Analysis of Gas Turbine Heat Integration in Combined Cycle Power Plants

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Abstract

Fuel efficiency is one of the key factors for the profitability of power plant projects. Recent improvements in gas turbine technology offer opportunities to integrate heat from other sources beyond the gas turbine's exhaust into the bottoming cycle of a combined cycle plant. Specifically, heat rejected from the gas turbine's internal cooling systems, in particular the turbine cooling air coolers and the combustor.

In a case study utilizing detailed thermodynamic models, the various heat integration schemes with large 60 Hz heavy duty gas turbines are analyzed and compared against power generation cycles without integration of cooling heat under ISO conditions and in off-design and part load operation. Parameter studies on ambient and load conditions are used to develop and compare load characteristics for different types of integration.

Results include detailed heat balance results and the discussion of the effects of the various heat integration schemes on the overall plant performance over the entire load range.

Introduction

Recent developments in gas turbine technology offer the opportunity to integrate heat available from internal gas turbine cooling systems with the water steam cycle of the combined cycle power plant. In order to reduce the amount of air extracted from the compressor and improve the cooling used to protect the material in the hot gas path of the gas turbine, lower re-injection temperatures of the cooling air that is taken off the air flow at a later or the final stage of the compressor are desired. Instead of rejecting this heat to the environment, the use of heat exchangers connected to the bottoming cycle of the plant offers the opportunity to increase the overall fuel efficiency of the plant.

This study investigates various solutions offered by gas turbine manufactures for the integration of the cooling heat of the gas turbine in a realistic plant scenario of a combined cycle power plant consisting of two gas turbine – HRSG trains and one steam turbine with air cooled condenser. In order to investigate the effects of ambient temperature and load level for different heat integration schemes, net fuel efficiency of the overall plant was evaluated over the entire load range of the respective plant configuration, and ambient temperature was varied between 40 F and 110 F. It was the particular intention of the study to elaborate potential differences in part load operation based on the assumption that a higher level of heat integration might produce better results at part load, since the higher level of heat losses from the gas turbine under such conditions may be partially regained. While it is not intuitive that the transfer of the heat from a more efficient gas turbine to a less efficient bottoming cycle would help, the benefit comes from a drop in the average cooling temperature in the GT, which allows for better cooling effectiveness and ultimately less cooling flow or higher firing temperatures in the gas turbine.

While conducting this study, it became obvious that the use of heat from the bottoming cycle to pre-heat the fuel gas and the inlet air for the gas turbine is a better integration that has a more distinct effect on the overall plant performance. While the benefit from heating of the fuel gas can easily be explained by the recuperation of heat from the bottoming cycle into the combustion process, the benefit from heating the inlet air to the gas turbine doesn't seem obvious at a first glance. By decreasing the density of the gas turbine's inlet air, inlet air heating reduces a gas turbine's base load output and increases its heat rate. The actual benefit of inlet heating is due to the improvement of the plant's part load performance by reducing the degree to which a plant's gas turbine(s) must be part loaded to hit a given plant part load set point. This part load plant efficiency improvement will be shown in the comparison of performance maps covering a wide range of power output and ambient temperatures in the results of this study.

Gas Turbines under Investigation

Table 1 below lists the seven gas turbines that were investigated, five with cooling heat integration and two without. In general, there are two main sources for cooling heat from the gas turbine that are used: the turbine cooling air which is extracted from a late stage or the exit of the air compressor, and heat removed in cooling the gas turbine combustor casing with steam.

OEM	Model Name	Heat Source	Integration Level
Ansaldo Energia	GT36-S6	Cooling air (OTC)	1.7 %
General Electric	7HA.02	none	0.0 %
MHPS	M501J	Cooling air (TCAC) and combustor (STC)	2.5 %
MHPS	M501JAC	Cooling air (TCAC)	1.4 %
MHPS	M501GAC	Cooling air (TCAC)	1.4 %
Siemens	SGT6-5000F	Cooling air (TCAC or OTC)	0.6 %
Siemens	SGT6-8000H	none	0.0 %

Table 1: Gas turbine models investigated in the heat integration study

The level of integration shown in Table 1 is calculated as the percentage of heat available through integration (excluding inlet air heating or fuel heating) divided by the heat consumption of the gas turbine at ISO conditions and full load. Heat from the turbine cooling air is typically integrated into the bottoming cycle in one of two ways:

1. as the high-pressure feedwater prior to the HP evaporator of the HRSG via a device called a turbine cooling air cooler (TCAC), or
2. as HP steam generated from HP feedwater in a kettle boiler operated at HP drum pressure. Most OEMs call this equipment the once-through cooler (OTC).

Heat from the combustor is typically integrated into the IP steam cycle in the so-called steam cooler (STC) which superheats steams taken off of the cold reheat line after saturated steam from the IP evaporator has been mixed in. Additional parameters of the heat integration schemes studied are presented in Table 4 in the next chapter describing the plant design used in the models.

The gas turbine performance data used in this study are based on information supplied by the respective OEMs in the form of performance tables or through web-based calculation tools. Table 2 below provides a comparison of the performance data supplied at ISO conditions (59F, 14.696 psia, 60 % rel. humidity). The table also includes information about the fuel temperature of the respective rating point, since the model calculation also accounts for a change in fuel supply temperature (see Figure 2). If the OEM-supplied curves have some internal air preheating (by re-circulating compressed air), the exact magnitude of this impact would be unknown, however, the impact would be included in the performance data. The addition of an external air heater would reduce the amount of recirculated compressed air, where needed.

	AE GT36-S6	GE 7HA.02	M501J	M501JAC
Power, MW	336.1	346.0	331.5	317.4
Heat Rate, BTU/kWh	8492.0	8080.0	8063.0	8068.0
Exhaust Flow, klb/hr	5555.6	5543.0	4943.0	4937.0
Exhaust Temperature, F	1166.0	1153.0	1171.0	1151.0
Total Cooling Duty, MW	14.3	0.0	19.4	10.4
Heat Consumption, MW	836.4	819.3	783.3	750.5
Fuel Temperature, F	59.0	440.0	392.0	392.0

Table 2: ISO rating of gas turbine models investigated in the heat integration study

	M501GAC	SGT6-5000F	SGT6-8000H
Power, MW	281.3	249.8	302.8
Heat Rate, BTU/kWh	8514.0	8664.9	8490.5
Exhaust Flow, klb/hr	4898.0	4611.2	5182.6
Exhaust Temperature, F	1137.0	1097.6	1169.6
Total Cooling Duty, MW	9.7	4.0	0.0
Heat Consumption, MW	701.9	634.4	753.5
Fuel Temperature, F	392.0	59.0	419.0

Table 2 continued: ISO rating of gas turbine models investigated in the heat integration study

The gas turbines were modelled in the VTU Gas Turbine Library add-on for the EBSILON®Professional heat balance software which uses gas turbine OEM supplied rating data and correction curves along with a calculation approach similar to the ASME PTC 22 correction procedures for gas turbine performance tests to calculate gas turbine performance at different ambient conditions and loads. Correction curves for the main factors that influence gas turbine performance were applied since the calculation of gas turbine performance based on physical equations for the compression, combustion and expansion processes is practically impossible without detailed design data for the gas turbine and knowledge of its underlying control philosophy and mechanisms.

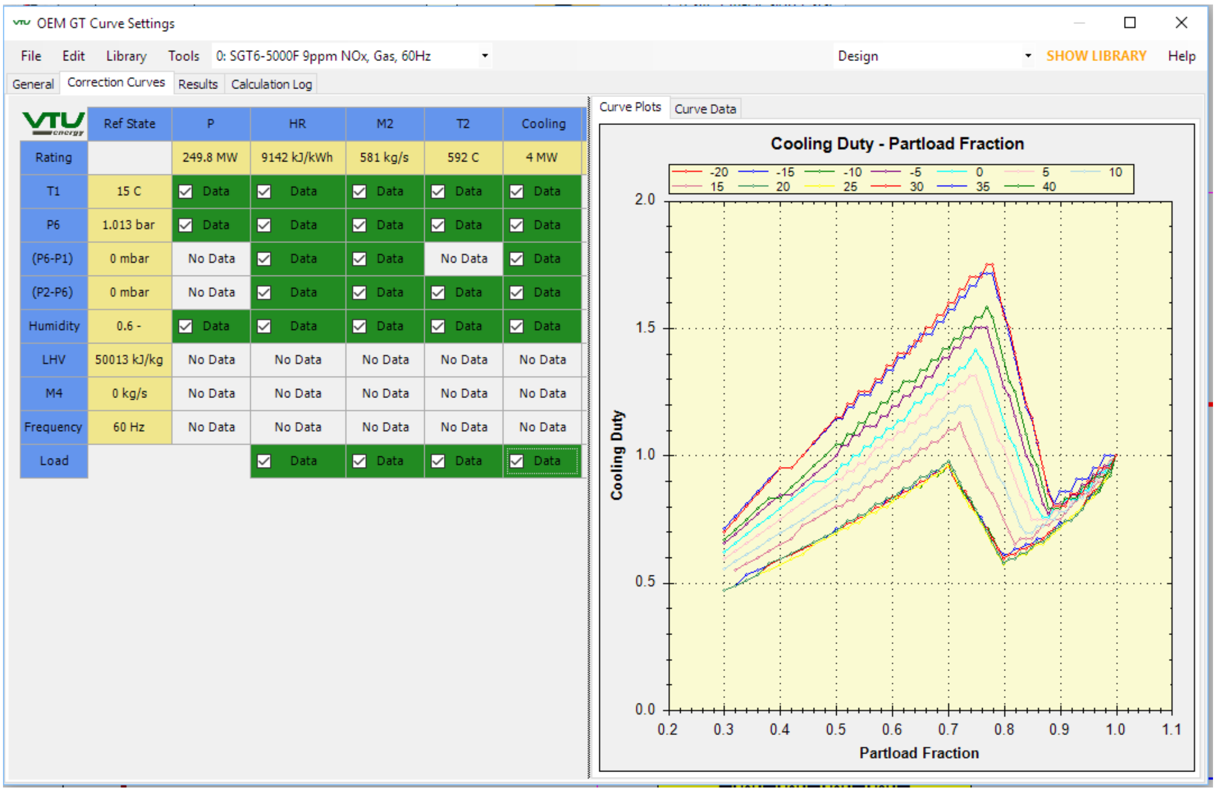
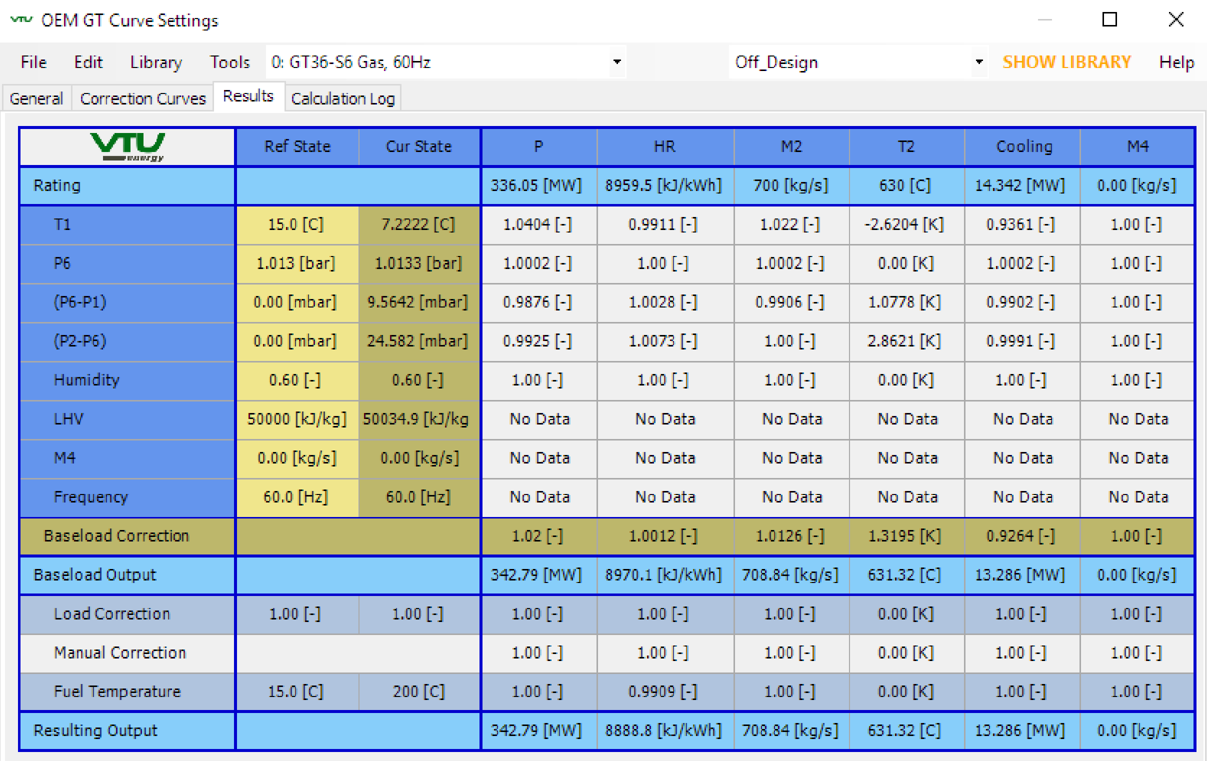


Figure 1: Sample of gas turbine correction curve based on vendor performance data (Siemens SGT6-5000F cooling duty as a function of ambient temperature and part load fraction, data source SIPEP)



OEM GT Curve Settings

File | Edit | Library | Tools | 0: GT36-S6 Gas, 60Hz | Off_Design | SHOW LIBRARY | Help

General | Correction Curves | Results | Calculation Log

VTU energy	Ref State	Cur State	P	HR	M2	T2	Cooling	M4
Rating			336.05 [MW]	8959.5 [kJ/kWh]	700 [kg/s]	630 [C]	14.342 [MW]	0.00 [kg/s]
T1	15.0 [C]	7.2222 [C]	1.0404 [-]	0.9911 [-]	1.022 [-]	-2.6204 [K]	0.9361 [-]	1.00 [-]
P6	1.013 [bar]	1.0133 [bar]	1.0002 [-]	1.00 [-]	1.0002 [-]	0.00 [K]	1.0002 [-]	1.00 [-]
(P6-P1)	0.00 [mbar]	9.5642 [mbar]	0.9876 [-]	1.0028 [-]	0.9906 [-]	1.0778 [K]	0.9902 [-]	1.00 [-]
(P2-P6)	0.00 [mbar]	24.582 [mbar]	0.9925 [-]	1.0073 [-]	1.00 [-]	2.8621 [K]	0.9991 [-]	1.00 [-]
Humidity	0.60 [-]	0.60 [-]	1.00 [-]	1.00 [-]	1.00 [-]	0.00 [K]	1.00 [-]	1.00 [-]
LHV	50000 [kJ/kg]	50034.9 [kJ/kg	No Data	No Data	No Data	No Data	No Data	No Data
M4	0.00 [kg/s]	0.00 [kg/s]	No Data	No Data	No Data	No Data	No Data	No Data
Frequency	60.0 [Hz]	60.0 [Hz]	No Data	No Data	No Data	No Data	No Data	No Data
Baseload Correction			1.02 [-]	1.0012 [-]	1.0126 [-]	1.3195 [K]	0.9264 [-]	1.00 [-]
Baseload Output			342.79 [MW]	8970.1 [kJ/kWh]	708.84 [kg/s]	631.32 [C]	13.286 [MW]	0.00 [kg/s]
Load Correction	1.00 [-]	1.00 [-]	1.00 [-]	1.00 [-]	1.00 [-]	0.00 [K]	1.00 [-]	1.00 [-]
Manual Correction			1.00 [-]	1.00 [-]	1.00 [-]	0.00 [K]	1.00 [-]	1.00 [-]
Fuel Temperature	15.0 [C]	200 [C]	1.00 [-]	0.9909 [-]	1.00 [-]	0.00 [K]	1.00 [-]	1.00 [-]
Resulting Output			342.79 [MW]	8888.8 [kJ/kWh]	708.84 [kg/s]	631.32 [C]	13.286 [MW]	0.00 [kg/s]

Figure 2: Sample of gas turbine calculation results under off-design conditions (AE GT36-S6)

Plant Design

The combined cycle power plant models of the study consist of two trains of gas turbines connected to an unfired three pressure reheat heat recovery steam generator with integral deaerator. Since the study assumes identical performance of the GT / HRSG trains, the total steam flows to/from the single three-pressure reheat steam turbine are modelled with multipliers/dividers (see Figure 3 below). The steam exiting the steam turbine is condensed in an air-cooled condenser (ACC) unit consisting of the necessary number of bays to produce the desired condenser pressure of 1.45 psia/100 mbar under design conditions (ISO). In off-design, the number of operating ACC bays is controlled to reduce the ST back pressure to a target pressure of 1.16 psia/80 mbar.

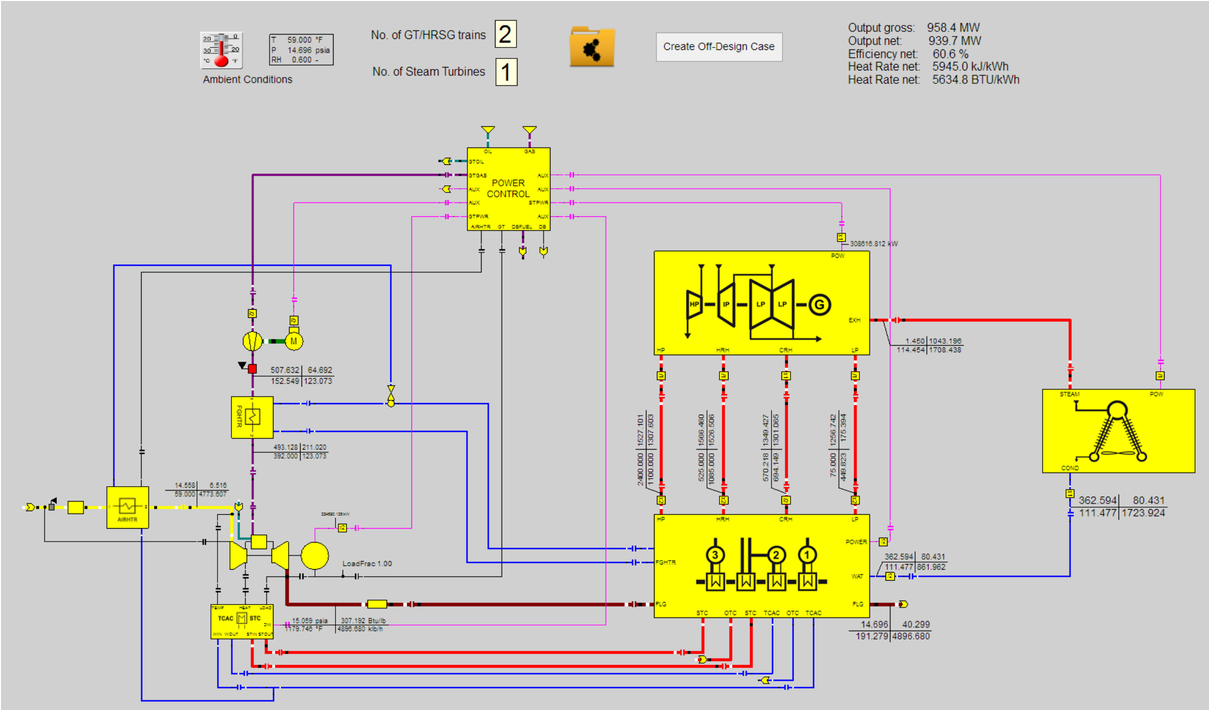


Figure 3: Plant model for MHPS 501J with heat integration for turbine cooling air cooler (TCAC), combustor steam cooling (STC), fuel gas heater (FGHTR), and inlet air heater (AIRHTR) in EBSILON®Professional

The heat integration equipment included with the gas turbine in the model comprises of the following elements if applicable for the chosen gas turbine:

- A Turbine Cooling Air Cooler – TCAC,
- A Once Through Cooler – OTC
- A Steam Cooler – STC (each if applicable),
- A fuel gas heater using HP feedwater to heat the gas fuel before it enters the GT combustor
- An inlet air heater also fed by HP feedwater to modulate the temperature of the air entering the gas turbine compressor. For the inlet air heating more suitable temperature levels exist which may result in slightly better performance, but this study uses a retrofit perspective utilizing existing connections for TCAC with HP feedwater at 350 to 400 F.

The model is capable of calculating off-design performance of the power plant applying physics-based equations on heat exchanger performance, pressure losses, steam turbine section efficiencies, steam turbine exhaust losses, etc. The level of detail applied in the modelling can also be seen in the flow sheet of the sub-model for the HRSG shown in Figure 4 which reflects the structure of the HRSG with individual heat exchange surfaces, the integral deaerator and the feedwater pre-heater.

The model also includes a controller unit that is capable of controlling the gas turbine load (and – if activated – the duty of the inlet air heater) to a specified target net power output of the plant when executed in off-design mode.

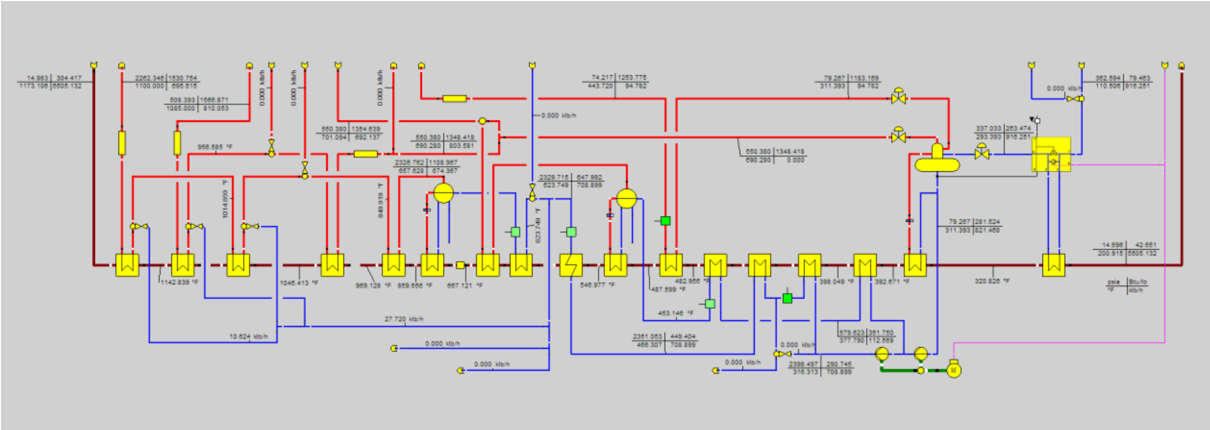


Figure 4: Sub-model of the 3-pressure reheat HRSG of the plant model

Table 3 and Table 4 below summarize the design parameters of the plant model and the key control parameters for the heat integration with the gas turbine.

Plant Design Parameter (@ ISO)	**Value**
GT inlet filter pressure loss	2.8 inH2O
Inlet air heater air-side pressure loss	1.0 inH2O
Inlet air heater water-side pressure loss	4.4 psia
Fuel gas heater gas-side pressure loss	14.5 psia
Fuel gas heater water-side pressure loss	7.3 psia
Duct + HRSG pressure loss	10 inH2O
HRSG HP steam temperature	1100 F
HRSG HP pressure	2400 psia
CRH relative pressure loss	7.0 %
HRSG IP steam temperature	1085 F
HRSG IP pressure	525 psia
HRSG LP steam temperature	450 F
HRSG LP pressure	75 psia
Condensate preheater control temperature	140 F
ST HP section isentropic efficiency	91.4 %
ST IP section isentropic efficiency	93.4 %
ST LP section isentropic efficiency	92.6 %
ST design point exhaust loss (at 820 ft/s)	9.32 BTU/lb
Air-cooled condenser pressure	2.95 inHg

Table 3 Design parameters of the plant model

In design mode as well as in off-design calculations, the flows of the cooling and heating media of the various pieces of heat integration equipment are controlled to establish a specific exit condition to the respective heat exchanger.

Heat Integration Control Parameters	**Value**
Inlet air heater maximum exit temperature	113 F
Fuel gas heater exit temperature	392 – 440 F*
TCAC exit subcooling for HP feedwater	27 R
OTC exit degrees of superheat for IP steam	180 R
STC exit degrees of superheat for IP steam	450 R

Table 4: Heat Integration Control Parameters

The range of target fuel gas temperatures is a result of the fact that the manufacturers specify different temperatures in their performance data (MHPS: 392 F, GE: 440 F, Siemens SGT6-8000F: 419 F). For gas turbines where the rated fuel gas temperature was specified at ambient temperature of 59 F, a value of 392 F for target fuel temperature was assumed. The water returned from the inlet air heater and fuel gas heater mixes with condensate at the inlet of the feed water preheater, thereby aiding the preheater.

Study Parameters and Evaluation Method

The plant model was executed over the entire load range of each plant type from minimum gas turbine load level (30 % for all GTs except for the Siemens SGT6-8000H which according to the SIPEP web portal has a minimum part load level of 45%) to base load in load steps of 5 MW and at ambient temperatures between 40 F and 110 F with step size of 5 F. In order to create data at ISO conditions, the temperature of 60 F was replaced with 59 F. Ambient pressure was kept constant at ISO conditions of 14.696 psia, and ambient relative humidity was set to 60 % in all cases.

Since the plants can produce certain net power output with either one or two gas turbines in operation (which of course produces a very different result in terms of fuel efficiency due to the low part load level when operating with two GTs), the maximum net power output for operating with only one gas turbine at base load was determined and a respective switching point was added to the array of target output values that covered the range between 100 MW and 1100 MW. Below this switching point, the plant model uses only one GT/HRSG train in operation, whereas two GT/HRSG trains are running above this value.

In total, every performance map consists of 3540 heat balance calculations. Since the Siemens SGT6-5000F gas turbine can be integrated with the bottoming cycle using both, TCAC and OTC, the study investigated eight plant configurations, each with three levels of heat integration:

(a) GT cooling heat integration only (no fuel gas heater, no inlet air heater)
(b) GT cooling heat integration plus fuel gas heater only
(c) GT cooling heat integration, fuel gas heater and inlet air heater

Thus the study covers a total of 3540*8*3 calculations giving a total of 84,960 heat balances.

The performance map provides a very informative overview of the plant capabilities by displaying the dependency of the fuel efficiency as a function of plant net power output and ambient temperature. As shown in Figure 5, the color-coding of the map represents the plant net fuel efficiency per the right-hand side color scale ranging in this example from 42 % to 61 %. Areas of the performance map with black color are either out of range of the scale or outside of the operating envelope of the power plant based on the minimum and maximum allowable loads for the gas turbine.

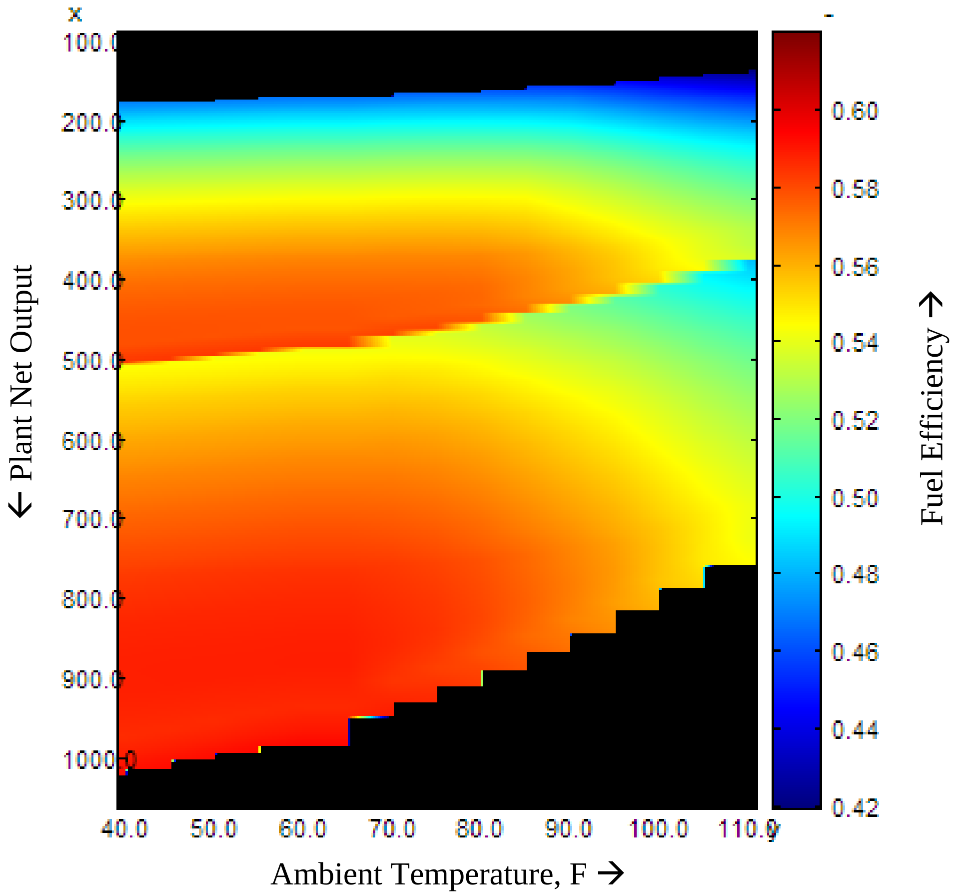


Figure 5: Sample of a plant performance map showing overall plant net fuel efficiency in color code (right-hand scale from 0.42/blue to 0.62/dark red) versus plant net power output (left-hand scale from 100 to 1100 MW top to bottom) and ambient temperature (bottom scale)

The two pronounced hot spots of good efficiency in Figure 5 depict the operation with one and with two gas turbines of the 2x1 CCGT plant. The ragged lines stem from the fact that analysis has been carried out by varying the ambient temperature in steps of 5 °F.

Results

Effect of Cooling Heat Integration

Table 5 compares net output and net heat rate at base load under ISO conditions for plant configurations with gas turbines with cooling heat integration with cases in which the GT cooling heat is not integrated with the bottoming cycle. The latter scenario is of course against the intention of the manufacturers and is not recommended in practice, but the comparison demonstrates that there would be significant losses in overall plant performance, if the cooling heat of these gas turbines was dissipated to the environment.

	Net Output		Change	Net Heat Rate		Change
Cooling Heat Integration	**with**	**without**		**with**	**without**	
GT Model \ UOM	MW	MW	%	BTU/kWh	BTU/kWh	%
AE GT36-S6	982.657	966.64	-1.63%	5750.5	5845.8	+ 1.66%
M501J	944.716	925.79	-2.00%	5656.9	5772.5	+ 2.04%
M501JAC	898.726	890.47	-0.92%	5696.9	5749.7	+ 0.93%
M501GAC	819.435	811.62	-0.95%	5845.8	5902.0	+ 0.96%
SGT6-5000F (W)	733.433	730.59	-0.39%	5944.5	5967.6	+ 0.39%
SGT6-5000F (S)	734.829	730.17	-0.63%	5933.2	5971.0	+ 0.64%

Table 5: Comparison of overall plant base load performance (net) under ISO ambient conditions with and without the integration of the cooling heat of the gas turbine.

It is interesting to note that – depending on the nature of the heat integration – the change in overall plant performance differs from the integration level for the individual gas turbines shown in Table 1. The removal of the cooling heat has a smaller impact on overall plant performance for plants with integration on the feedwater level than for plants with heat integration using steam. This can be seen in particular when comparing the SGT6-5000F plants where the cooling heat can be integrated with either option, a TCAC producing slightly sub-cooled HP feedwater - denoted as SGT6-5000F (W) in Table 5) - or a OTC producing saturated HP steam – denoted as SGT6-5000F (S).

In order to investigate the effect of cooling heat integration on part load performance compared to gas turbines without such integration, plant performance maps were produced for eight plant configurations of which two (GE 7HA.02 and Siemens SGT6-8000H) do not apply cooling heat integration. None of the plant models includes a fuel gas or an inlet air heater with their respective pressure losses. Consequently, the ISO net power output of these plant configurations is slightly higher than that for the plant configurations utilizing fuel gas heaters and both, fuel gas heater and inlet air heating, which are discussed in the following chapters.

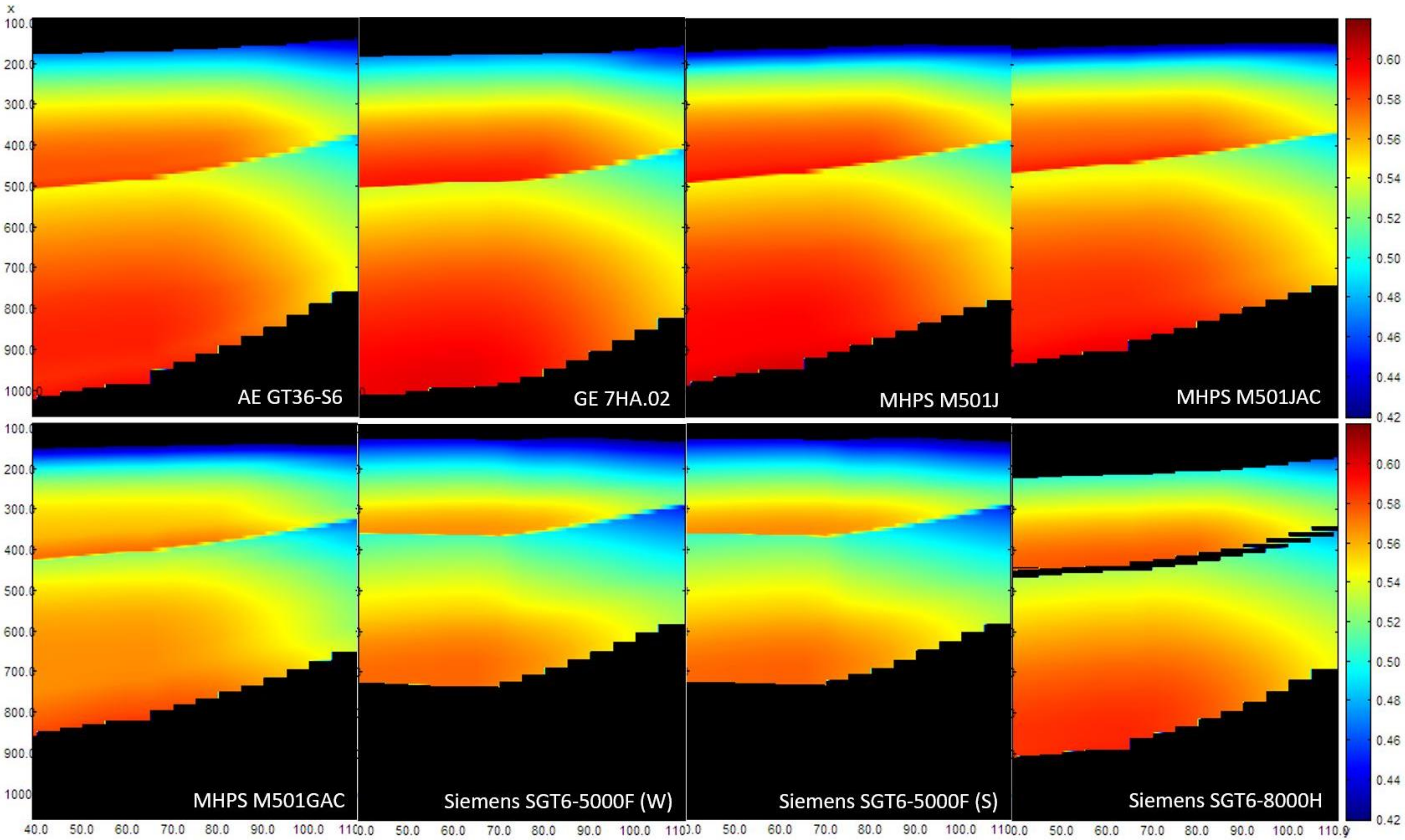


Figure 6: Plant performance maps for plant configurations without fuel gas heater and inlet air heating. All gas turbines except GE 7HA.02 and Siemens SGT6-8000H are equipped with cooling heat integration with the bottoming cycle at levels between 0.6 and 2.5% of the GT heat consumption.

From the visual comparison of the plant performance maps in Figure 6, no significant differences in part load performance can be detected between gas turbines with cooling heat integration and those that are not integrated. For all gas turbines, base load operation at low ambient temperatures is of course most efficient. The two plants based on the SGT6-5000F have the lowest output capacity which is even more restricted by a generator cap limiting the net power output per turbine to a value of 249.8 MW at ambient temperatures below 68 F. Since the contribution from the cooling heat increases with ambient temperature, the overall plant output thus increases with temperature from 726 MW at 40 F to 737 MW at 68 F.

Overall plant efficiency in all cases decreases with ambient temperature and the lower the part load level of the gas turbine which separates the map in two distinct areas with two or one gas turbines in operation, respectively.

For the SGT6-8000H plant (performance map at the far right in bottom row in Figure 6) a band of overall plant output exists over the entire temperature range in which the plant cannot be operated. This is due to the limitation of the minimum load level of the gas turbine to 45 percent, so that the minimum output of the plant with two gas turbines in operation is larger (460 MW) than the output achievable with one gas turbine running at base load (449MW).

Effect of Fuel Gas Heating

A summary of the effect of fuel gas heating at base load operation under ISO conditions for the eight plant configuration is presented in Table 6 below.

	Net Output		**Change**	**Net Heat Rate**		**Change**
Fuel Gas Heater	**without**	**with**		**without**	**with**	
GT Model \ UOM	MW	MW	%	BTU/kWh	BTU/kWh	%
AE GT36-S6*	982.657	980.107	-0.26%	5750.5	5729.1	-0.37%
GE 7HA.02	989.593	986.161	-0.35%	5688.6	5661.4	-0.48%
M501J*	944.716	942.256	-0.26%	5656.9	5633.4	-0.42%
M501J*	898.726	896.379	-0.26%	5696.9	5673.3	-0.41%
M501JAC*	819.435	817.145	-0.28%	5845.8	5820.5	-0.43%
M501GAC*	733.433	731.368	-0.28%	5944.5	5918.3	-0.44%
SGT6-5000F (W)*	734.829	732.761	-0.28%	5933.2	5907.0	-0.44%
SGT6-5000F (S)*	887.042	884.631	-0.27%	5803.1	5777.6	-0.44%
SGT6-8000H	982.657	980.107	-0.26%	5750.5	5729.1	-0.37%

Table 6: Comparison of overall plant base load performance (net) under ISO ambient conditions with and without fuel gas heater. *Fuel temperature before combustor 392 F except for GE 7HA.02 (440 F) and SGT6-8000H (419 F)

The addition of the fuel gas heater creates a decrease in overall plant net power output, since only the gas turbine heat rate is affected by the pre-heating, and base load output remains unchanged while the steam turbine output is reduced by transferring heat from the bottoming cycle to the fuel gas heater instead of the HP drum's feedwater. A second contributor to the loss in overall net output is the additional auxiliary power required to compensate for the increase in pressure loss in the fuel supply.

The fuel gas heater however reduces the overall plant net heat rate in the range from 0.37 to 0.48 %, if fuel is preheated to 392 F and 440 F, respectively.

The effect of the fuel gas heating in part load operation is shown in the heat rate versus net output diagram at constant ambient temperature in Figure 7 below.

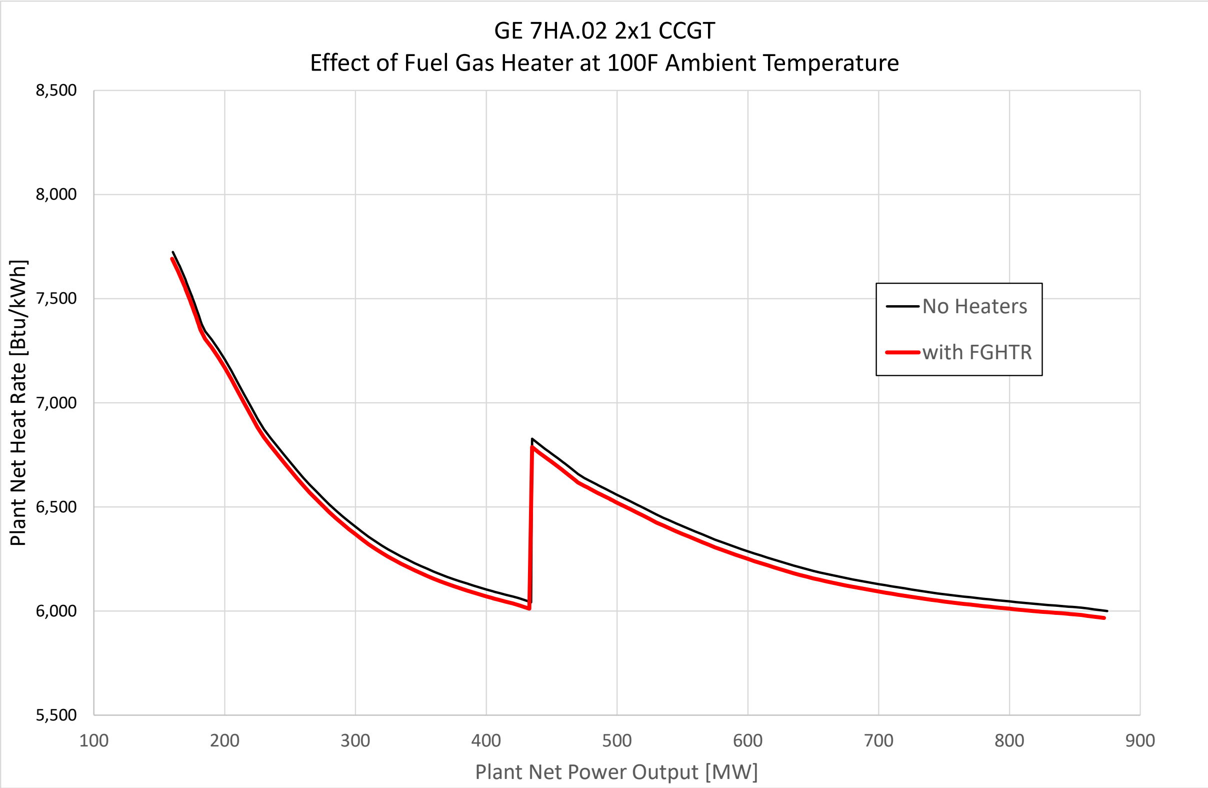


Figure 7: Effect of fuel gas heating for GE 7HA.02 at 100F

The overall plant heat rate is improved over the entire load range, but – since it is proportional to the fuel flow rate – it is most distinct at the base load points of the gas turbine.

Effect of Inlet Air Heating

Inlet heating has an effect on the overall plant performance even when the heater is not in operation, since it adds pressure loss in the air duct feeding into the gas turbine compressor. This negatively impacts both, output and heat rate of the gas turbine. For the overall plant, there are two small exceptions with the SGT6-5000F plants as can be seen from Table 7, the summary of plant performance changes due to the addition of the inlet air heater for which a pressure loss of one inch of water is assumed.

	Net Output		**Change**	**Net Heat Rate**		**Change**
Inlet Air Heater	**without**	**with**		**without**	**with**	
GT Model \ UOM	MW	MW	%	BTU/kWh	BTU/kWh	%
AE GT36-S6*	980.107	977.236	-0.29%	5729.1	5731.7	+ 0.05%
GE 7HA.02	986.161	983.536	-0.27%	5661.4	5662.4	+ 0.02%
M501J*	942.256	939.571	-0.28%	5633.4	5635.6	+ 0.04%
M501JAC*	896.379	894.023	-0.26%	5673.3	5674.2	+ 0.02%
M501GAC*	817.145	814.835	-0.28%	5820.5	5822.7	+ 0.04%
SGT6-5000F (W)*	731.368	731.946	+ 0.08%	5918.3	5920.4	+ 0.04%
SGT6-5000F (S)*	732.761	733.354	+ 0.08%	5907.0	5909.0	+ 0.03%
SGT6-8000H	884.631	882.095	-0.29%	5777.6	5780.6	+ 0.05%

Table 7: Comparison of overall plant base load performance (net) under ISO ambient conditions with and without inlet air heater installed (fuel gas heater in operation in both cases, inlet air heater off).

The positive effect on plant net output for the two SGT6-5000F plants is due to the fact that the gas turbine is actually operating at the same generator output in both cases, since this gas turbine operates at its generator cap. The power loss due to the lower absolute inlet pressure is offset by the higher part load fraction applied to reach the 'nominal' base load point. Performance corrections for the cooling heat available for TCAC/OTC are affected positively by an increase in inlet pressure loss however, so that the steam turbine output and consequently the overall plant output increases.

The purpose of the inlet heater is to improve overall plant fuel efficiency in part load operation by keeping the gas turbine(s) at base load or higher part load levels. Table 8 below summarizes the effect of inlet air heating by comparing operation under ISO conditions at three different part load percentages relative to the respective base load output with inlet heater off shown in the second column with numbers in Table 7. With very few exceptions, part load fuel efficiency is significantly better with inlet heating on compared to inlet heating off (i.e. compressor inlet air temperature at ambient of 59 F). In order to explain why the positive effect is not continuously present, a load swing of a plant from minimum to maximum output with three plant configurations is shown in Figure 8.

	Net HR @80% ISO O/P			Net HR @60% ISO O/P			Net HR @40% ISO O/P		
Inlet Air Heater	off	on		Off	on		off	on	
GT Model	BTU/kWh	BTU/kWh	%	BTU/kWh	BTU/kWh	%	BTU/kWh	BTU/kWh	%
AE GT36-S6	5802.0	5807.0	0.09%	6045.3	5955.8	-1.48%	5942.0	5940.3	-0.03%
GE 7HA.02	5783.9	5752.5	-0.54%	6086.5	5974.1	-1.85%	5898.4	5861.1	-0.63%
M501J	5755.9	5740.4	-0.27%	6024.0	5916.7	-1.78%	5875.9	5864.7	-0.19%
M501JAC	5814.4	5794.8	-0.34%	6081.9	5954.6	-2.09%	5936.8	5909.7	-0.46%
M501GAC	5993.8	5930.1	-1.06%	6178.2	6150.1	-0.46%	6127.3	6052.7	-1.22%
SGT6-5000FW	6040.5	5979.6	-1.01%	6403.1	6375.5	-0.43%	6161.0	6108.2	-0.86%
SGT6-5000FS	6029.0	5965.9	-1.05%	6388.3	6357.0	-0.49%	6151.0	6093.7	-0.93%
SGT6-8000H	5880.1	5813.5	-1.13%	6190.6	6070.5	-1.94%	6012.5	5956.2	-0.94%

Table 8: Effect of inlet air heating on overall plant heat rate under ISO conditions at load levels representing 80%, 60%, and 40% of the base load net output in operation with inlet air heater off.

With colder ambient temperatures, the positive effect of inlet air heating becomes more pronounced, since the range of base load operation is extended. The control scheme for inlet air heating and part loading can be demonstrated with the display of both overall plant heat rate and inlet air heater exit temperature, in Figure 8 below.

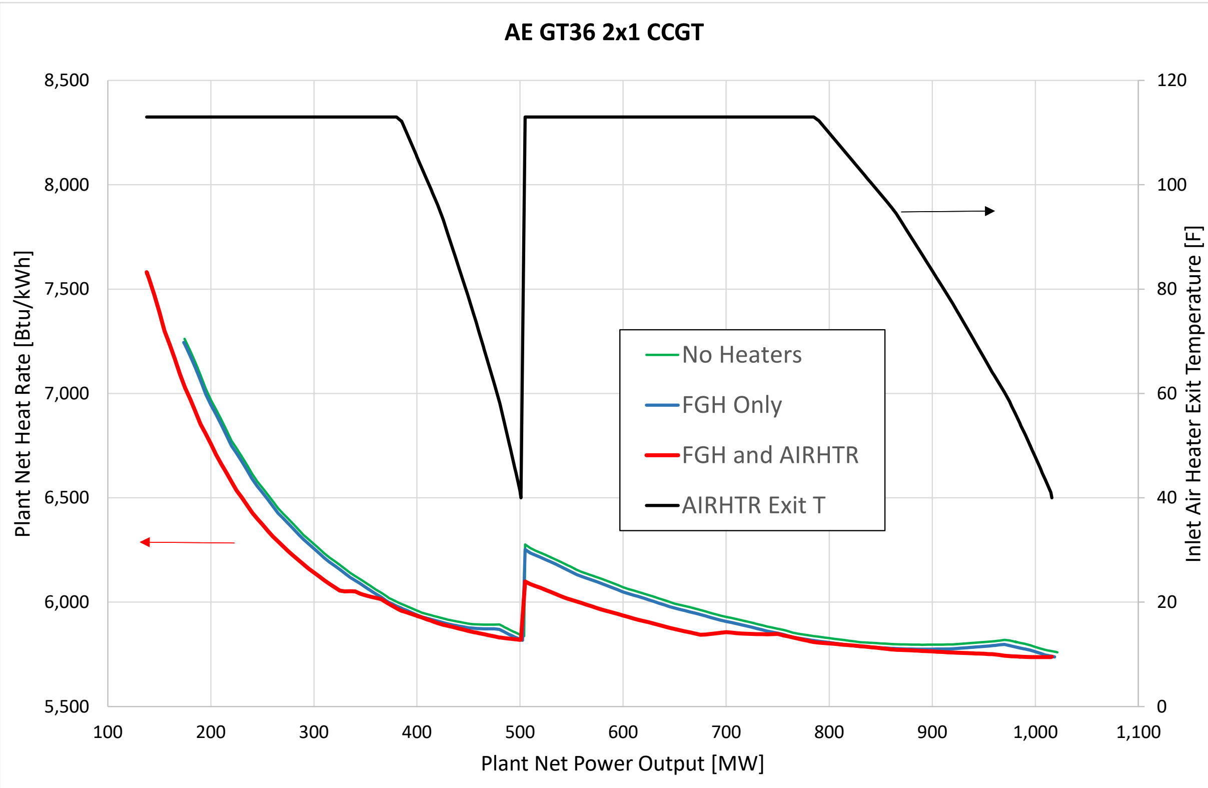


Figure 8: Effect of fuel gas heater and inlet air heater at 40F Ambient Temperature on overall plant net heat rate over the entire output range for the AE GT36-S6 plant.

Since maximum output can be reached at lowest inlet temperature, the inlet air heater is not in operation at the base load point. The small differences in output and heat rate between the three cases compared in Figure 8, which are a plant without heaters installed ('No Heaters', green), a plant with fuel gas heater only ('FGH Only', blue), and a plant with fuel gas heater and inlet air heater ('FGH and AIRHTR', red), have been addressed in the comparison of base load operation provided earlier.

Inlet heating is in operation with maximum air exit temperature (113 F in this study) between the minimum load for the gas turbine and the base load point for the gas turbine at this temperature (resulting in plant output of 371 MW for one GT and 754 MW for two GTs in operation). Above these base load points, plant output is increased by reducing the air exit temperature.

For operation of this plant with two gas turbines, there are two areas where the heat rate can be significantly reduced by inlet heating: at net output between 500 and 750 MW, and between 950 and 1000 MW. Operation with one gas turbine shows the same pattern below 350 MW and in the range between 460 and 501 MW.

From the comparison of this behavior with similar plots for the GE 7HA.02 plant in Figure 9, the MHPS M501J plant in Figure 10, and the Siemens SGT6-5000F (S) plant in Figure 11 one can see that every gas turbine generates a different pattern, and the root cause for theses difference lies in the different GT load control schemes implemented by the different OEMs.

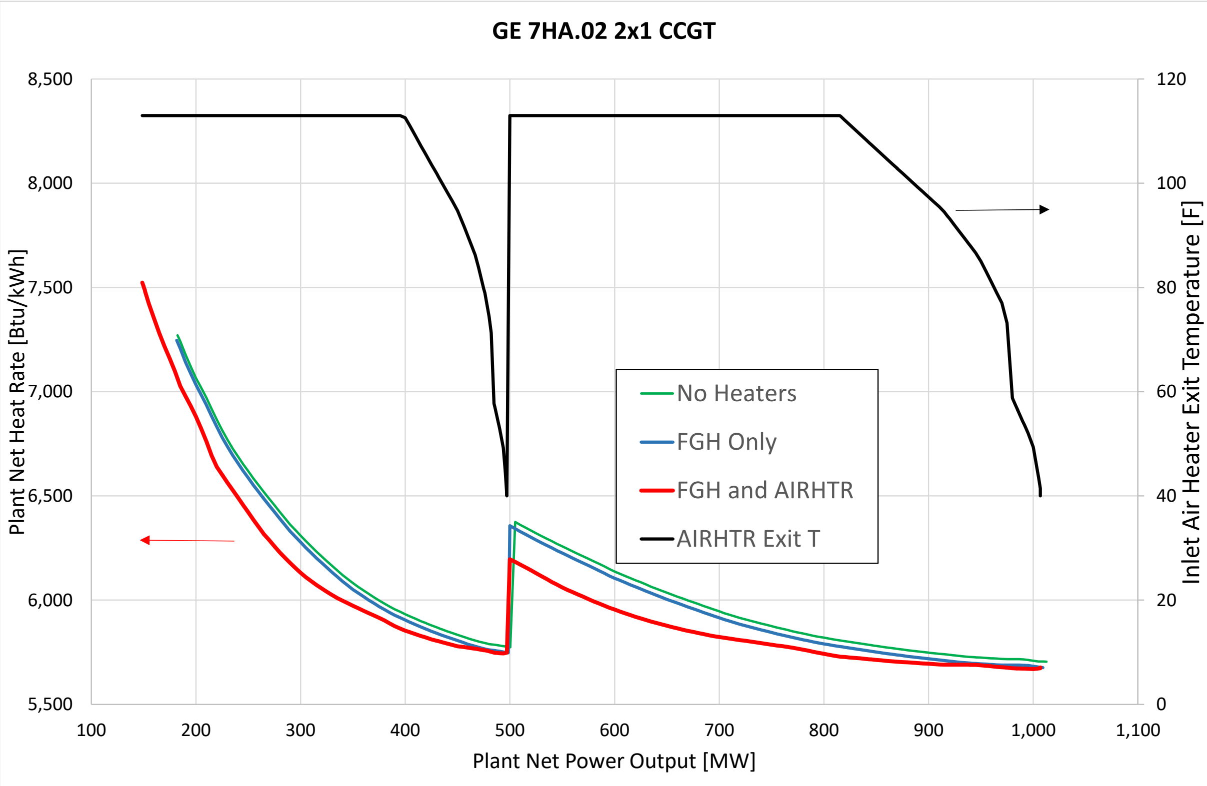


Figure 9: Effect of fuel gas heater and inlet air heater at 40F Ambient Temperature on overall plant net heat rate over the entire output range for the GE 7HA.02 plant.

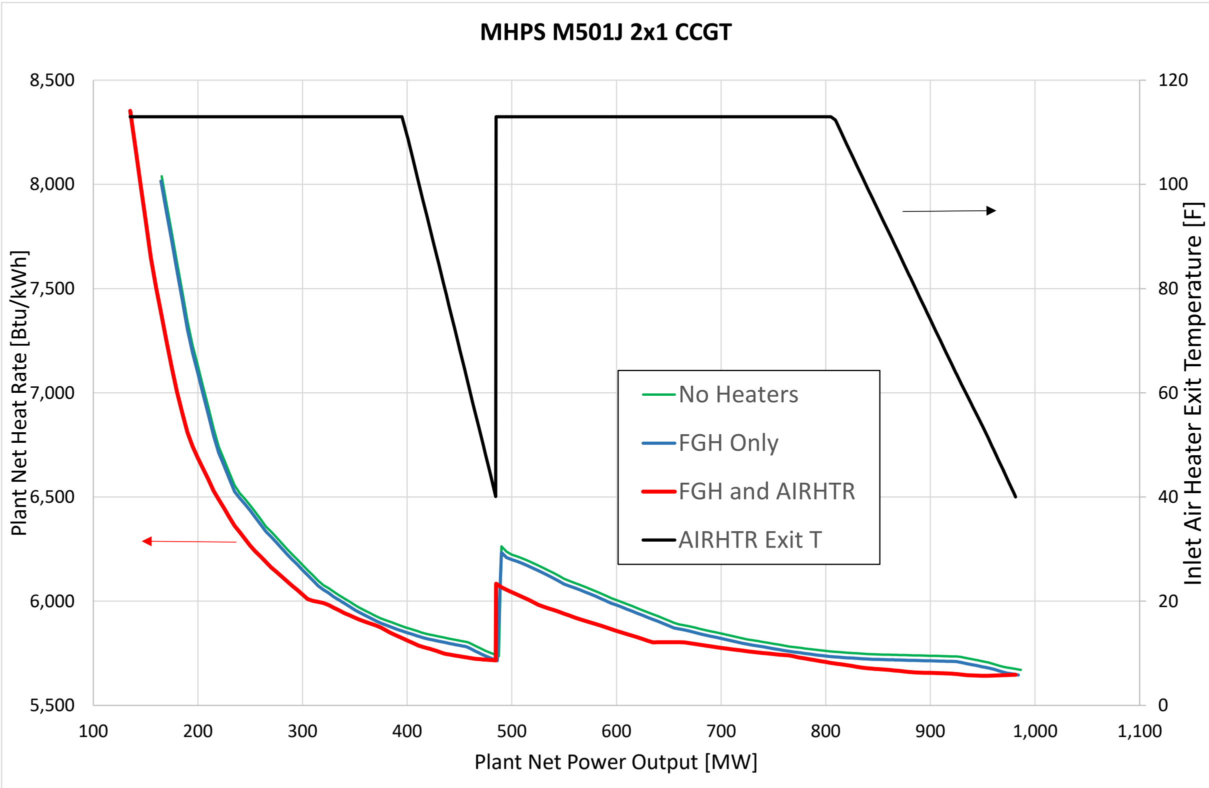


Figure 10: Effect of fuel gas heater and inlet air heater at 40F Ambient Temperature on overall plant net heat rate over the entire output range for the MHPS M501J plant.

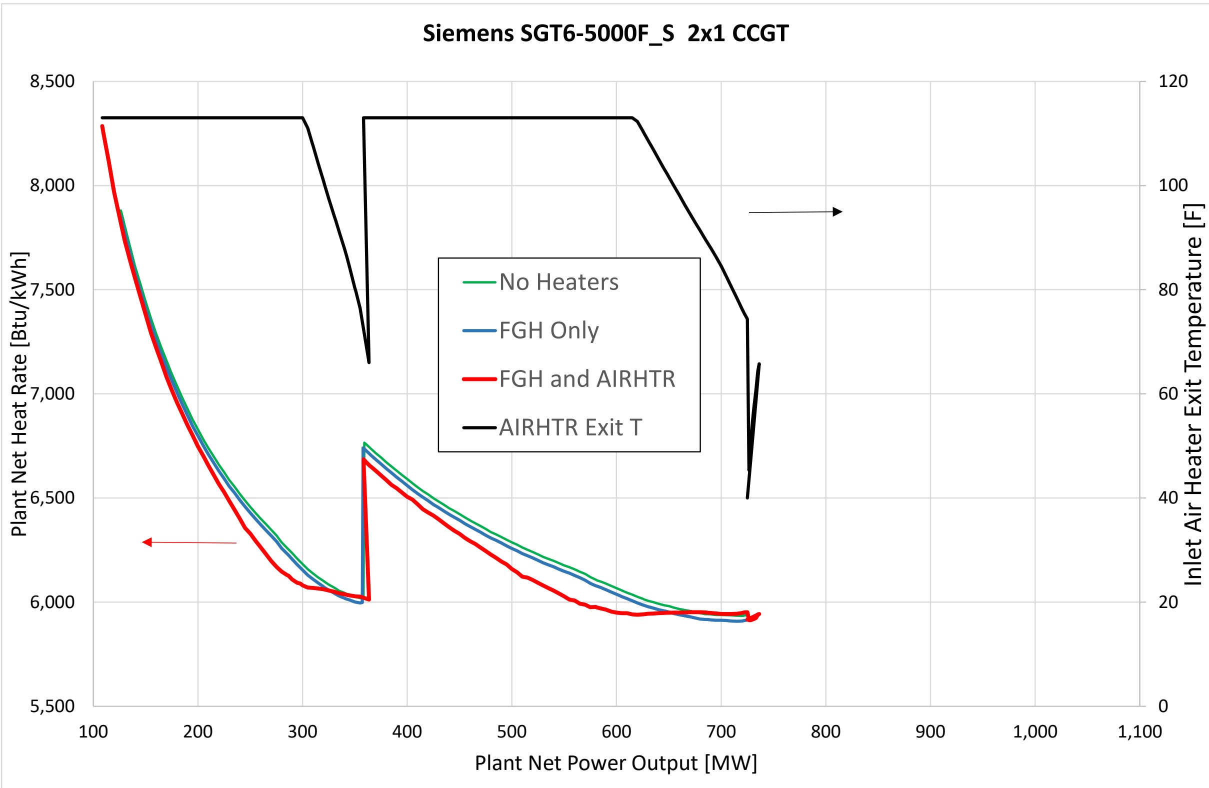


Figure 11: Effect of fuel gas heater and inlet air heater at 40F Ambient Temperature on overall plant net heat rate over the entire output range for the Siemens SGT6-5000F (S) plant.

The SGT6-5000F gas turbine was the only engine in the study that showed a significant negative effect of inlet air heating in parts of its operating range. As can be seen from Figure 11 above, there is a very positive effect on fuel efficiency at medium and low part-load levels, but the overall plant performance is better without inlet air heating when approaching the maximum output at a certain ambient temperature. The reason behind this behavior lies in the fact that this engine is effectively running at part load at ambient temperatures below 68 F due to output limitations of its generator. Consequently, a different control scheme for inlet heating would need to be developed, or the use of a different generator may be considered. Considerations on the latter are however always subject to economic considerations that would need to be evaluated against detailed analysis of load scenarios over the entire operating year, which is beyond the scope of this paper.

The extension of the load range of the plants in terms of minimum power output can also be demonstrated as a benefit of inlet air heating. Since the minimum part load level is defined by load fraction, the minimum power output in absolute numbers can be achieved at highest air inlet temperature. Comparing the performance maps for plants with and without inlet heating shown in Figure 12 to Figure 15 below, the low-load point at highest inlet air temperature can thus be achieved over almost the entire temperature range.

In all four sample plants shown, the area of high fuel efficiency is significantly extended through inlet air heating, and the drop in fuel efficiency towards the switching point from operation with two gas turbines to operation with a single gas turbine is effectively reduced.

For the SGT6-8000H plant which in the cases without inlet air heating was not able to operate in the gap between minimum load with two gas turbines (which is restricted to 45%) and base load with one gas turbine, Figure 15 reveals that this problem can effectively be mitigated through the application of inlet air heating.

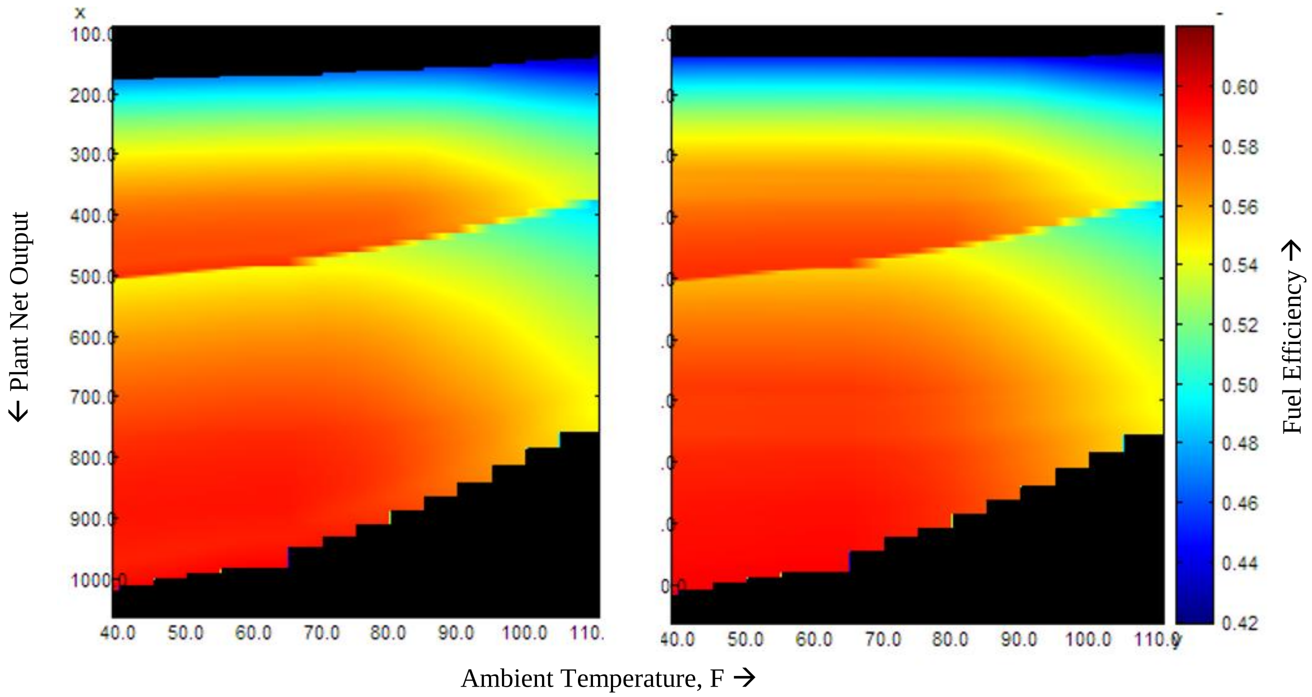


Figure 12: Performance maps for AE GT36-S6 plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

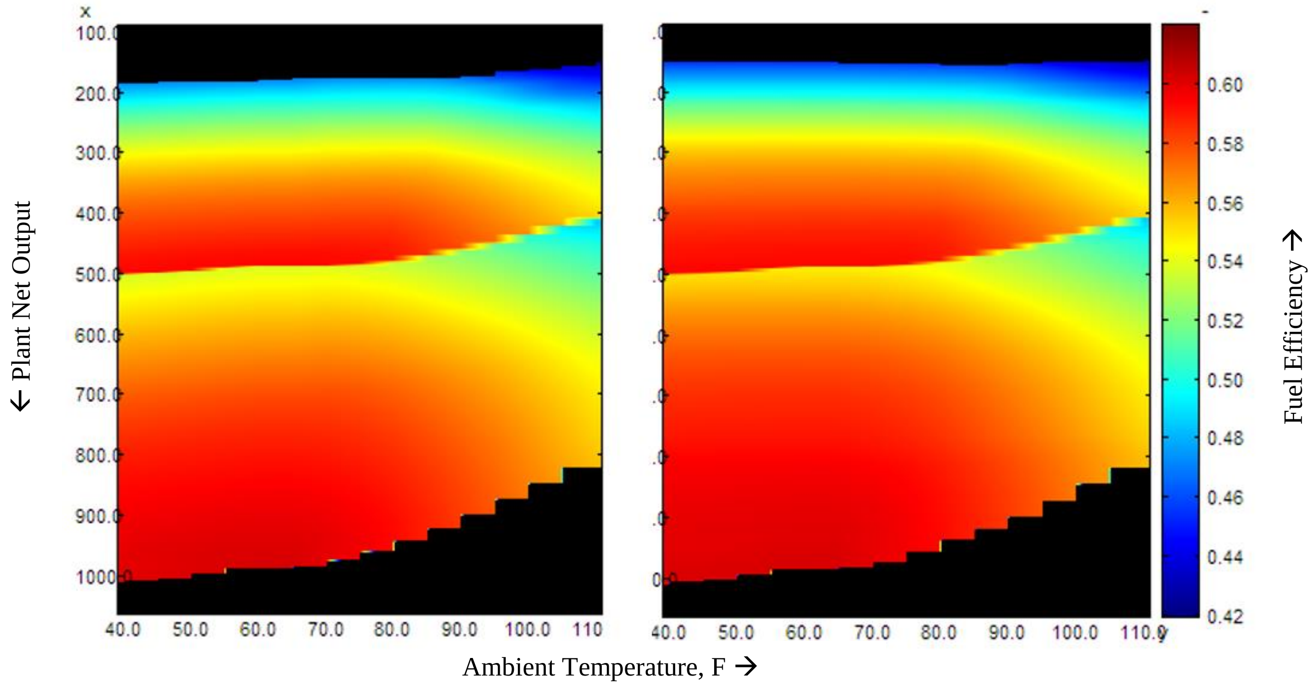


Figure 13: Performance maps for GE 7HA.02 plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

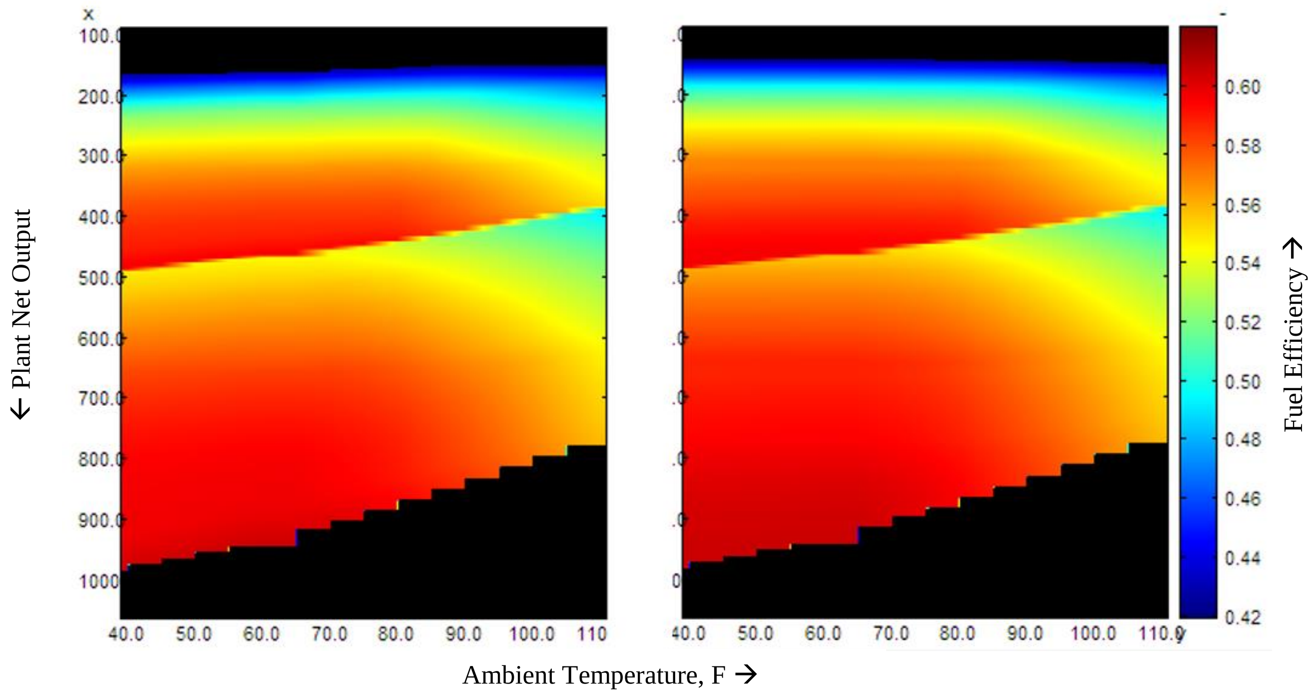


Figure 14: Performance maps for MHPS 501J plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

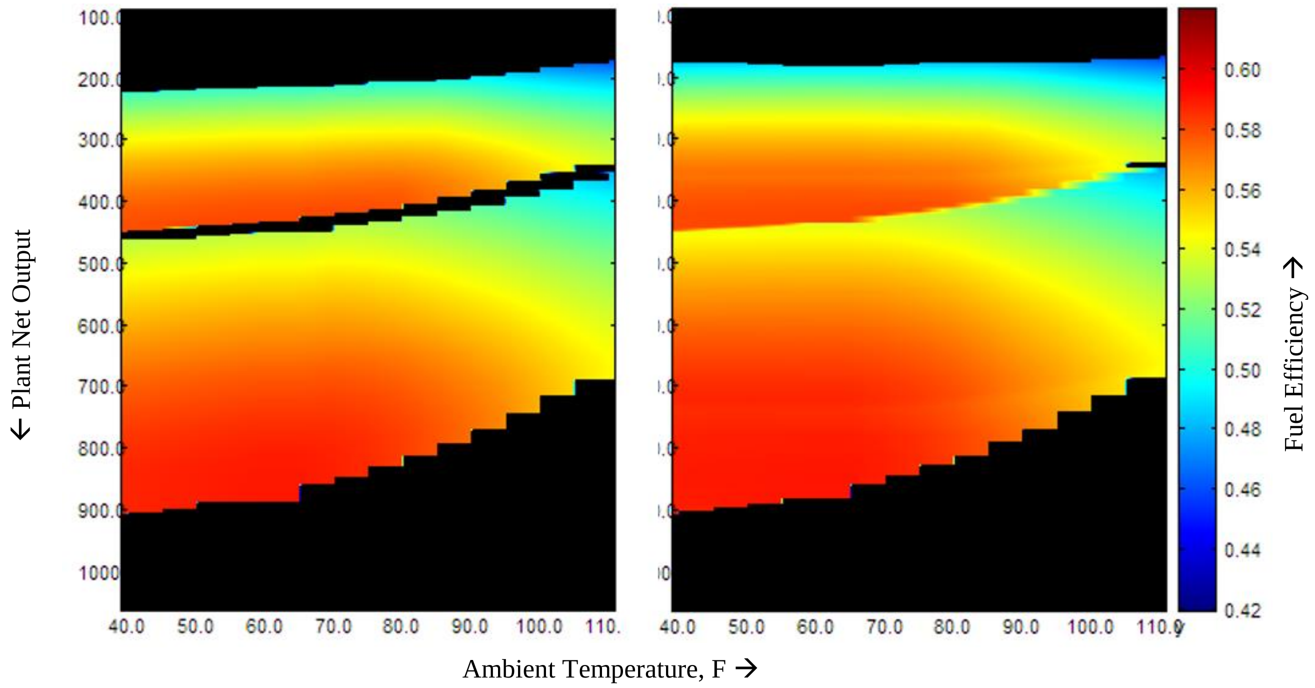


Figure 15: Performance maps for Siemens SGT6-8000H plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

In order to highlight the effect of the expansion of areas with high fuel efficiency in part load operation through inlet heating, the following figures show the performance maps for the same plants as above, but with a different efficiency scale ranging from 57 to 61 %. Comparing the areas with minimum 57 % fuel efficiency without and with inlet air heating, the in operating area at or above such fuel efficiency becomes obvious.

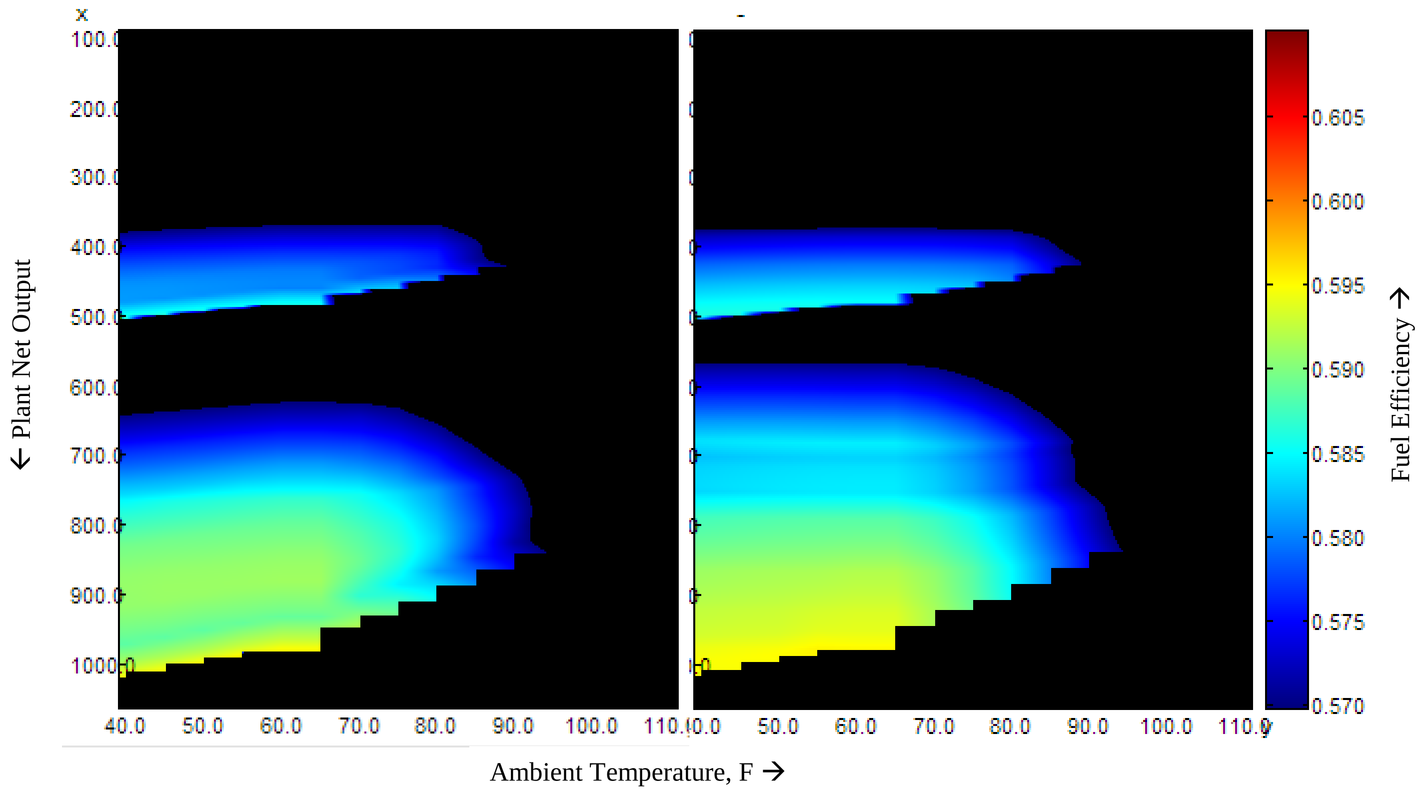


Figure 16: Performance maps with minimum fuel efficiency of 57% for AE GT 36-S6 plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

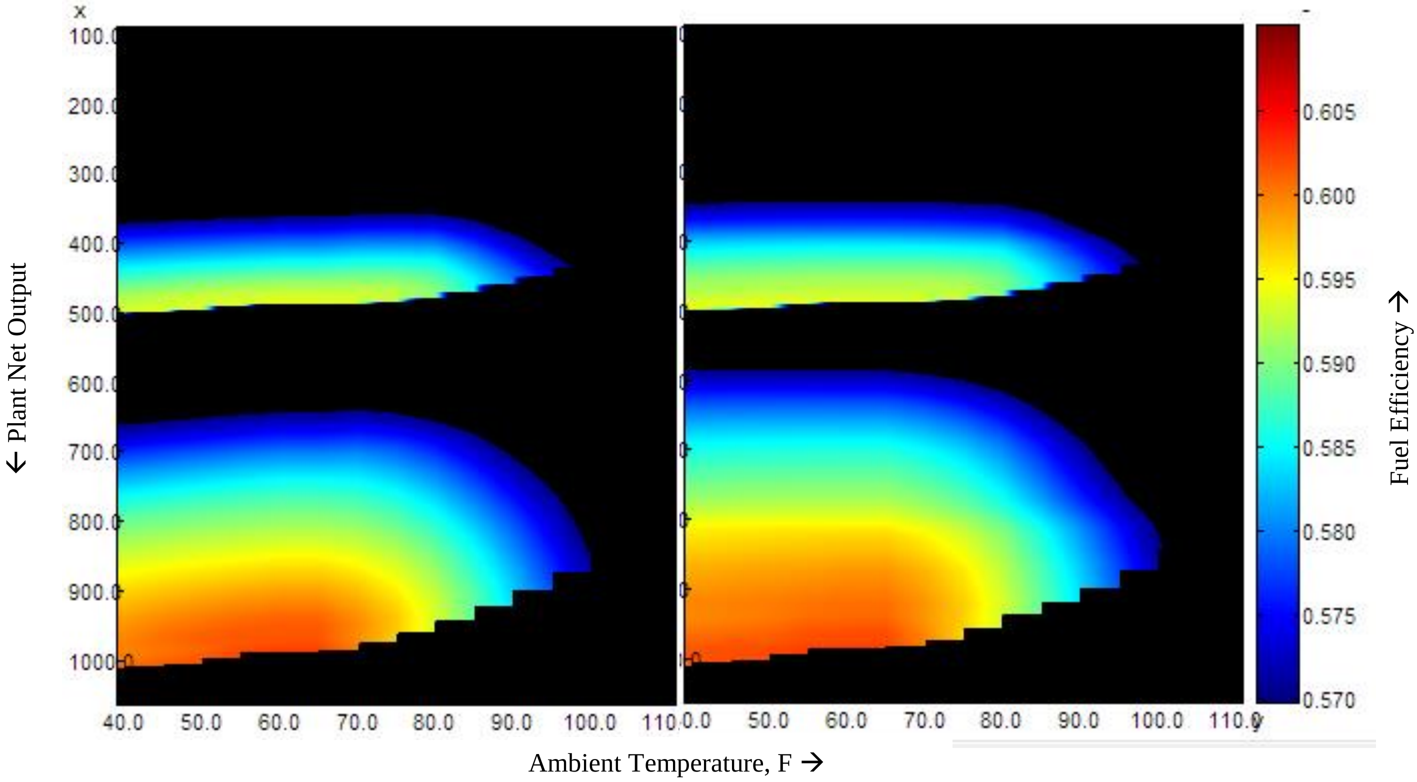


Figure 17: Performance maps with minimum fuel efficiency of 57% for GE 7HA.02 plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

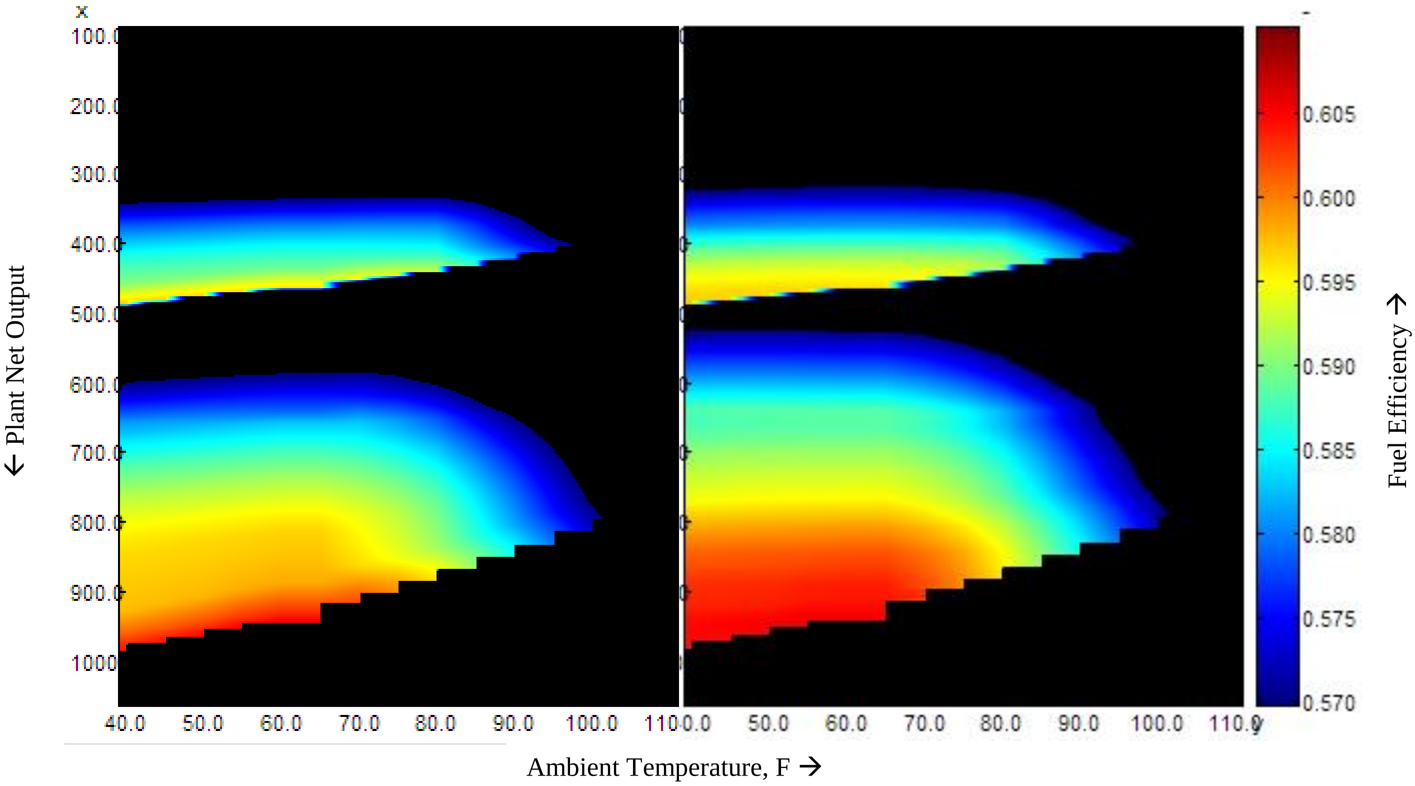


Figure 18: Performance maps with minimum fuel efficiency of 57% for MHPS M501J plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

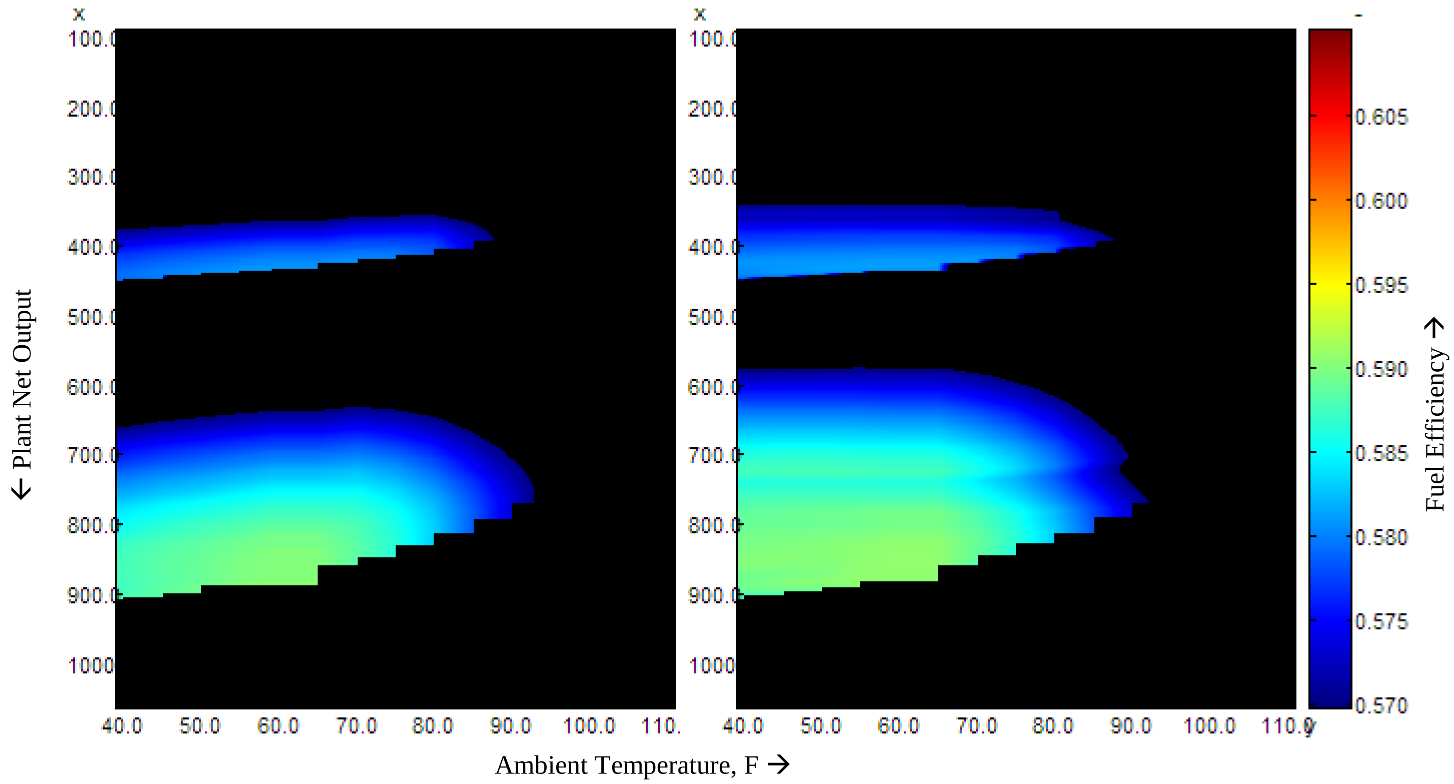


Figure 19: Performance maps with minimum fuel efficiency of 57% for Siemens SGT6-8000H plant with fuel gas heater only (left) and with fuel gas and inlet air heater (right).

Summary & Conclusions

Several large, high efficiency gas turbines which use heat integration are available in the market. In order to evaluate the effect of heat integration, a comparative study with detailed thermodynamic simulation models of 2x1 combined cycle plants with air cooled condenser was undertaken, in which three plant configurations were evaluated for each gas turbine under investigation over their entire load range and ambient temperatures between 40 and 110 F. These plant configurations were (a) cooling heat integration only, (b) cooling heat integration and fuel gas heating, and (c) the former configuration plus inlet air heating to maximize part load efficiency.

From comparing the performance maps of gas turbines with heat integration with those of two modern gas turbines without cooling heat integration, it cannot be concluded that cooling heat integration is advantageous. After all, the two best performing engines (at full load) are the GE 7HA.02 and the MHPS M501J, the engines with the lowest and highest integration respectively.

For the study comprising eight different gas turbine models from four different vendors, there is no gas turbine model that is consistently the best performer over the range of ambient temperature and power.

Fuel gas heating that shifts heat from the bottoming cycle to the gas turbine and thereby reduces fuel consumption is shown to provide a positive effect for all gas turbine models.

The inlet air heater integration can benefit all of the large GTs, regardless of part load control curves and, despite a slight drop in capacity due to its added inlet pressure loss. The benefit from inlet air heating occurs in part load operation and is due to the expansion of the base load area – by reducing GT output as an effect of the increase in inlet air temperature. This yields higher part load levels of the gas turbine(s) in the low load range of the plant which makes them operate more efficiently and improves overall plant efficiency. For operation at lower ambient temperature, inlet heating also produces a wider operating range by allowing for lower minimum load points of the gas turbine in absolute numbers.

The exact point where the benefits occur and how large the benefit is, is mostly a function of the load control mechanisms of the gas turbine. The overall benefits at part load versus the disadvantage of a loss in capacity due to higher pressure losses as well as the investment cost for the inlet heater would need to be weighed off, by taking into account typical running hours during the course of the year at respective ambient conditions. In some cases, inlet air preheating can achieve a fuel reduction on the order of 3% at lower loads.