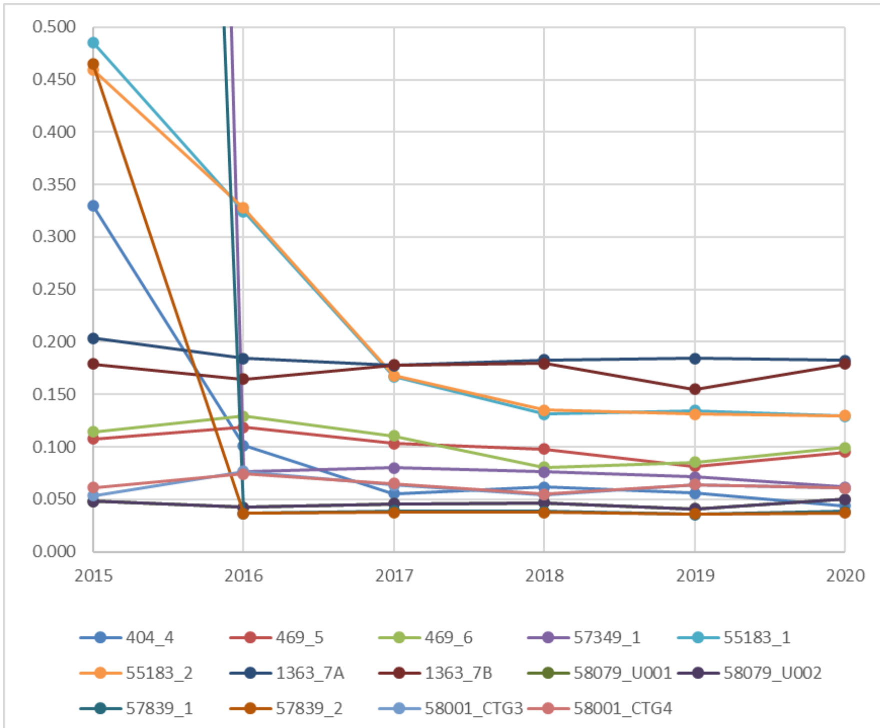


Figure 20. NOx emission rate, lb/MWh, by year for new units started in 2016

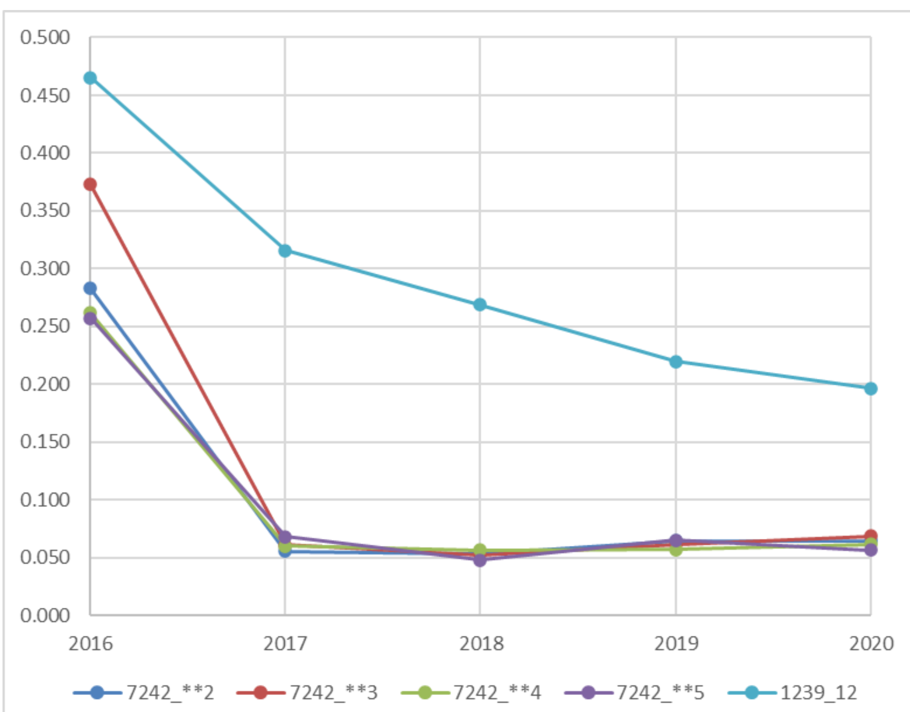


Figure 21. NOx emission rate, lb/MWh, by year for new units started in 2017

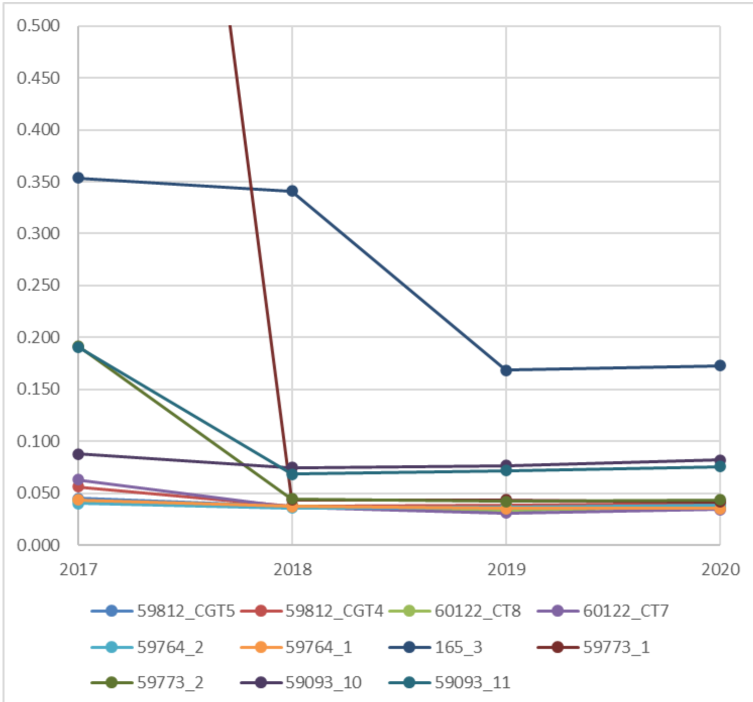


Figure 22. NOx emission rate, lb/MWh, by year for new units started in 2018

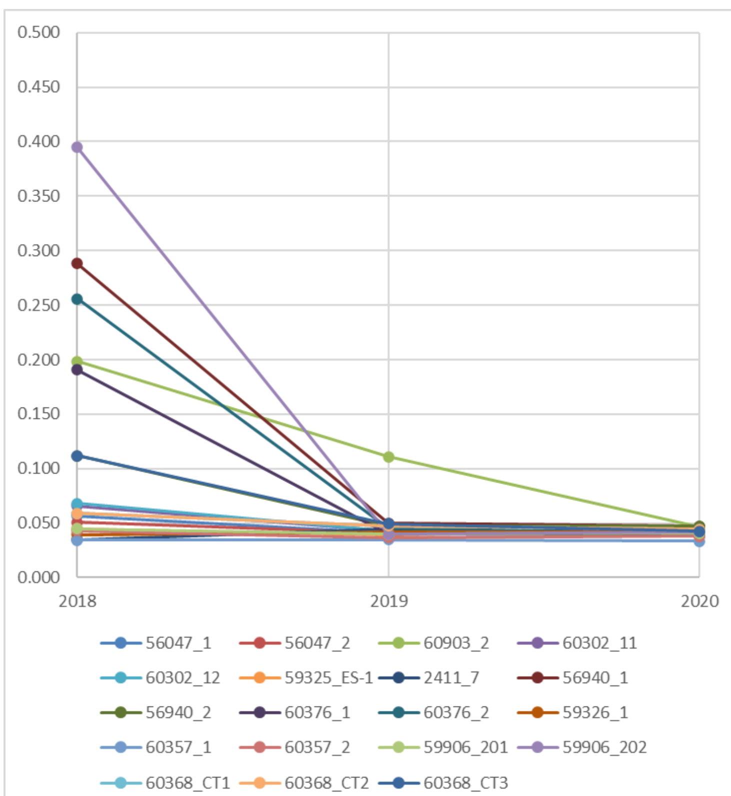


Figure 23. NOx emission rate, lb/MWh, by year for new units started in 2019

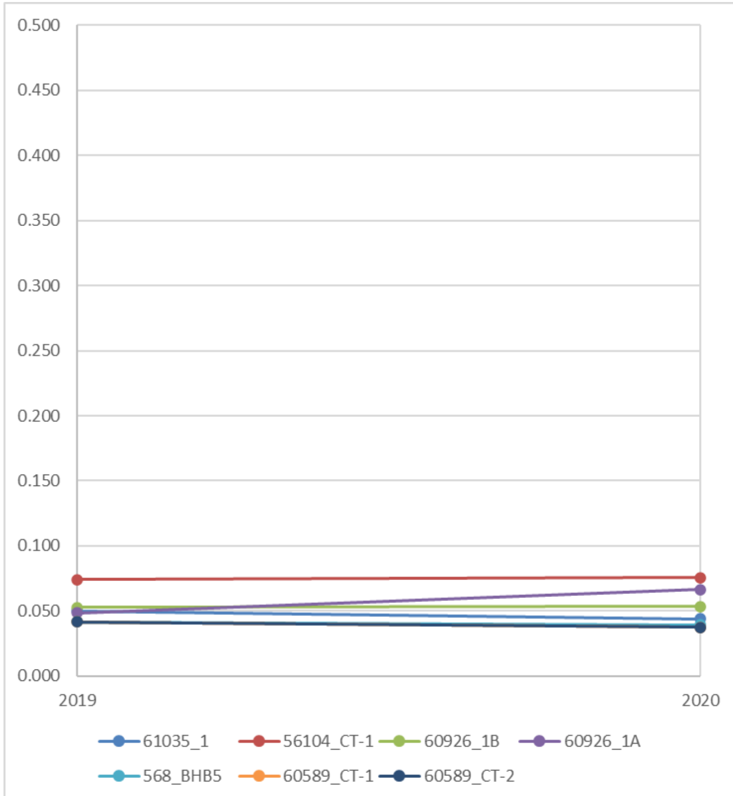
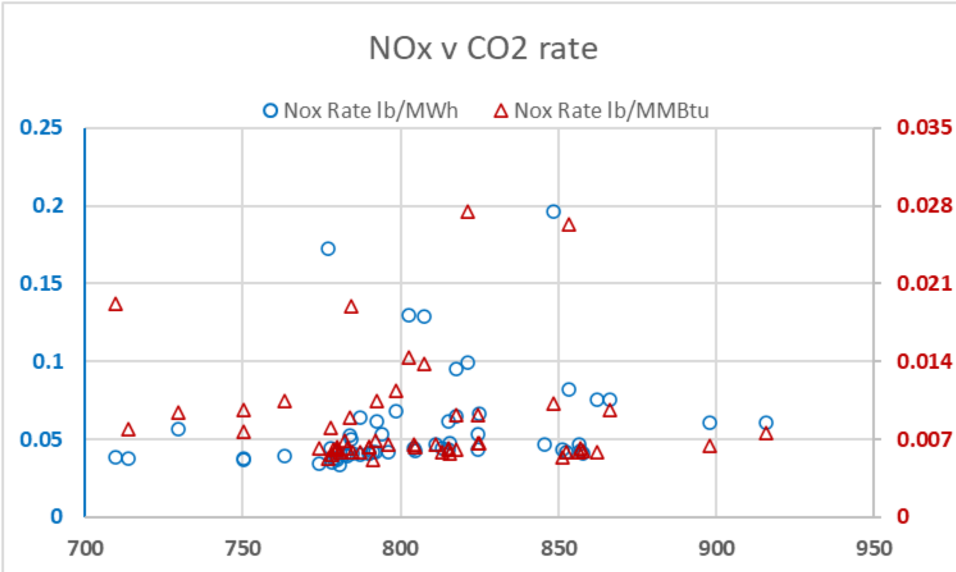


Figure 24 shows 2020 NOx emission rates for all units built since 2015 that are equipped with SCR and are operating in combined-cycle mode (CO_2 emission rate under 1,100 lb/MWh). CO_2 rate is essentially a surrogate for heat rate, and this figure shows no real relationship between NOx emissions and CO_2 rate.

Figure 24. 2020 NOx emission rate for all, new, SCR-equipped units operating in combined-cycle mode versus CO_2 rate (lb/MWh).



3. Summary of NGCC NOx emissions

The average and standard deviation of the 2020 emission rates for NOx for those units installed since 2015 with CO2 emission rates below 1,100 kb/MWh (not in simple cycle mode) and equipped with SCR are shown in Table 2. As shown, average emission rates are 0.0572 lb/MWh and 0.0084 lb/MMBtu. The standard deviation is significant, with standard deviation over 50% of the average in both cases.

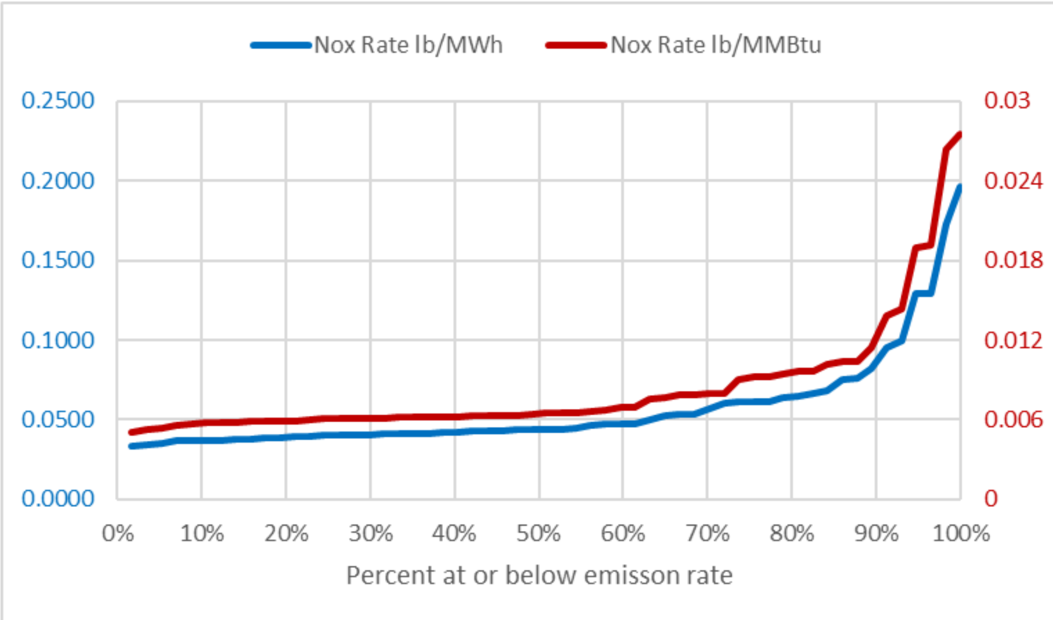
Figure 25 shows 2020 NOx emission rate and the percent at or below the emission rate for those units with SCR (all but the two at Cane Run). The curves of the figure are very flat for most of the units, and start to turn up at around 70% of the units, with the slope growing steeper. As shown, 90% of the units have NOx emission rates at or below 0.082 lb/MWh or 0.0114 lb/MMBtu. It is unclear why the five other units[7] cannot achieve lower emissions, or why the slope of the curve of Figure 25 increases so steeply above 90% (emissions are much higher) for the remaining five units.

Table 2. 2020 NOx emission rates for SCR-equipped units built since 2015 with and CO2 emissions under 1,100 Lb/MWh

	Nox, lb/MWh	Nox, lb/MMBtu
avg	0.0572	0.0084
stdevp	0.0318	0.0046

[7] These are Cherokee 5 & 6, Nelson energy Center 1 & 2, and Grand River Dam Authority 3

Figure 25. Emission rate distribution for 2020 NOx emissions (units with SCR), percent at or below emission rate



D. N_2O emissions from NGCC power plants equipped with SCR systems

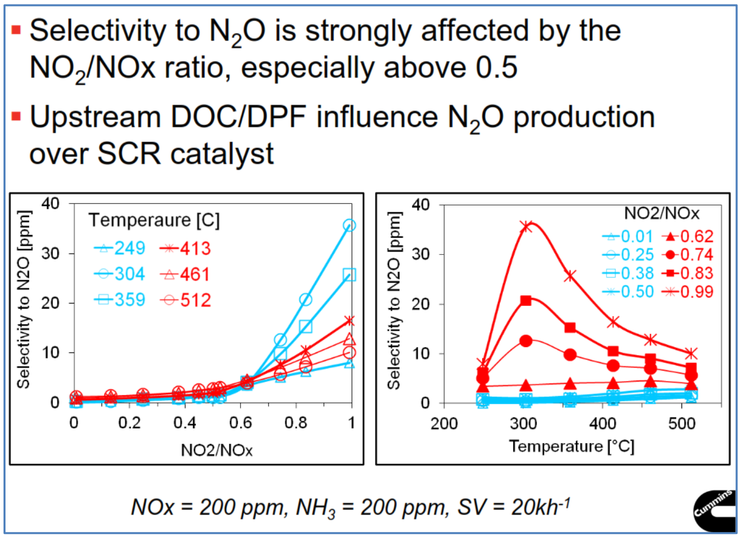
Nitrous Oxide (N_2O) is a potent greenhouse gas that may be emitted from SCR units as well as from oxidation catalyst units. N2O emissions are impacted by a range of factors, including:

- Concentration of NOx
- Fraction of NOx as NO_2
- Flue gas temperature
- Catalyst type
- For oxidation catalysts, the nature of hydrocarbon species

Concentration of NOx - The concentration of NOx is significant because a fraction of the NOx reduced can be converted to N_2O. This becomes challenging for sources with high NOx levels, such as diesel engines, that do not have the options for minimizing the amount of NOx produced in the combustion process that gas turbines have. This is why much of the research on N_2O emissions from SCR equipped sources has focused on diesel engine emissions. It is also a reason why it is beneficial to reduce NOx as much as possible upstream of the SCR through combustion control, and this is common practice.

Fraction of NOx as NO_2 - The selectivity of the reaction to produce N2O will be greater when there is a higher fraction of NOx as NO_2, as shown in Figure 26. This is a greater concern when there is an upstream oxidation catalyst that may convert a portion of the NOx to NO_2. This is commonly the case for diesel engines, and may be the case for gas turbines since some gas turbines installations are not equipped with an oxidation catalyst. It is most significant when NO_2 to total NOx ratio is greater than 0.5

Figure 26. Impact of NO_2 on N_2O formation across an SCR
(DOC stands for Diesel Oxidation Catalyst and DPF stands for Diesel Particulate Filter)[8]



Flue gas temperature – The flue gas temperature will determine which mechanism is dominant in forming N_2O . At low temperatures (around 250°C) ammonium nitrate (NH4NO3) can form from NOx and ammonia, and this can thermally decompose to N2O. At higher temperatures (around 500°C), ammonia can oxidize to form N_2O . For gas turbines, these mechanisms can be mitigated by catalyst selection or use of tempering air to control temperature.

Catalyst type – All classes of catalyst have the potential to produce N_2O . SCR catalysts are more likely to be of the Vanadia-Titania type than other types, such as zeolite-based catalysts. According to one catalyst supplier, the vanadia-titania catalysts are less selective to production of N_2O than some of the other catalyst types.

the nature of hydrocarbon species – For diesel oxidation catalysts (DOCs), the nature of the hydrocarbons being destroyed are significant. Data has shown that for DOCs, there was higher selectivity to N_2O when dodecane ($C_{12}H_{26}$) was the dominant hydrocarbon rather than when propene (C_3H_6) was the dominant species, with higher concentrations (up to over 1000 ppm) resulting in higher conversion to N_2O . These species can be in higher concentrations with diesels than with gas turbines.

In general, N_2O generation from SCR is a greater concern from diesel engines equipped with SCR than for gas turbines for a number of reasons relating to differences in exhaust gas conditions. Although N_2O can be generated from gas turbines equipped with SCR, the information that is available appears to suggest that it will usually be a small amount.

---

[8] Kamasamudram, K, et. al., N2O Emissions From 2010 SCR Systems, Directions in Engine-Efficiency and Emissions Research (DEER) Conference, October 3-6, 2011, Detroit

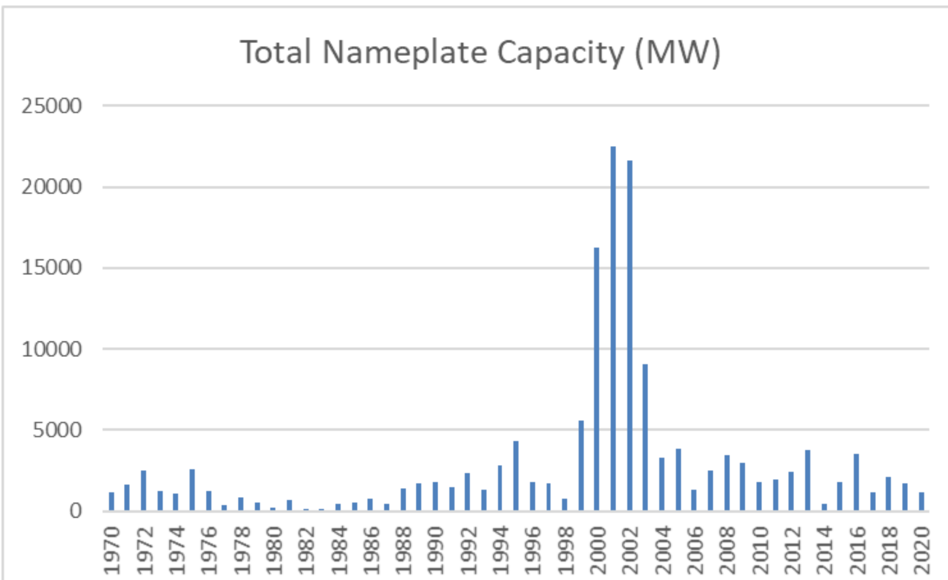
II. CT Power Plants

A. Historical installations of CT power plants

The history of installations of CT power plants is shown in Figure 27. As shown, there was a very large peak in installations in 2002 and 2003. Since then installations have been generally in the range of about 2,000 -3,000 MW per year, with some years higher and some lower.

As Figure 28 shows, average CT plant size has increased over the past several decades, with average size of roughly 40-50 MW in the 1970s to roughly 80 MW today, with some higher. The impact is that these larger turbines may have other differing characteristics. Theoretically, larger turbomachines are more efficient.[9] Also, more recent NGCC plants may have other technological advantages in terms of efficiency or emissions.

Figure 27. Historical installations of CT power plants (nameplate MW installed)[10]

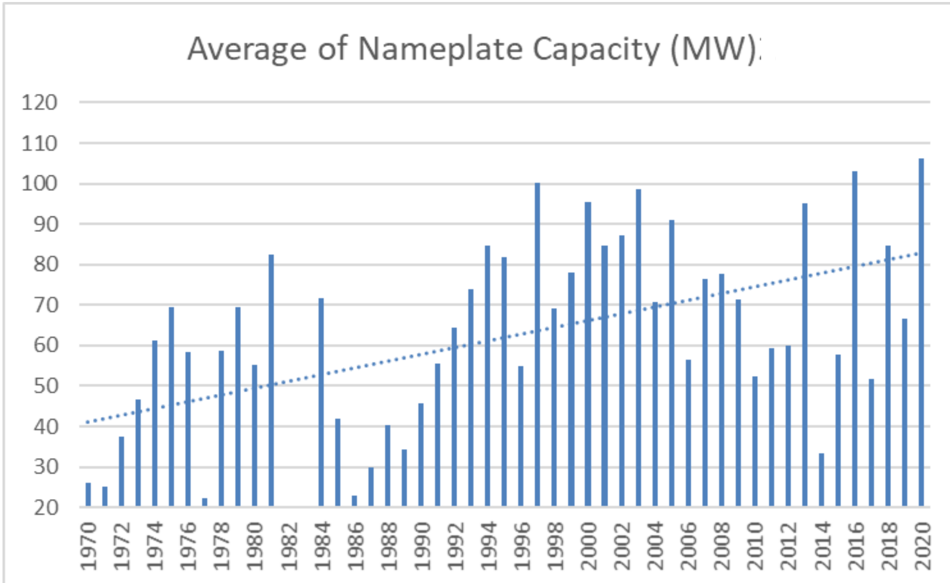


While CO_2 emission rates for natural gas power plants are a direct function of the efficiency of the turbine, NOx emission rates depend upon other factors, such as BACT or LAER analysis, and the resulting emission rate that is required. Many CT plants have SCR, but most do not. This is because a BACT analysis is case-specific, and will differ from one application to the next and, as a technology forcing emission rate, BACT rates have decreased over time.

[9] Tip leakage and surface losses per volume flow are lower for larger turbomachines

[10] Developed from EIA Form 860

Figure 28. Average unit size for CT plants[11]



B. CO_2 emissions from CT power plants

1. Emissions for all units operating in 2020

Figure 29 shows 2020 CO2 emission rates for all CT units operating that year plotted against 2020 generation. As shown, the CT units that generate the most tend to be the most efficient, and therefore the lowest emitting, units. This trend is consistent with the trends in Figures 30 and 31, that show that the CT units with the highest operating hours and the highest capacity (rated by max heat input) also have the lowest CO2 emission rates.

[11] Ibid

Figure 29. 2020 average CO_2 emission rates versus 2020 generation for all CT plants in air markets program data.

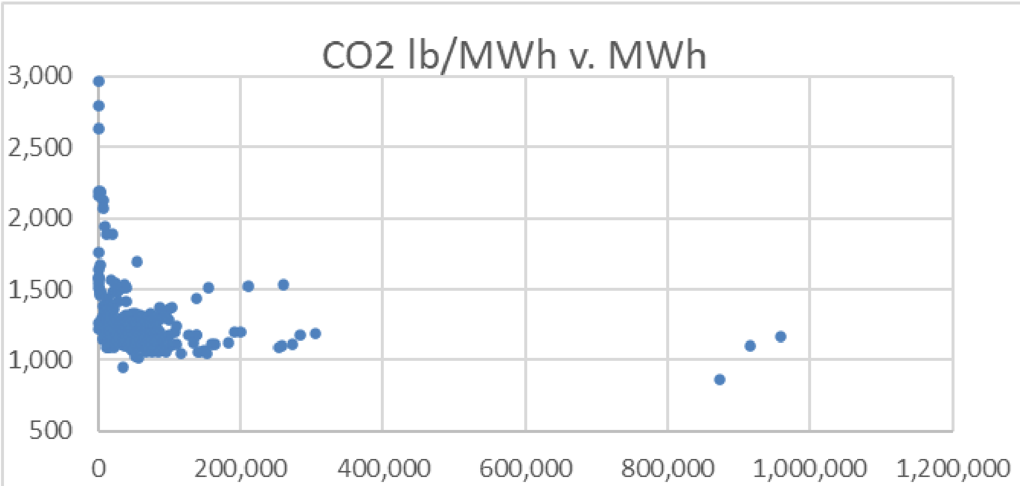


Figure 30. 2020 average CO_2 emission rates versus 2020 operating hours for all CT plants in air markets program data.

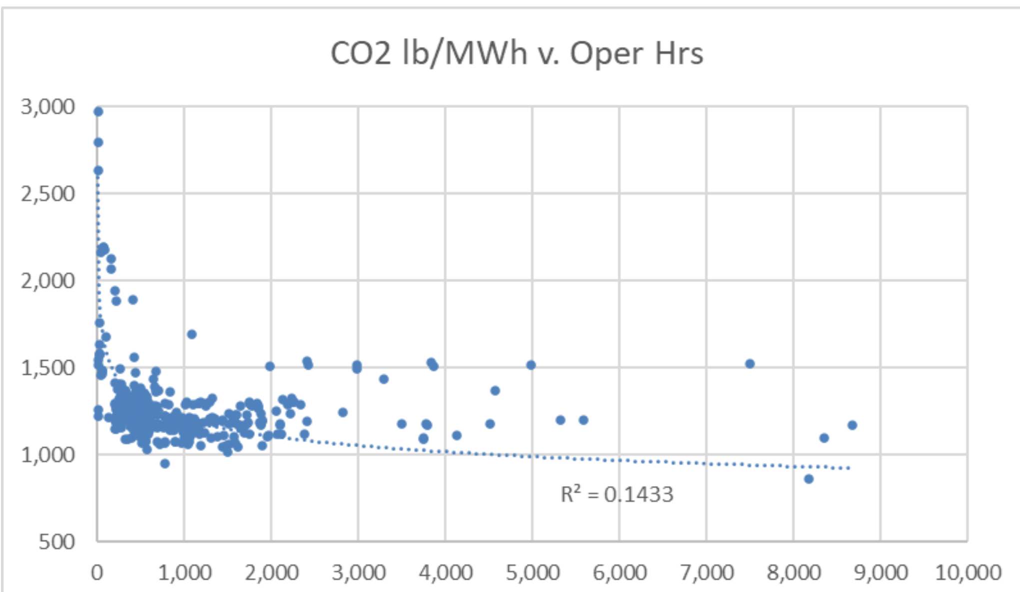
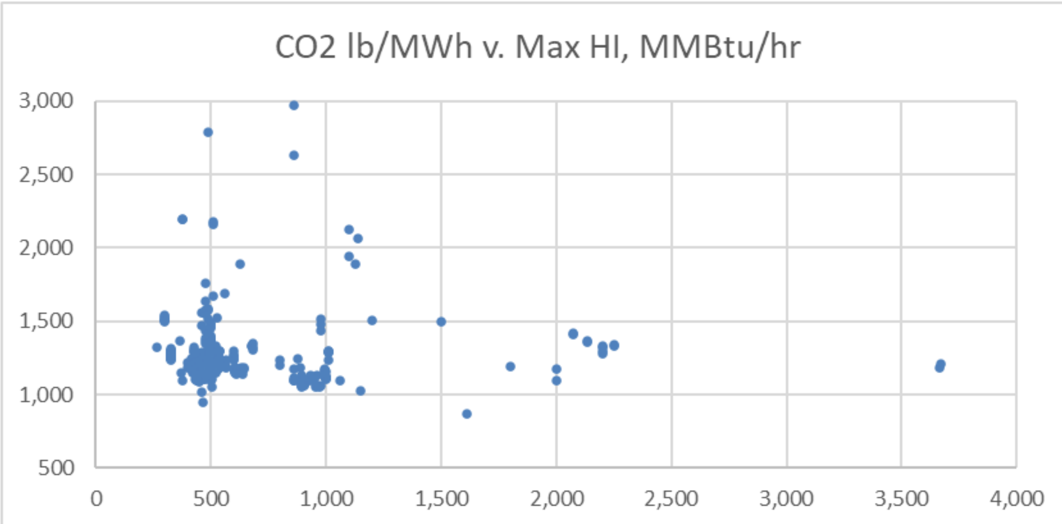


Figure 31. 2020 average CO_2 emission rates versus maximum heat input for all CT plants in air markets program data



1. Emissions for new units installed since 2015

Data for only units installed since 2015 was examined to see the relationships for only new units. Figures 32-34 show 2020 average annual CO_2 emission rates versus cumulative operating hours, cumulative generation, and year in service. As shown in figure 32 and 33, the units with the greatest generation and operating hours tend to be more consistently lower in CO_2 emissions. The year in service, however, did not seem to make a significant difference.

Figure 32. 2020 average CO_2 emissions versus cumulative operating hours

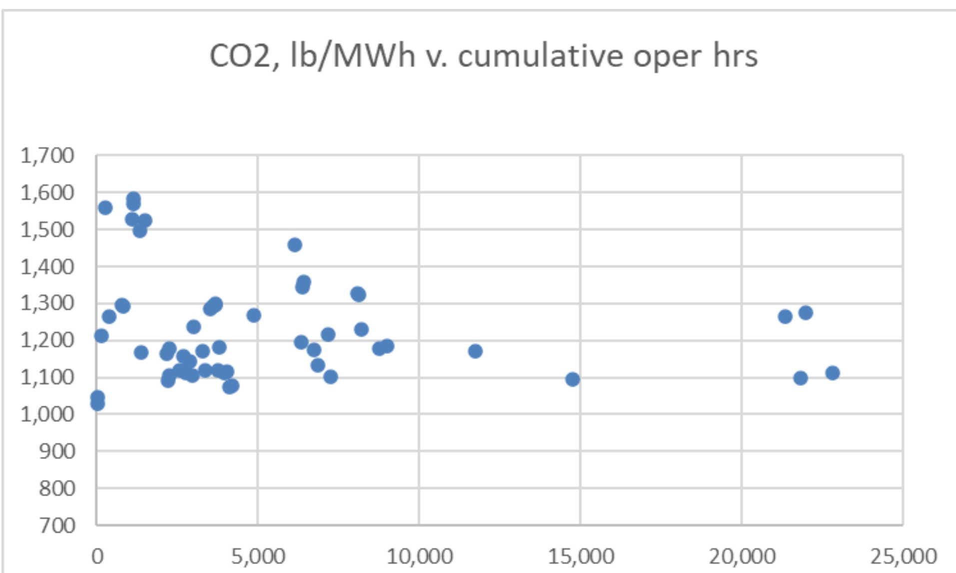


Figure 33. 2020 average CO_2 emissions versus cumulative generation

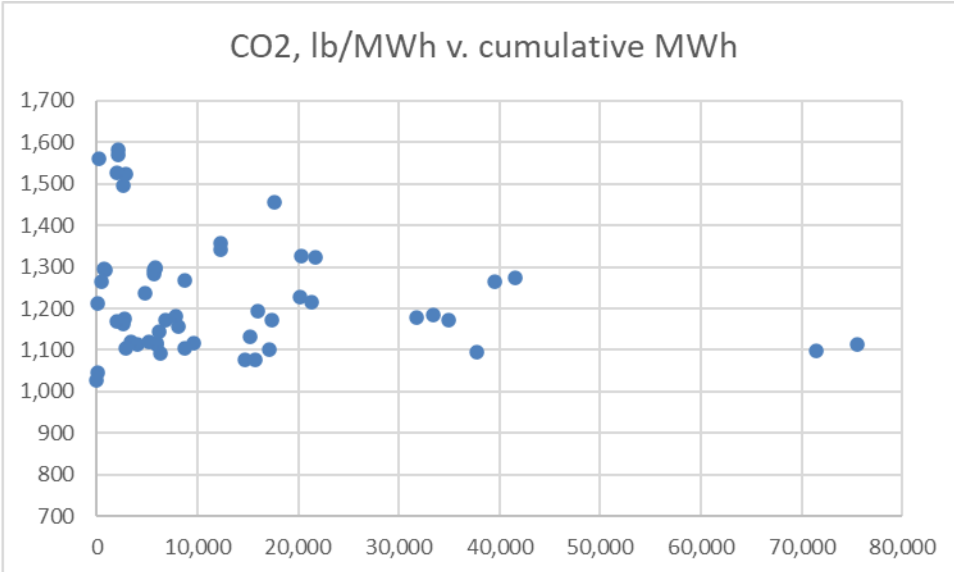
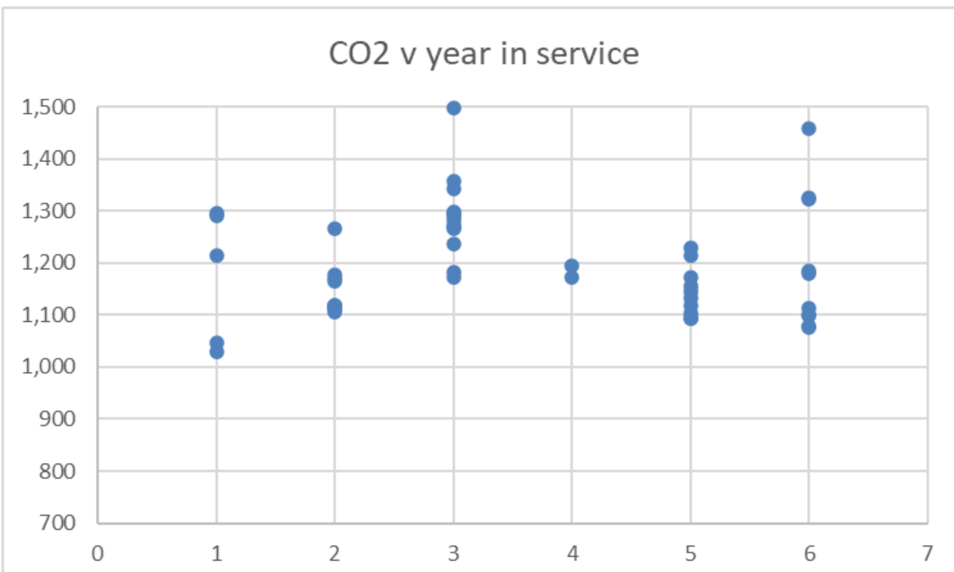


Figure 34. 2020 average CO_2 emissions versus year in service



In an effort to gauge the effect of temperature, CO_2 emissions versus latitude was examined. This is shown in Figure 35. Lower latitudes (under 30 degrees) showed a wider range of CO_2 emission rates than higher latitudes (over 40 degrees). Otherwise, no real trend was noted, indicating that other effects are important. Figure 36 demonstrates that 2020 CO2 emission rates bore no relationship to unit size as indicated by maximum heat input rate.

Figure 35. 2020 average CO2 emissions versus latitude

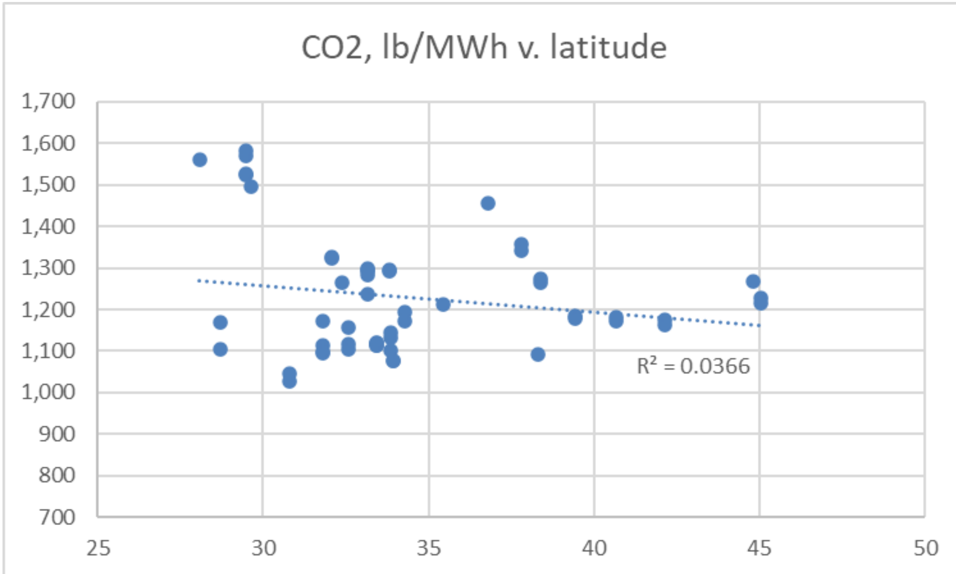
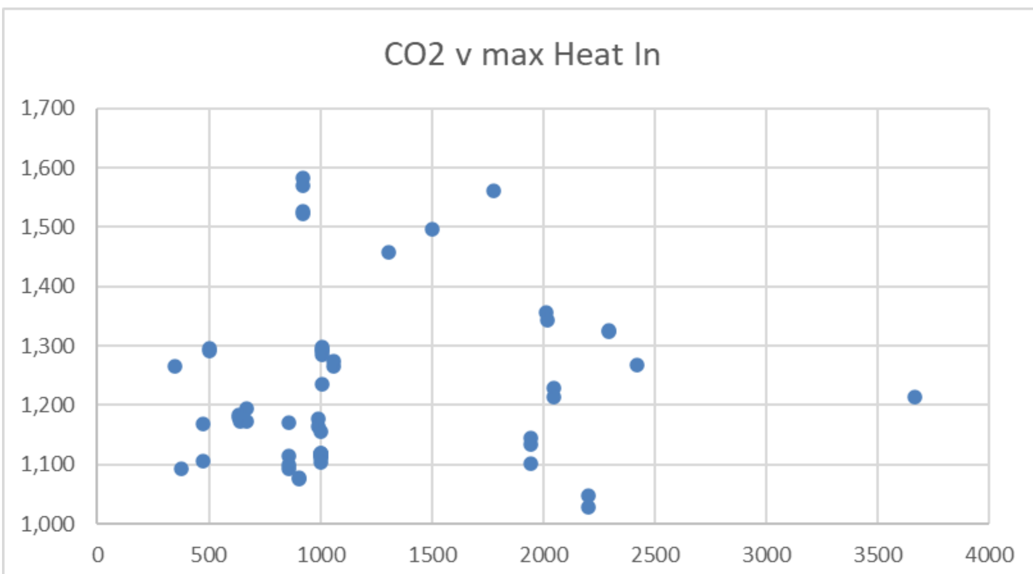


Figure 36. 2020 average CO2 emissions versus maximum heat input



Figures 37 through 41 show CO_2 emission rates by year for units installed in years 2015, 2016, 2017, and 2018, respectively. As shown, for some units CO_2 emission rate decreased after the first year of operation.

Figure 37. Annual CO2 emission rate (lb/MWh) by year for CT units that started operation in 2015

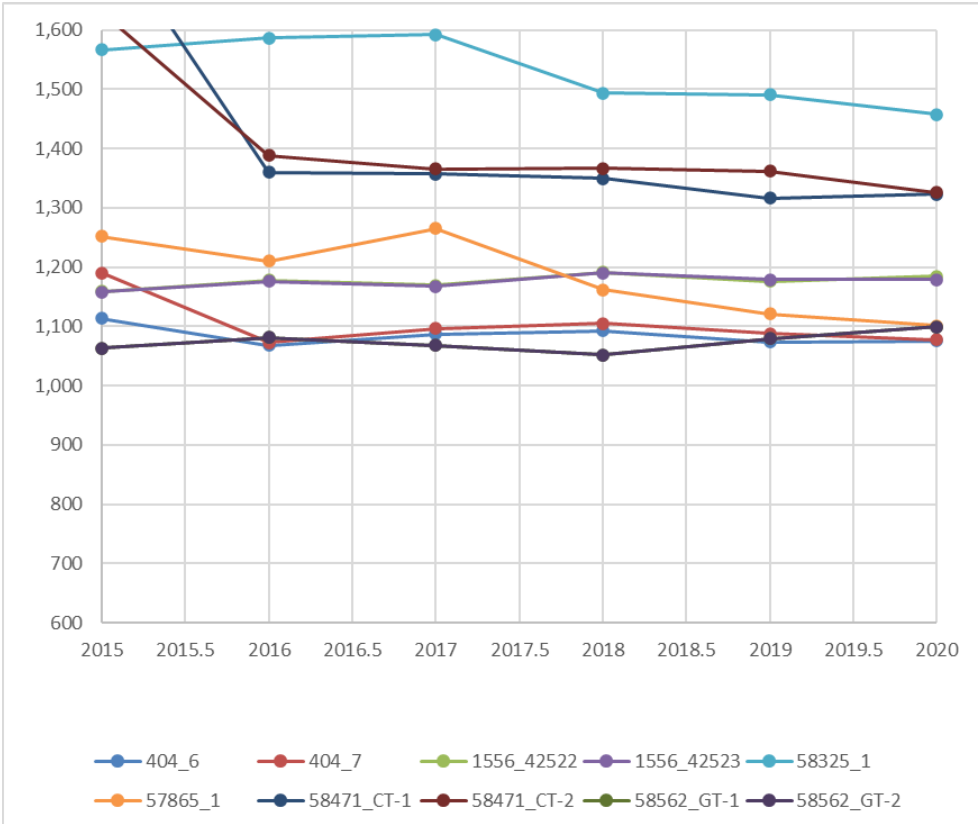


Figure 38. Annual CO2 emission rate (lb/MWh) by year for CT units that started operation in 2016

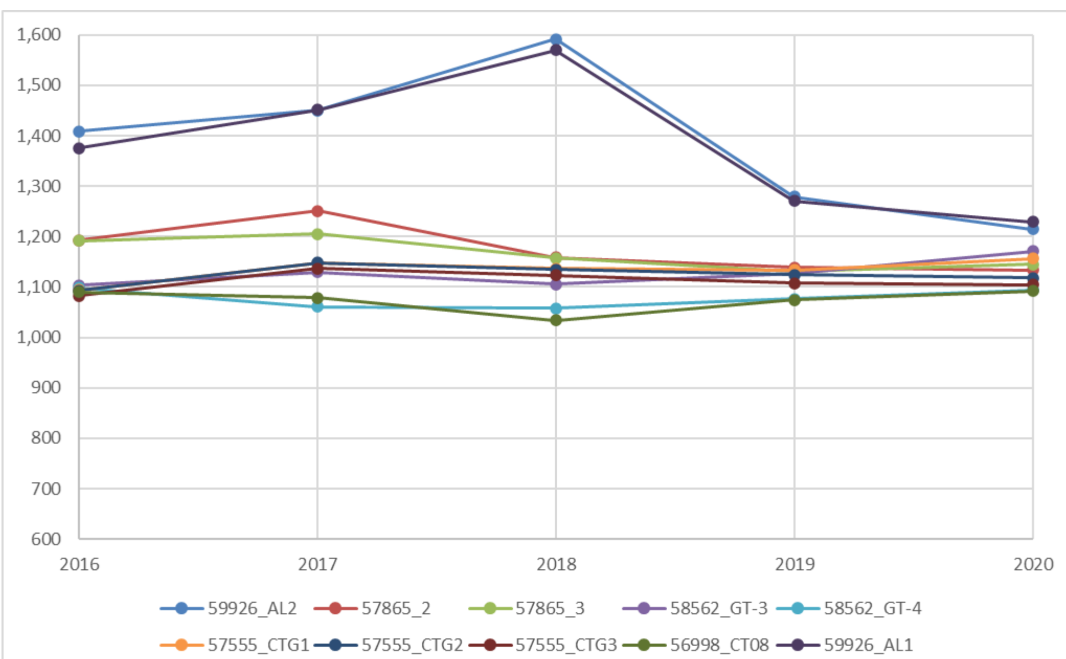


Figure 39. Annual CO2 emission rate (lb/MWh) by year for CT units that started operation in 2017

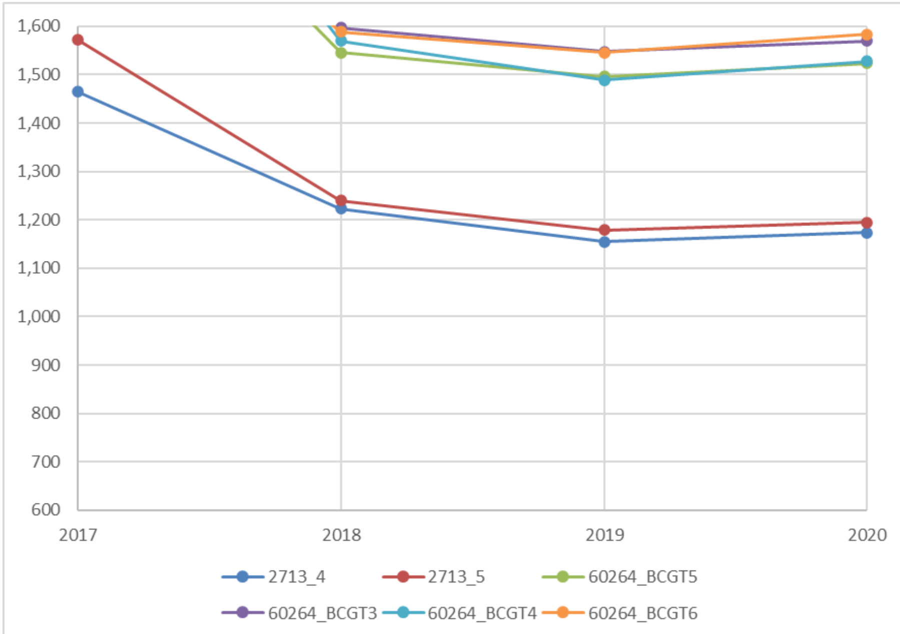


Figure 40. Annual CO2 emission rate (lb/MWh) by year for CT units that started operation in 2018

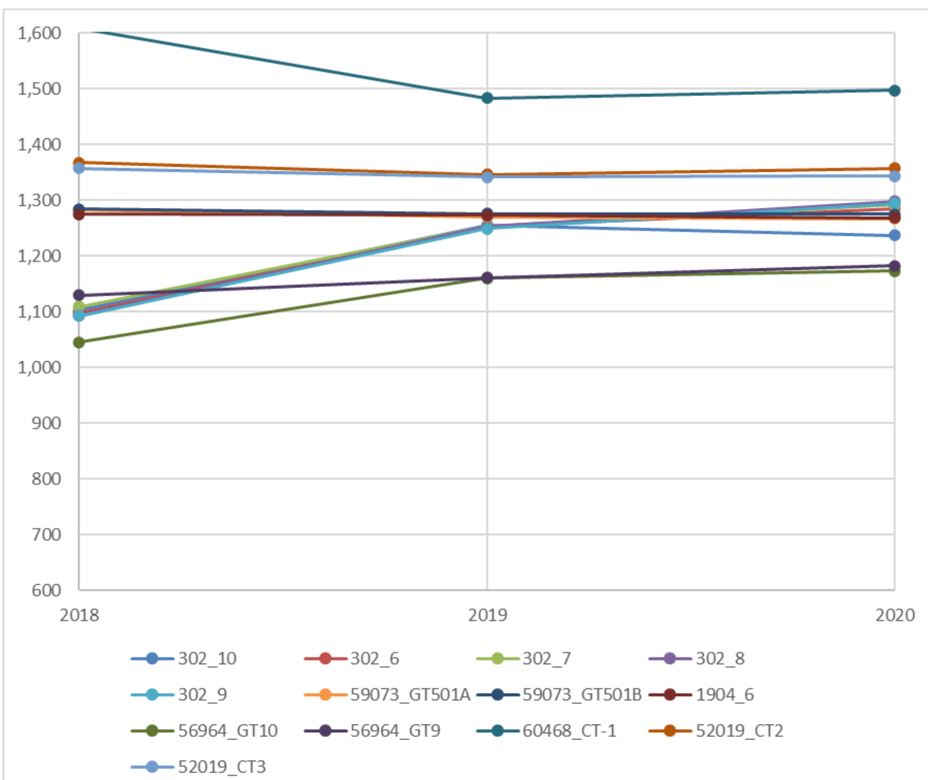
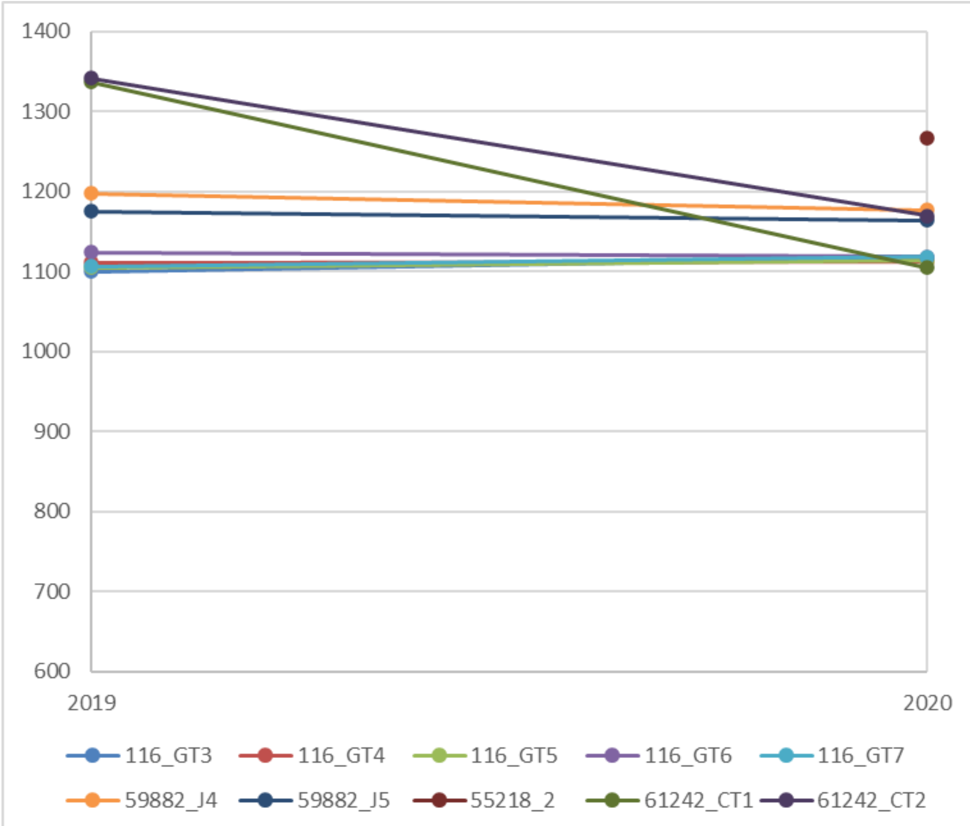


Figure 41. Annual CO2 emission rate (lb/MWh) by year for CT units that started operation in 2019[12]

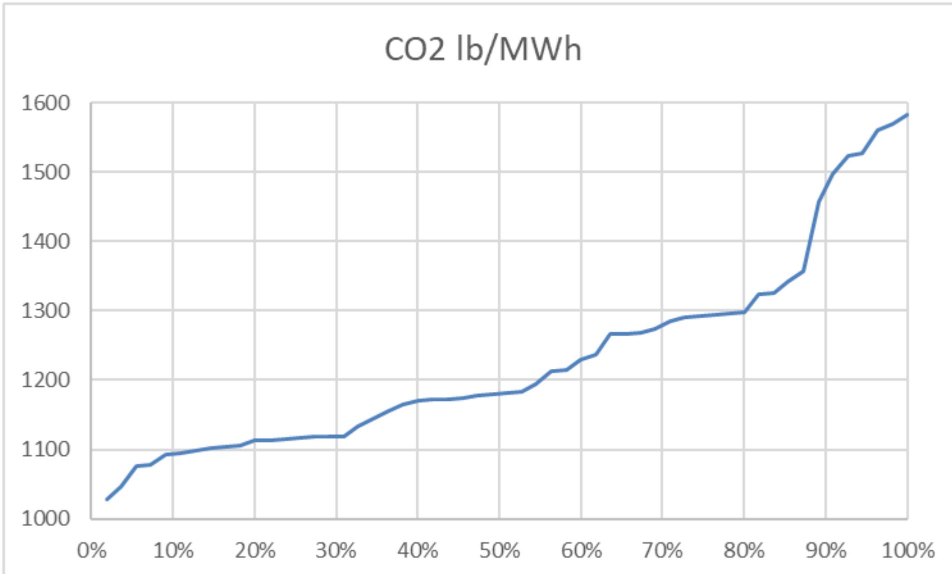


2. Summary of CT CO_2 emissions

The average 2020 CO2 emission rate for new CT units installed since 2015 is 1230 lb/MWh with a standard deviation of 141 lb/MWh. Figure 42 shows the emission rate distribution for the 55 CT units built since 2015. It shows that 80% of all units have emission rates under 1300 (1,298) lb/MWh and 90% with emission rates below 1500 (1497) lb/MWh, with the highest emitter at under 1600 (1583) lb/Mwh. However, over 50% of the units achieve rates under 1,200 lb/MWh and over 30% achieve emission rates under 1,120 lb/MWh.

[12] Hinds Energy Facility unit 2 (55218_2) did not have enough 2019 operating time for emissions data.

Figure 42. Emission rate distribution for 2020 CO2 emissions (CT units) for units built since 2015, percent at or below emission rate



C. NOx emissions from CT power plants

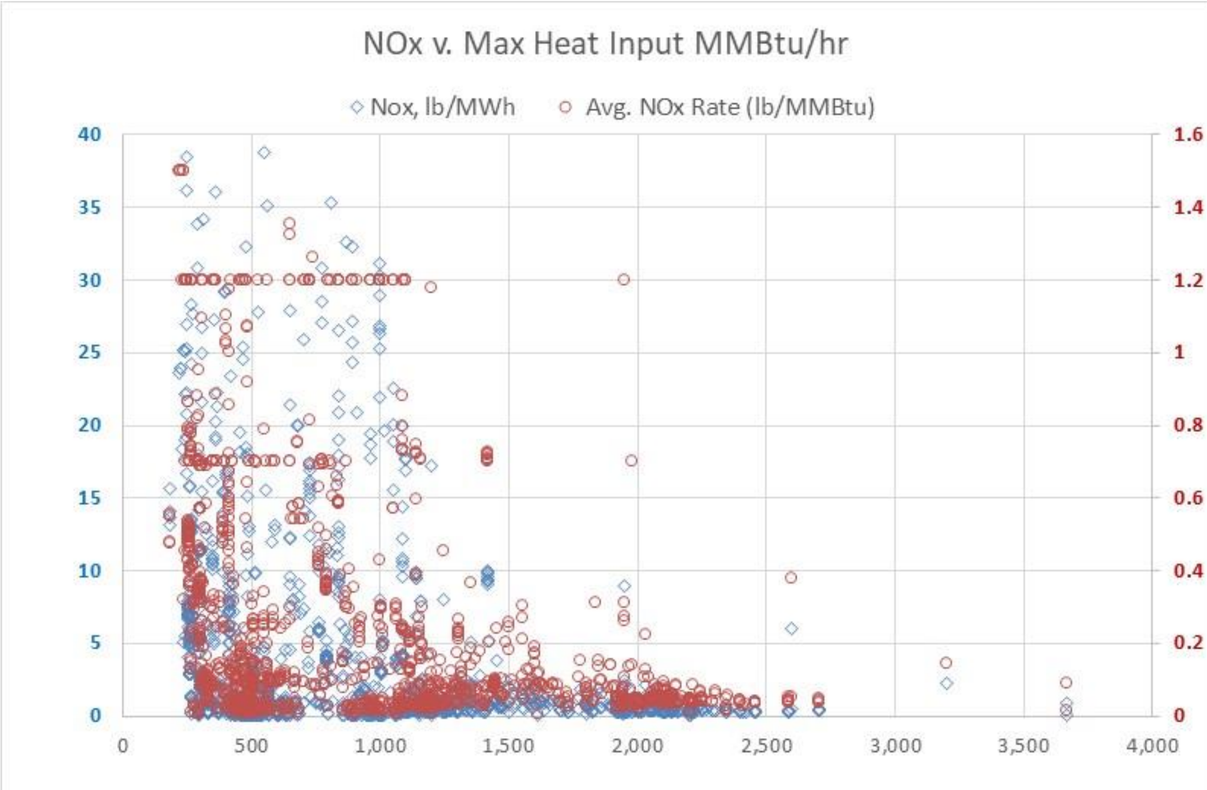
As will be shown, there is a wide range in NOx emission rates for CT power plants. This is because:

1. Many units are not equipped with SCR for NOx control
2. Newer units, even those without SCR, have much lower emission rates than legacy units because of advances in low NOx combustion technology.

1. NOx emission rates from all CT units

Figure 43 shows the 2020 average NOx emission rate versus maximum heat input for all units (only showing emission rates up to 40 lb/MWh). As shown, there is a very wide scatter, especially for smaller sized units. For larger facilities the NOx emission rates are more consistently low. This is likely the result of BACT and LAER analysis that, over time, have resulted in higher emission rates for older and smaller units.

Figure 43. 2020 average NOx (at or below 40 lb/MWh) versus maximum heat input, all units



Figures 44 and 45 also show NOx emission rates versus generation and operating hours, with similar trends – very high scatter at low generation or operating hour levels and fairly consistently low emission rates at high generation or operating hour levels. The patterns are consistent with units that are smaller, older and with lower operation being subject to less stringent NOx emission standards.

Figure 44. 2020 average NOx (at or below 40 lb/MWh) versus 2020 generation (MWh)

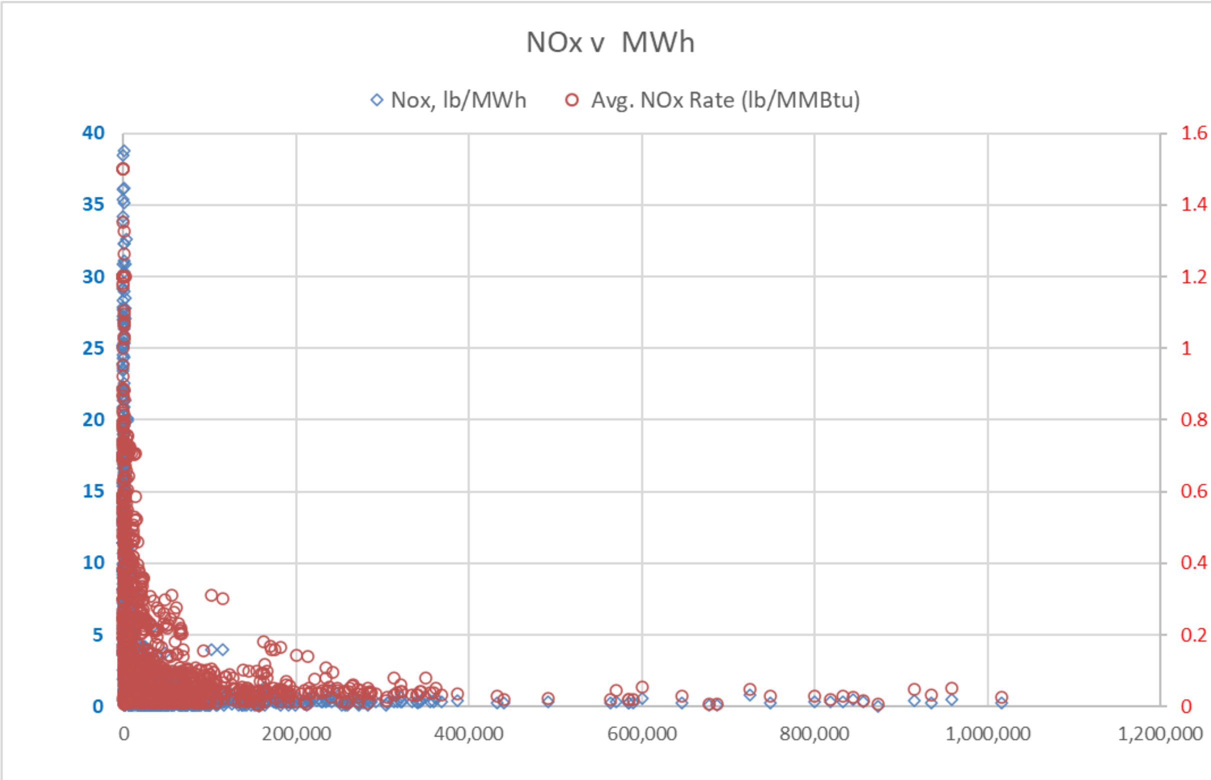
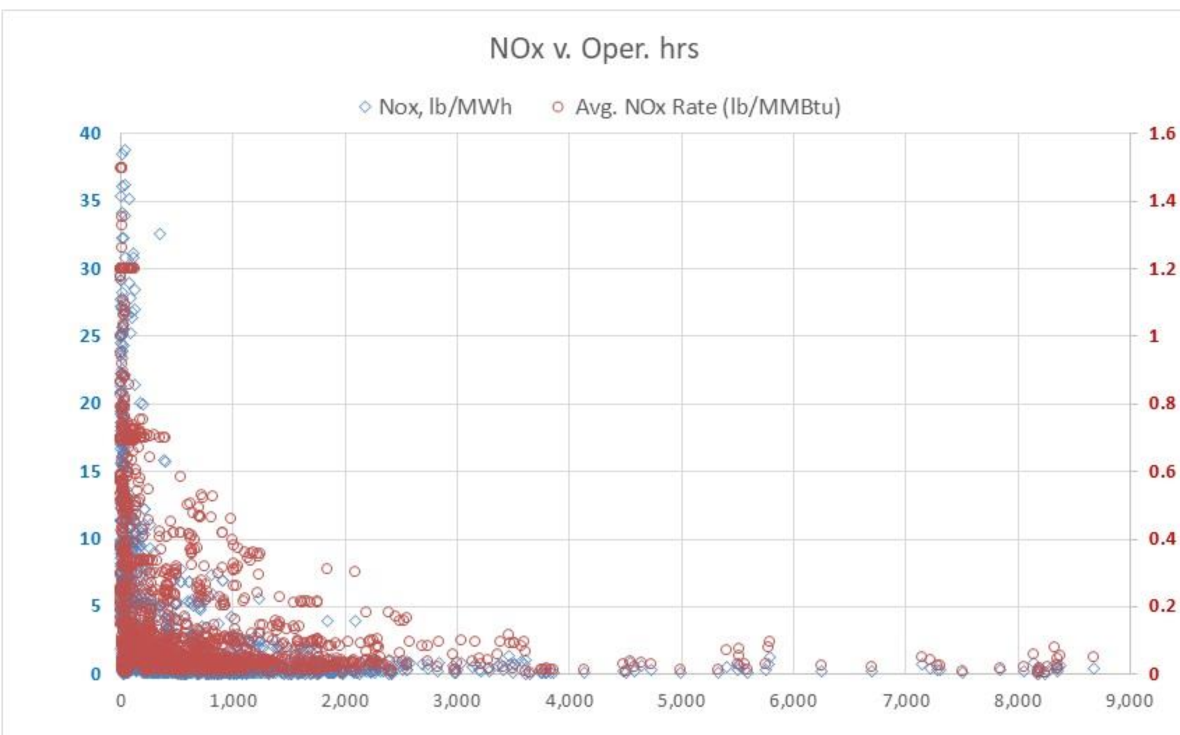


Figure 45. 2020 average NOx (at or below 40 lb/MWh) versus 2020 operating hours



2. Emissions from new units

Table 3 shows the average of 2020 NOx, CO_2 and maximum heat input for units placed in service between 2015 and 2020. Figures 46 and 47 are plots of the data in Table 3, plotting NOx emission versus CO2 emission rate (a surrogate for efficiency) and NOx emission versus maximum heat input. As shown in Figure 46, the units without SCR also correspond to the units with the highest average NOx and CO2 emission rates. Figure 48 shows that there is not a relationship between NOx and maximum heat input, except perhaps the very largest units. However, Figure 48 does demonstrate that, for even the smallest CT units, low NOx emissions are possible.

It is notable that the highest 2020 NOx emission rates for new units built in 2015 and since are well below the 2020 emission rates shown for many pre-existing CT units. This is largely a result of advancements in low NOx combustion technology that became available for CTs that was more effective than the technology available in years past.

Table 3. Average 2020 NOx, CO2, and max heat input (MMBtu/hr) by NOx control method, only new units since 2015

Row Labels	Average of Nox Rate lb/MMBtu	Average of Nox Rate lb/MWh	Average of CO2 lb/MWh	Average of Max HI
No controls indicated	0.0218	0.2486	1,352	1,462
Ammonia Injection Selective Catalytic Reduction	0.0363	0.3479	1,339	473
Dry Low Nox Burners	0.0954	1.1512	1,480	1,686
Dry Low Nox Burners Selective Catalytic Reduction	0.0906	0.9247	1,213	3,668
Dry Low Nox Burners Water Injection Selective Catalytic Reduction	0.0148	0.1450	1,186	992
Selective Catalytic Reduction	0.0187	0.1748	1,082	761
Water Injection	0.1168	1.3150	1,533	1,039
Water Injection Ammonia Injection Selective Catalytic Reduction	0.0290	0.2872	1,087	643
Water Injection Selective Catalytic Reduction	0.0165	0.1686	1,156	931

Figure 46. Data from Table 3, avg Nox (2020) versus avg CO_2 emission rate (lb/MWhr)

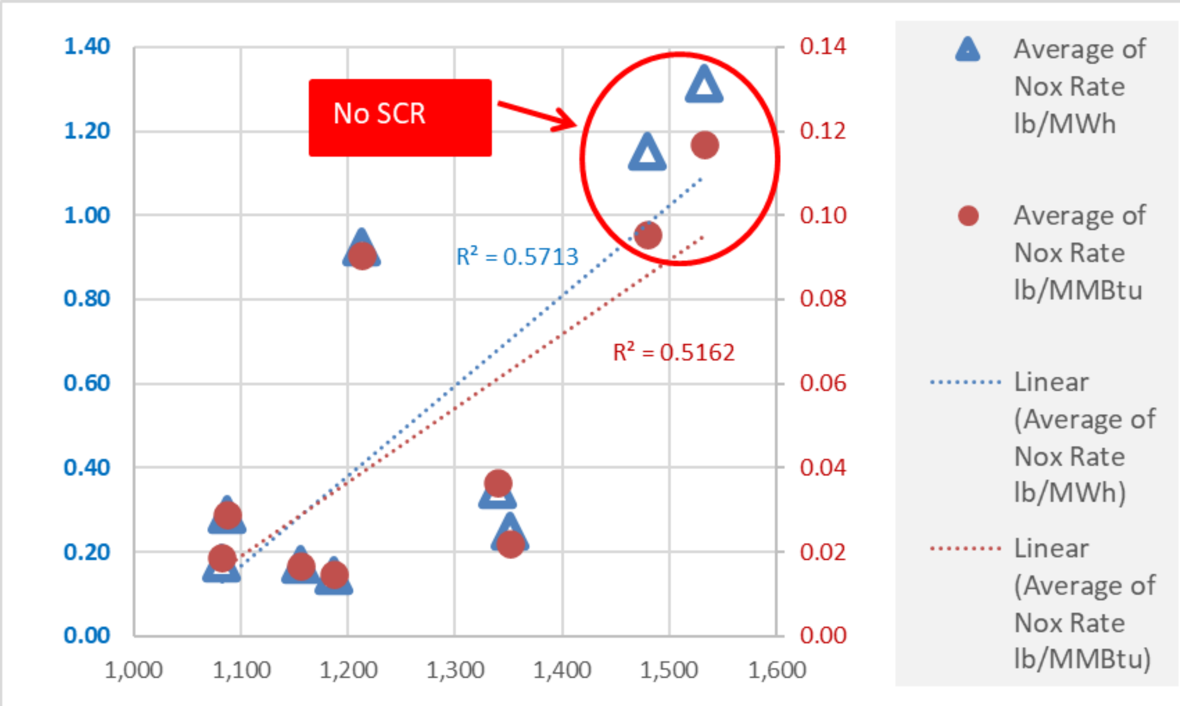


Figure 47. Data from Table 3, avg Nox versus avg max HI

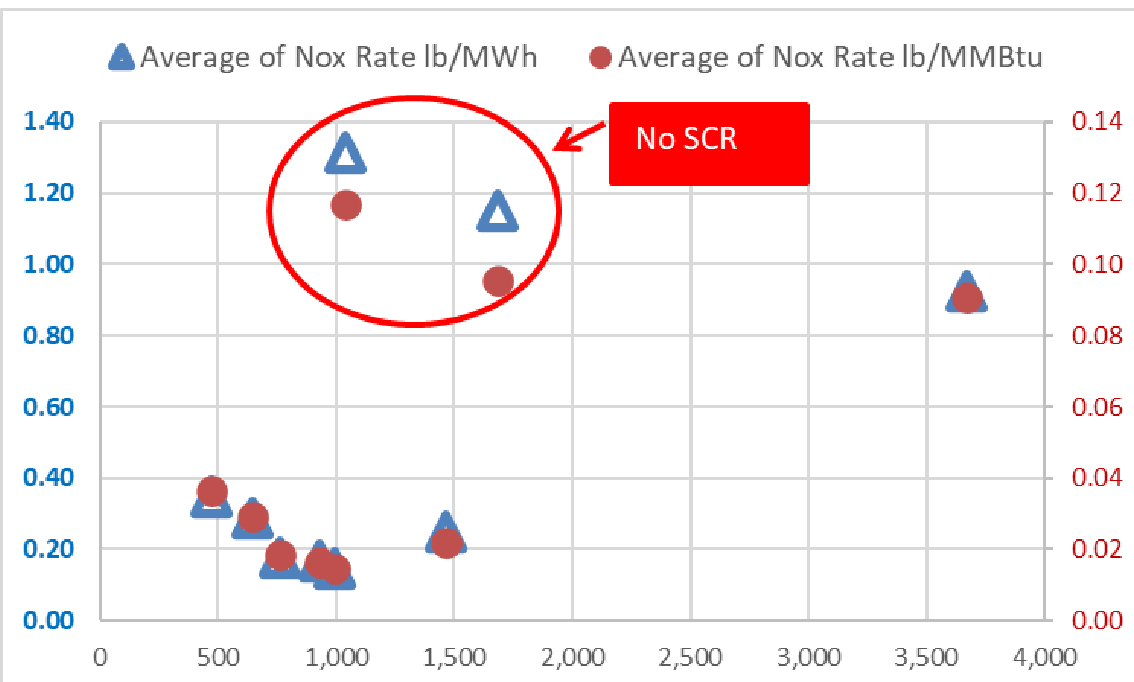
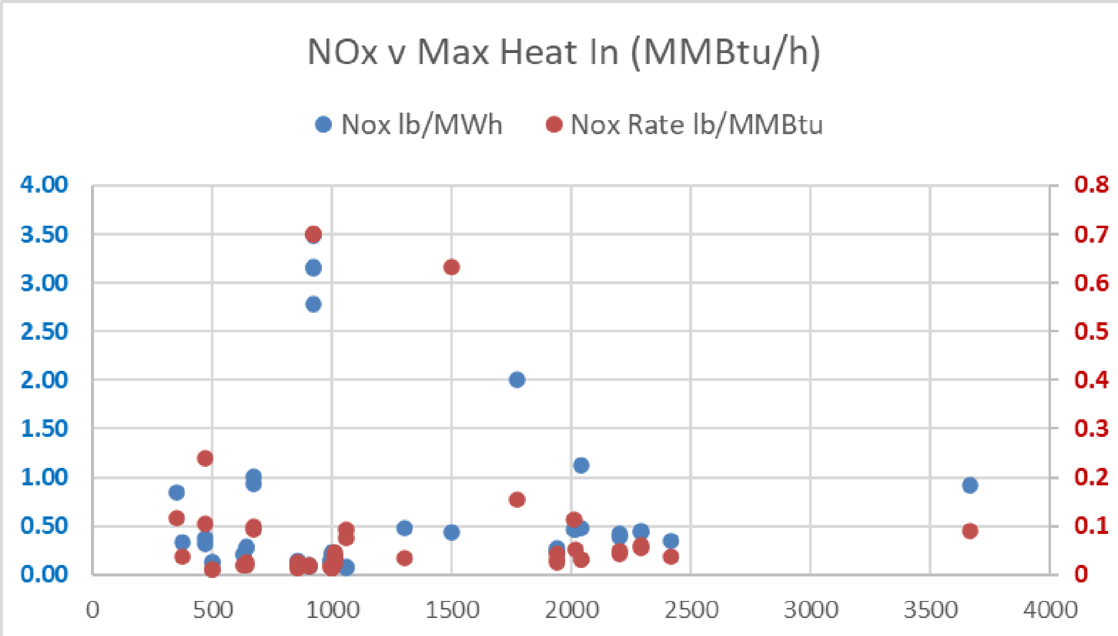


Figure 48. 2020 average NOx versus maximum heat in (MMBtu/hr)



Figures 49 and 50 demonstrate that those units that operate the most, as measured by either cumulative operating hours or by cumulative generation, consistently have the lowest NOx emissions, while units with fewer cumulative operating hours or cumulative generation may or may not have among the lowest NOx emissions rates. Figure 51 demonstrates that there is not a clear trend in emission rates based upon the year in service. Although those units in their fifth or sixth year of service had lower emissions, those in the fourth year of service generally had the highest NOx emissions. Figure 52 shows why this is the case. Those units with the highest average annual operating hours also have the lowest emissions and those with lower average annual operating hours have a wider range of emission rates.

Figure 49. 2020 average NOx versus cumulative operating hours

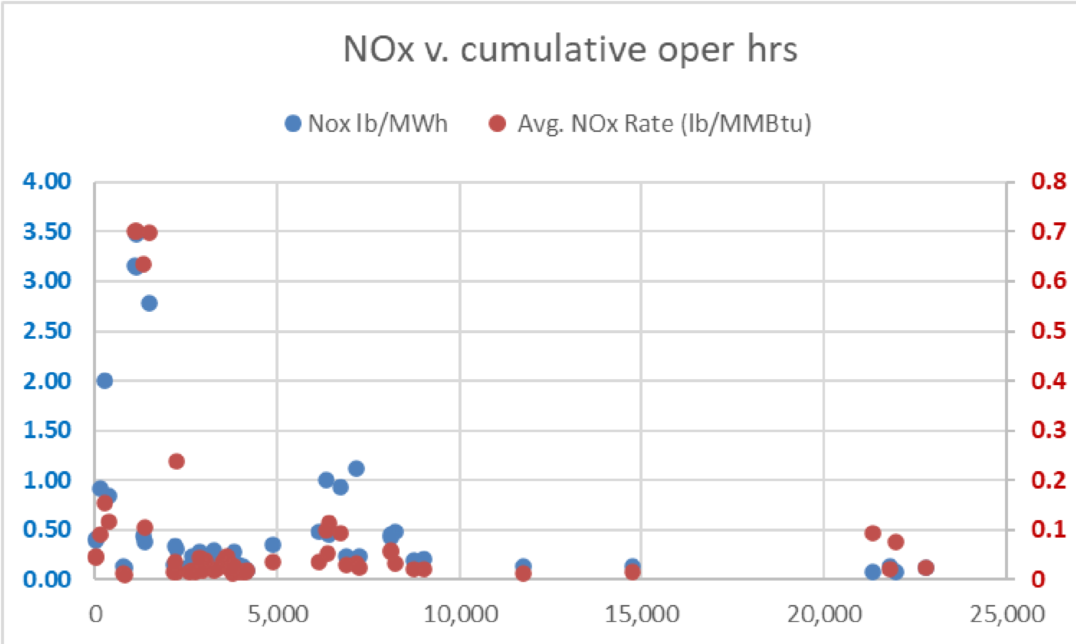


Figure 50. 2020 average NOx versus cumulative operating hours

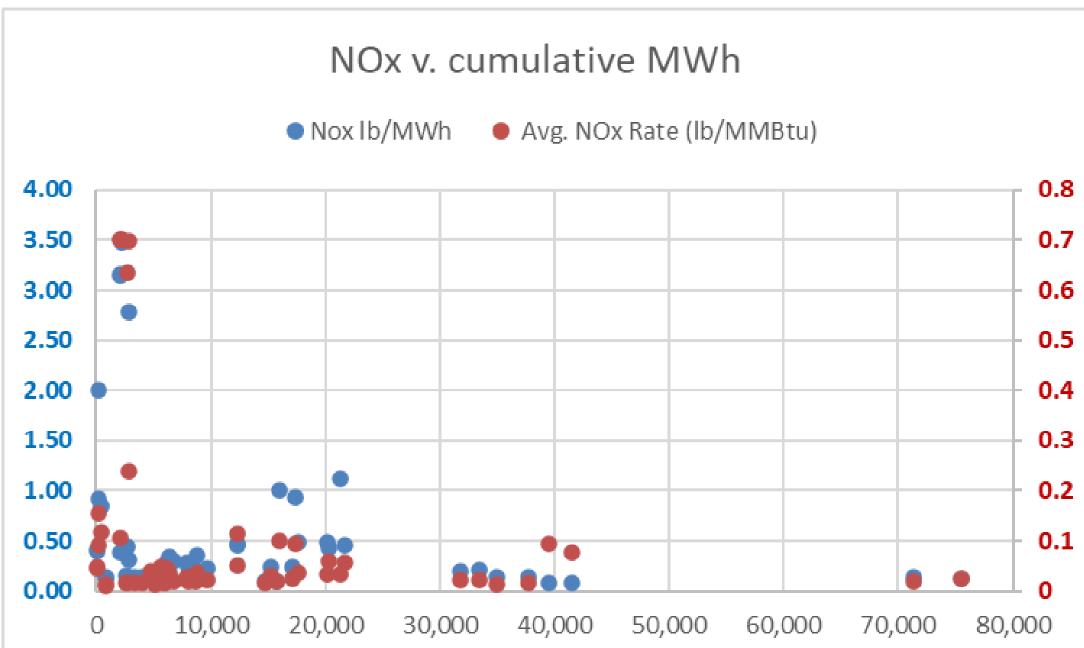


Figure 51. 2020 average NOx versus year in service

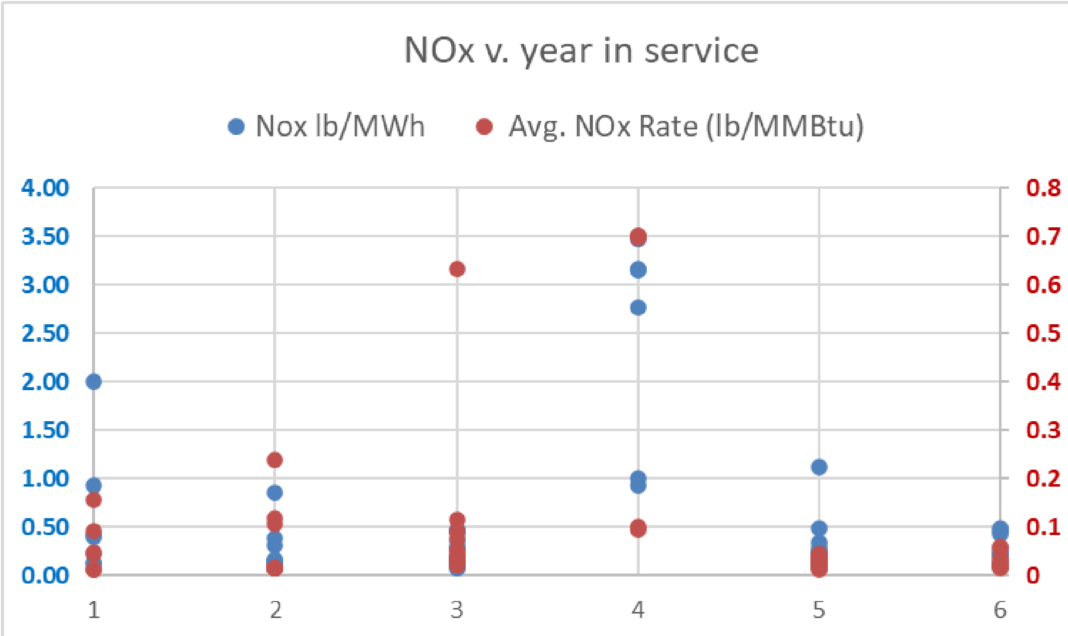
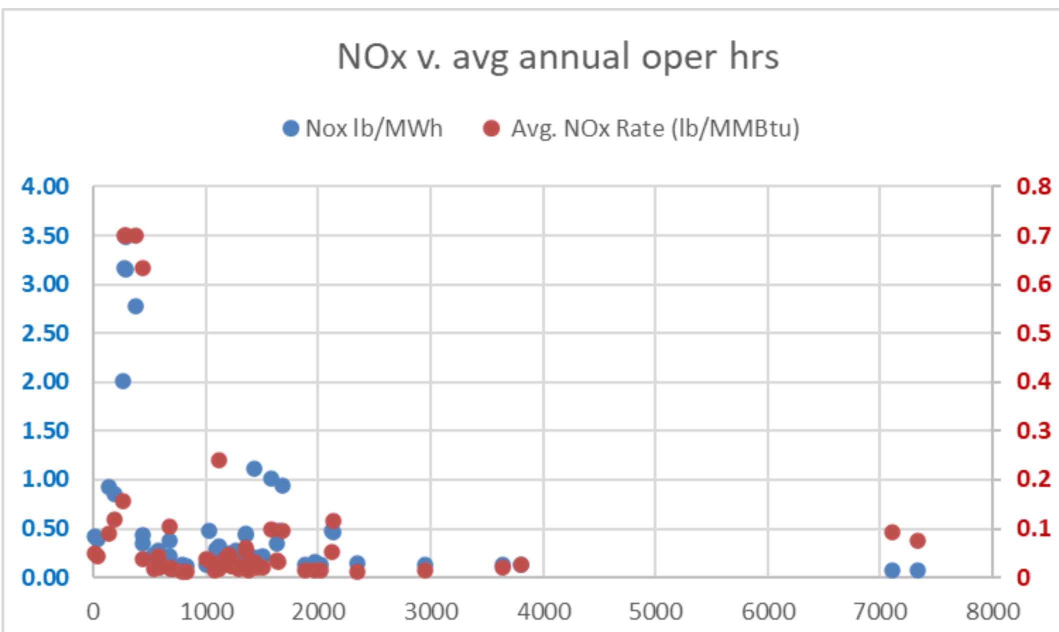


Figure 52. 2020 average NOx versus average annual operating hours



Figures 53 through 62 show NOx emissions by year and operating hours by year for units commencing operation in years 2015, 2016, 2017, 2018 and 2019. Some units clearly reduced their NOx emissions after the first year of operation. Operating hours definitely plays a role in NOx emissions. Noticing Alpine power plant (59926 AL1 and AL2), which commenced operation in 2016, experienced a drop in operating hours in 2019 as well as an increase in NOx emissions rate.

Figure 53. NOx emissions (lb/MWh) by year for CT units commencing operation in 2015

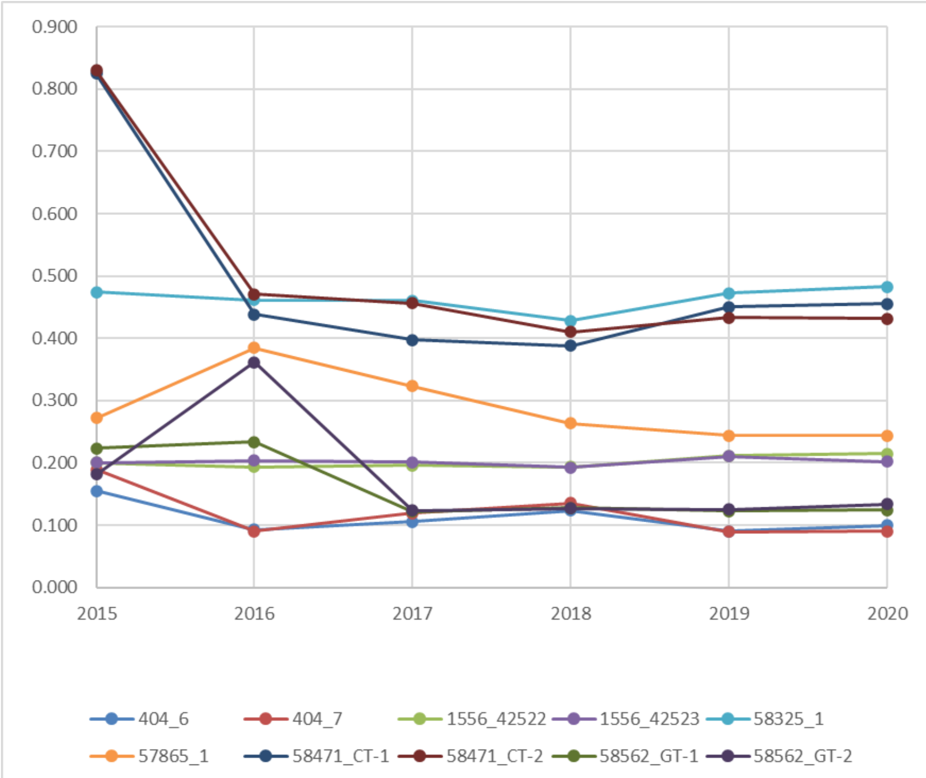


Figure 54. Operating hours by year for CT units commencing operation in 2015

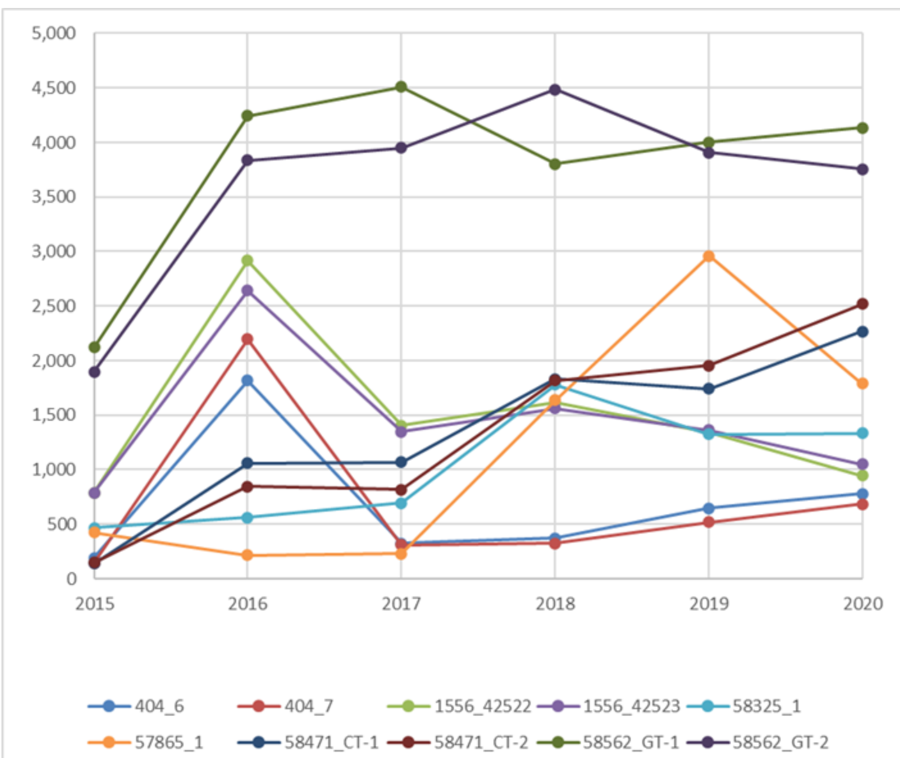


Figure 55. NOx emissions (lb/MWh) by year for CT units commencing operation in 2016

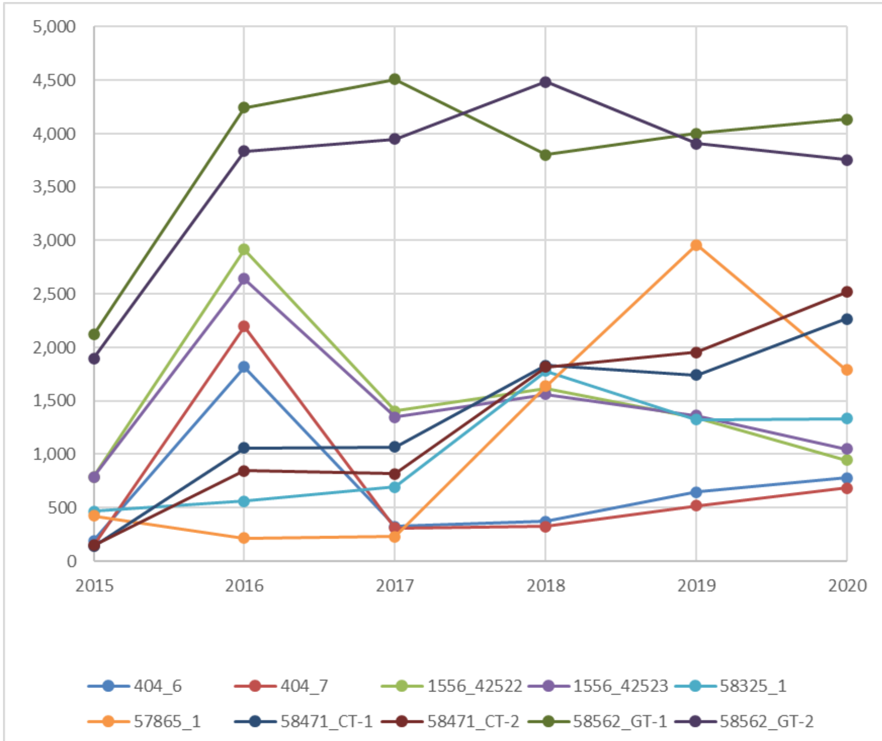


Figure 56. Operating hours by year for CT units commencing operation in 2016

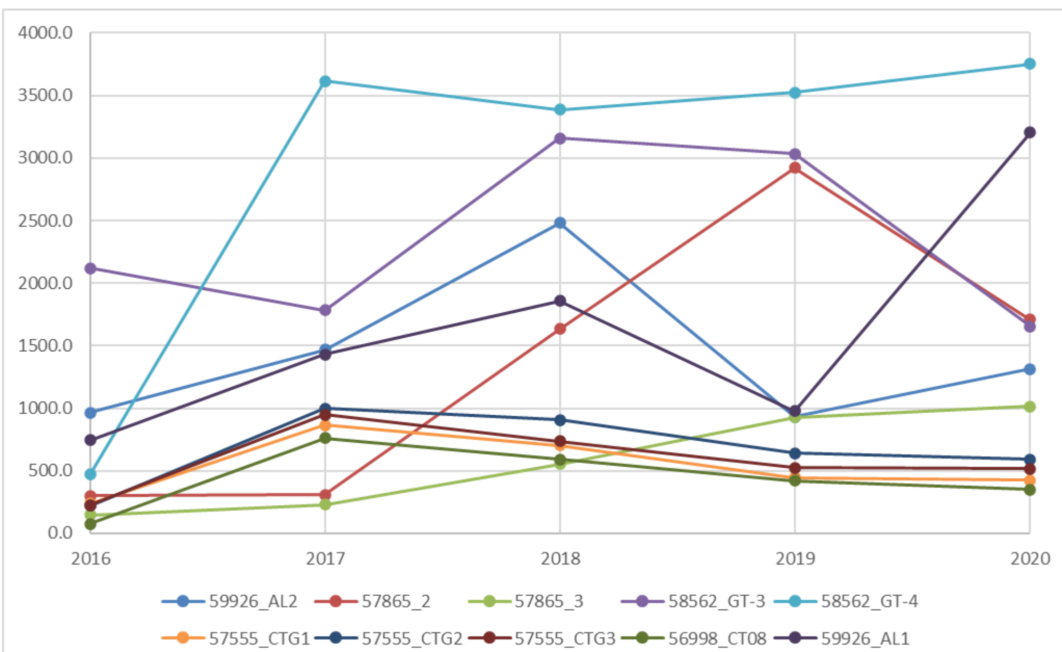


Figure 57. NOx emissions (lb/MWh) by year for CT units commencing operation in 2017

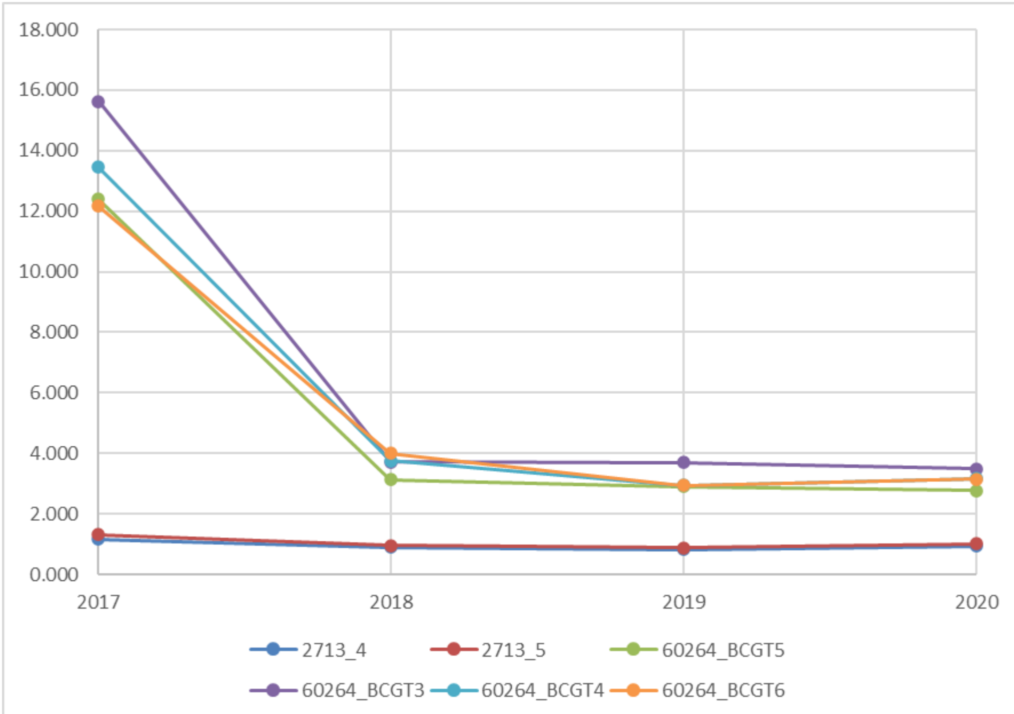


Figure 58. Operating hours by year for CT units commencing operation in 2017

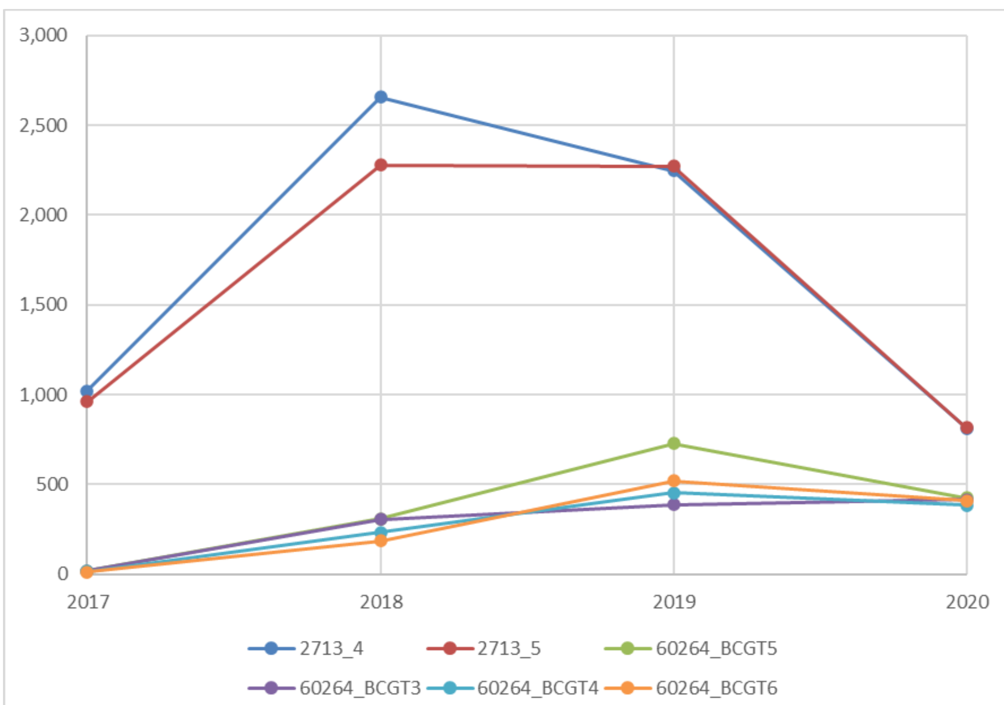


Figure 59. NOx emissions (lb/MWh) by year for CT units commencing operation in 2018

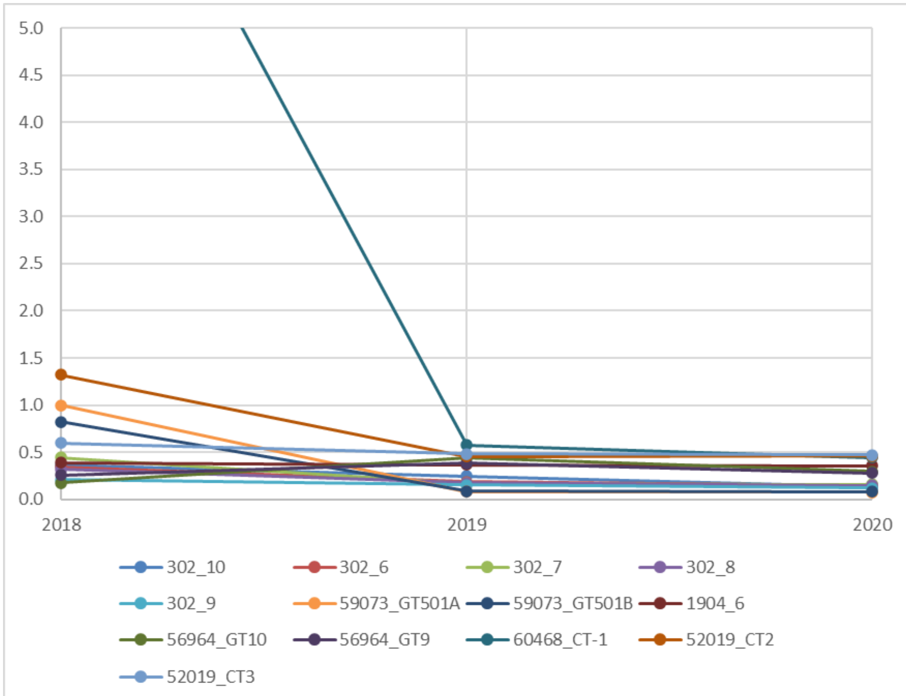


Figure 60. Operating hours by year for CT units commencing operation in 2018

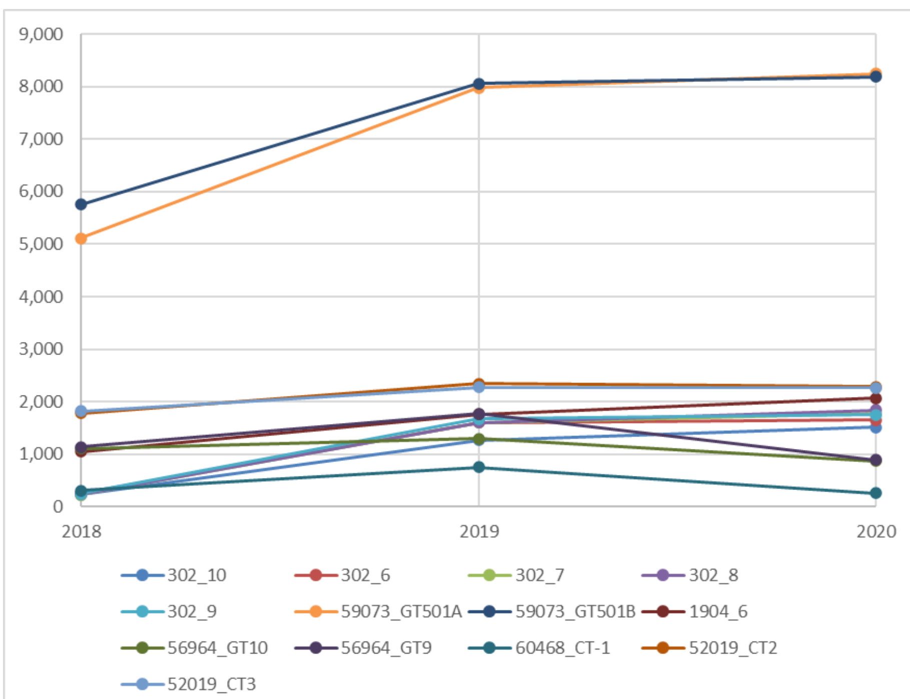


Figure. 61 NOx emissions (lb/MWh) by year for CT units commencing operation in 2019[13]

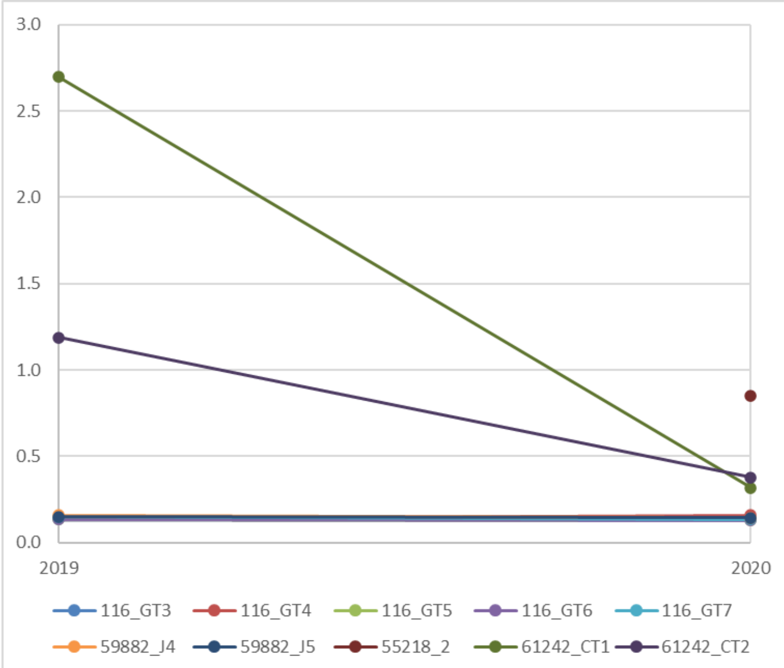
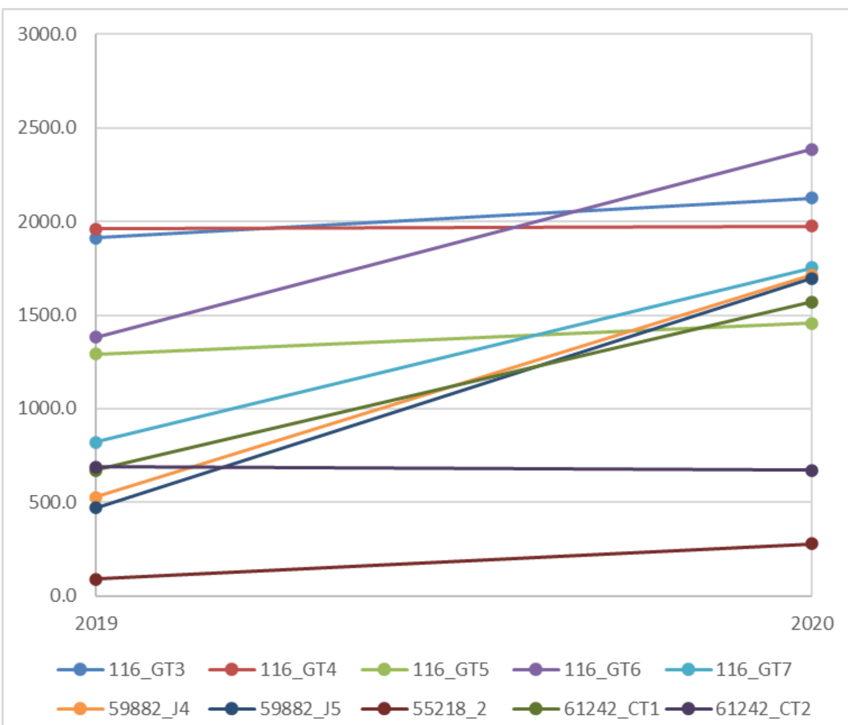


Figure 62. Operating hours by year for CT units commencing operation in 2019



[13] Hinds Energy Facility unit 2 (55218_2) did not have enough 2019 operating time for emissions data.

3. NOx emissions from CT plants

Table 4 shows the average and standard deviation of 2020 NOx emission rates for CT plants installed since 2015. The emission rates are differentiated by whether or not an SCR is installed.

Figures 63 and 64 show the NOx emission rate distribution for all CT units installed since 2015 in terms of lb/MMBtu or lb/MWh, respectively. As expected, the emission rate for units equipped with SCR is well below the emission rate for units without SCR. As these figures show, 61% of those units without SCR and 97% of those units with SCR have emission rates at or below 0.05 lb/MMBtu. On the basis of lb/MWh, all units with SCR and 61% of units without SCR have emission rates at or below 0.50 lb/MWh. As shown in Figure 52, these rate are being achieved by CT units even at low average annual operating hour rates.

Table 4. the average and standard deviation of 2020 NOx emission rates for CT plants installed since 2015

		Nox Rate lb/MWh	Nox Rate lb/MMBtu
No SCR	average	1.0156	0.0854
	stdevp	1.0604	0.0784
With SCR	average	0.1432	0.0211
	stdevp	0.1538	0.0149

Figure 63. Emission rate distribution for 2020 NOx emissions (CT units) for units built since 2015, percent at or below emission rate – all units, lb/MMBtu, without SCR, with SCR

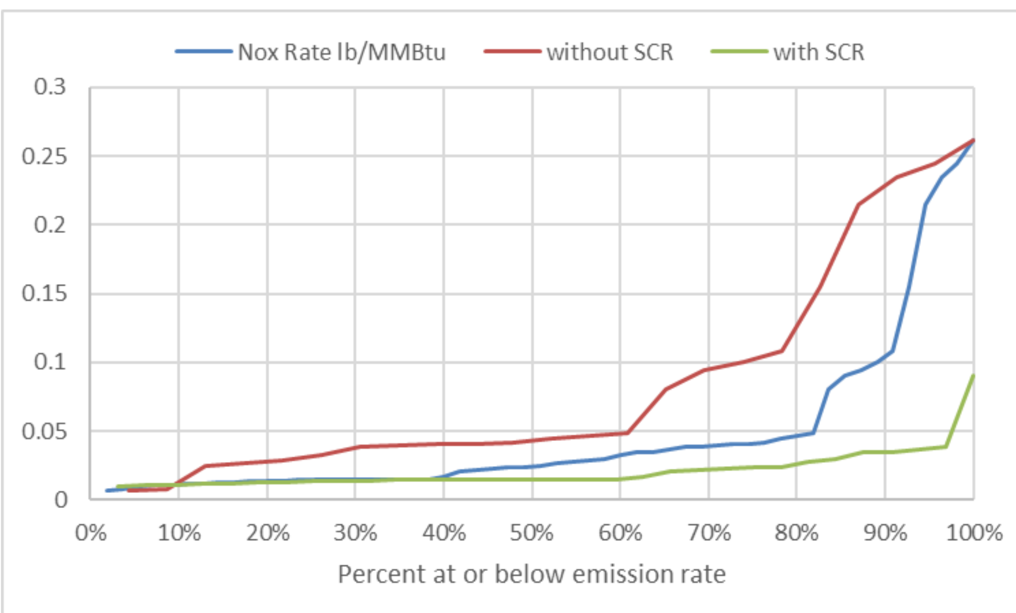
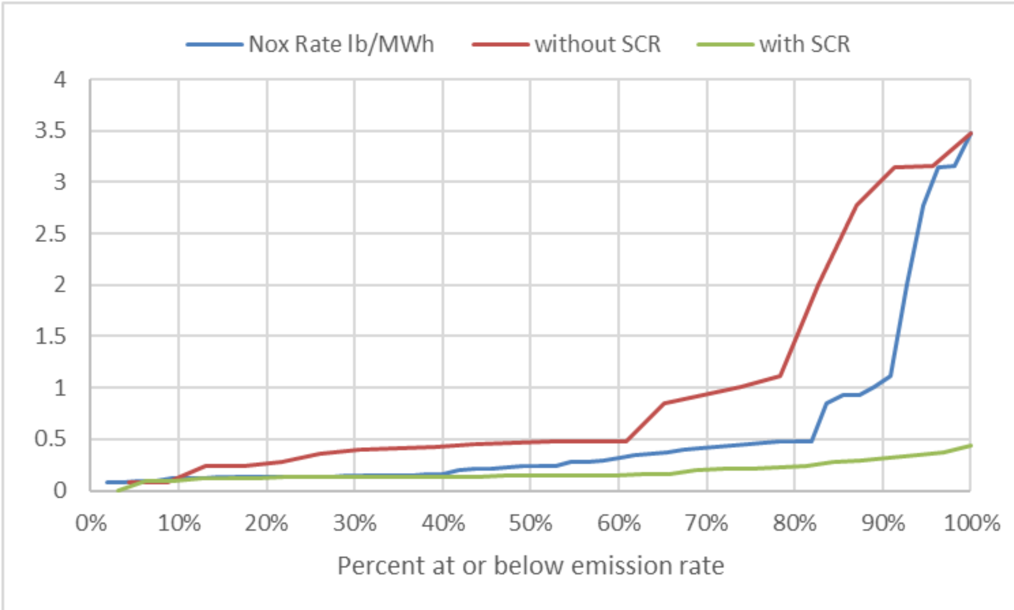


Figure 64. Emission rate distribution for 2020 NOx emissions (CT units) for units built since 2015, percent at or below emission rate– all units, lb/MMBtu, without SCR, with SCR



D. N_2O emissions from CT power plants equipped with SCR

As noted earlier in this report, N2O emissions are possible from SCR systems, but are impacted by several factors. In general, N_2O generation from SCR is a greater concern from diesel engines equipped with SCR than for gas turbines for a number of reasons relating to the exhaust conditions. Although N_2O can be generated from gas turbines equipped with SCR, the information that is available appears to suggest that it will usually be a fairly small amount. This is an area that will require additional attention in the future as more information is gathered.