Emissions Intensity of Power Plants

Document no: SK031100-0000-NC-RPT-0020
Revision no: A

Energy Market Authority Singapore
EMA-ITQ-2022-0054

Technical Consultancy Study for Emissions Intensity of Power Plants
Dec 2022

Jacobs International Consultants Pte. Ltd.

150 Beach Road
Gateway West, 34th Floor
Singapore 189720
Singapore

T +65 6391 0350
www.jacobs.com

Executive Summary

The Energy Market Authority (EMA) seeks to ensure sustainable electricity supply in Singapore and has committed to net zero emissions by 2050. Today, the power sector contributes around 40% of Singapore's carbon emissions. Planning for gradually reduced reliance on fossil fuels is required to reach the target of net zero emissions.

Natural gas combined cycle gas turbines (CCGTs) are the backbone of Singapore's electricity market and can potentially remain a major source of Singapore's electricity generation for many years. The emissions intensity of a CCGT power plant is a function of its efficiency and the fuel used. A more efficient power plant will use less fuel, resulting in lower carbon emissions. This study is to determine the emissions intensity (tCO_2e/MWh) of advanced CCGTs running on natural gas. This study, as one of the steps in achieving net zero carbon emissions, will provide insight as to the emissions intensity achievable with the current available power generation units, as well as the improved technologies available to fire with alternative low carbon fuels.

The study estimates the emissions intensity from power generation with a focus on advanced CCGTs (e.g. H-Class). The plant efficiency is lower with increases in heat rate, at lower part load operation compared to higher part load. The plant heat rate will also be higher with increased degradation in accordance with operating hours and operating conditions. As such, annual emissions intensity increases with lower part load operation, which is estimated based on respective year plant load factor (PLF), and degradation condition. In any particular year after the respective plants have accumulated operating hours, there will be non-recoverable degradation and recoverable degradation (through maintenance works). The degradation starts from zero when the plant is new and increases to around 2.1%, averaged over a lifespan of 25 years.

The emissions intensity range from this study is provided in summary form in Table A. The range is for a plant operating 99% of duration with natural gas-fired operation and 1% on diesel-fired operation, with PLF ranging from 50% to 93.2%, considering new conditions and expected maximum degradation over a 25-year lifespan[1]. This study reports that new advanced CCGTs based on current technology would be able to achieve around 0.353 tCO_2e/MWh at 75% PLF throughout operational life.

Table A. Summary of Emissions Intensity of Advanced CCGTs selected for this study

Plant type	Emissions intensity at 100% Load (New - Max degradation at year 25)
Advanced CCGTs	0.335 – 0.344 tCO_2e/MWh

At the current stage, all original equipment manufacturers (OEMs) have technologies allowing around at least 30% (vol) hydrogen co-firing with natural gas. All OEMs are planning 100% hydrogen-fired-capable plants in the future. The use of hydrogen-blended fuel will reduce the carbon emissions intensity; however, the reduction in emissions intensity will be non-linear relative to the volume of hydrogen blended in. Hence disproportionately higher volume of hydrogen will be required to be blended with natural gas when a larger CO_2 emissions reduction is required. Actual carbon emissions intensity from a particular project will also be influenced by hydrogen generation technology. Current hydrogen generation technology includes steam methane reforming (grey hydrogen), incorporating carbon capture system (blue hydrogen, to further reduce carbon emissions), and water electrolysis using renewable energy (green hydrogen).

[1] Energy Market Authority (EMA) (2020). *Review of Vesting Contract Technical Parameters for the Period of 1 January 2021 to 31 December 2022*

Important note about the report

The sole purpose of this report and the associated services performed by Jacobs is to assist Energy Market Authority Singapore (EMA or the "Client") to determine the Emissions Intensity of Power Plants ("Project") by providing information and estimation in accordance with the scope of services set out in the contract between Jacobs and the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information provided to Jacobs. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be inaccurate or incomplete, then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the Project and subsequent data analysis, and re-evaluation of the data, findings, observations, and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures, and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full, and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context. This report has been prepared on behalf of, and for the exclusive use of, Jacobs' Client, and is subject to, and issued in accordance with, the provisions of the contract between Jacobs and the Client. Jacobs accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

Contents

Appendices

Tables

Figures

Terms and abbreviations

The following standard terms and abbreviations are referenced in this report.

Term	Description
BOP	Balance of Plant (systems, equipment)
Carbon Emissions Intensity	CO_2 equivalent amount of greenhouse gases emitted per unit of power generation
CCGT	Combined Cycle Gas Turbine Plant
CH_4	Methane
CO_2	Carbon Dioxide
COD	Commercial Operations Date
CWS	Cooling Water System
deg. C	Degree(s) Celsius
EMA	Energy Market Authority of Singapore
EOH	Equivalent Operating Hours
FOR	Forced Outage Rate
GE	General Electric
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
IPCC	Intergovernmental Panel on Climate Change
MHI	Mitsubishi Power (parent organisation Mitsubishi Heavy Industries)
$MtCO_2e$	Metric Ton(s) Carbon Dioxide Equivalent
MWh	Megawatt Hour(s)
N_2O	Nitrous Oxide
NACF	Net Available Capacity Factor
NDC	Nationally Determined Contribution
OCGT	Open Cycle Gas Turbine Plant
OEM	Original Equipment Manufacturer
PLF	Plant Load Factor
POR	Planned Outage Rate
RVCTP	Review of Vesting Contract Technical Parameters
SOR	Scheduled Outage Rate
ST	Steam Turbine

1. Introduction

1.1 Background

Singapore's energy sector has come a long way since its early days, where it has shifted to lower-carbon power sources from oil to natural gas. As Singapore is committed to meet its Nationally Determined Contribution (NDC) target to reduce emissions to around 60 metric tons carbon dioxide equivalent ($MtCO_2e$) by 2030 after peaking emissions earlier and reach net zero emissions by 2050, the Energy Market Authority (EMA) seeks to ensure sustainable and reliable electricity supply in Singapore. The EMA has a key role to ensure a reliable and secure energy supply, promote effective competition in the energy market, and develop a dynamic energy sector in Singapore.

Natural gas combined cycle gas turbines (CCGTs) are the backbone of Singapore's electricity market and have the potential to remain a major source of Singapore's electricity generation for many years. Today, the power sector accounts for around 40% of Singapore's total carbon emissions[2]. This study on the variation in emissions intensity of power generation units through operational life and with varying operating regimes will help in the planning of a power generation mix in the coming years to meet the carbon emission reduction targets.

1.2 Objectives

The main objective of this study is to determine the emissions intensity (tCO_2e/megawatt hours [MWh]) of advanced CCGTs running primarily on natural gas and to examine how the emissions intensity would change across the lifespan of the plant and at varying plant load factors (PLF). The emissions intensity includes all greenhouse gases (CO_2, CH_4, N_2O) emitted from electricity generation.

[2] *Energy 2050 Committee Report: Charting the Energy Transition to 2050 (dated March 2022)*

2. Approach and methodology

Jacobs used the following approach and methodology to carry out the scope of work outlined in the previous section (Figure 2-1).

Figure 2-1. Approach for the project

2.1 Data collection

Jacobs requested the identified original equipment manufacturers (OEM[3]) to provide performance information of their advanced CCGT power generation units. Combined cycle power generation units selected for the study are H-Class single-shaft power blocks from General Electric (GE), Siemens, and J-Class M701 JAC single-shaft power block from Mitsubishi Power (MHI).

i. General Electric (GE)

GE advised GT PRO[4] modelling data may be applied for this study. This study considers GT PRO modelling output for GE 9HA.01 CCGT (H-Class, gas- and diesel-fired operation).

ii. Siemens

Siemens provided part load heat rate information for its SGT5-9000HL (H-Class) multi-shaft plant, which has a net power output of more than 700 MW, higher than the considered net output of circa 600 MW for this study. This study considers GT PRO modelling output for SGT5-8000H CCGT (H-Class, considering approximately 600-MW net output).

iii. MHI

This study considers the MHI-provided performance information for M701 JAC (J-Class) for gas- and diesel-fired operation. GT PRO modelling results are used as reference only.

2.1 Heat rate data development

For each OEM's advanced CCGT plant configurations, heat rate at various PLFs and degraded condition were tabulated for both natural gas and diesel fired operation. Degraded heat rate calculations considered average and maximum degradation factors. In addition, averaged performance values for advanced class CCGTs, from the three OEMs, provide a more representative heat rate values for future power generation consisting of different OEMs' advanced CCGTs.

2.2 Emissions intensity curve development

Emissions intensity data and curves were generated by using values from multiplication of degraded heat rates (of respective years) and carbon emissions factor. Natural gas- and diesel-fired operation carbon emission

[3] The OEMs approached are the ones whose machines are used in the Singapore power sector.

[4] GT PRO, a commercial software from Thermoflow, automates the process of creating a gas turbine/combined cycle plant design to attain an optimal configuration and technical parameters. Built-in expert logic automatically selects appropriate options and inputs for the various details, based on the users' high-level selections. The program designs the new plant, computes its performance, its detailed heat and mass balance, and other design details.

factors (in $kgCO_2e/GJ$) were based on the carbon emission factors from Intergovernmental Panel on Climate Change (IPCC) guidelines.

Emissions intensity was calculated using respective year degraded heat rate values (across the varying PLFs) considering 99% natural gas-firing and 1% diesel-firing. The curves were then developed based on the resultant emissions intensity values.

3. Emissions intensity parameters

Calculations were performed using available data and assuming parameters that follows EMA's *Review of Vesting Contract Technical Parameters* (RVCTP) for the period of 1 January 2021 to 31 December 2022.

The following sections describe selected key parameters that impact the calculated emissions intensity.

3.1 Carbon emission factors

Table 3-1 shows the calculated carbon emission factors when firing natural gas and diesel. For consistency with the methodology used for carbon tax reporting, the 2006 IPCC guidelines[5] for emission factors and the global warming potentials, listed in First Schedule of the Carbon Pricing Act[6], were applied in this study.

Table 3-1. Carbon Emission Factors

Natural gas-fired operation parameters	Unit	Constituents		
		CO_2	CH_4	N_2O
Utility source emission factor	kg CO_2/TJ LHV	56100	1	0.1
Global warming potential	kg/kg	1	21	310
Carbon emission factor	kg CO_2e/TJ LHV	56100	21	31
Convert to HHV	kg CO_2e/GJ HHV	50.49	0.0189	0.0279
Total for natural gas-fired operation	kg CO_2e/GJ HHV	50.54		
Diesel-fired operation parameters	**Unit**	**Constituents**		
		CO_2	CH_4	N_2O
Utility source emission factor	kg CO_2/TJ LHV	74100	3	0.6
Global warming potential	kg/kg	1	21	310
Carbon emission factor	kg CO_2e/TJ LHV	74100	63	186
Convert to HHV	kg CO_2e/GJ HHV	70.395	0.05985	0.1767
Total for diesel-fired operation	kg CO2e/GJ HHV	70.63		

3.2 Heat rate

This study considers heat rate values at 5% incremental PLF, between 50% to plant net available capacity factor (NACF). Part load factor is derived from the NACF of 93.2% and respective PLF values. This derived part load factor (from PLF values) essentially provides an averaged part load applicable for the duration when plant is generating power. A particular value of PLF may be achieved by operating the plant at 100% load for fewer

[5] IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Published: IGES, Japan.

[6] https://sso.agc.gov.sg/Act/CPA2018

hours in a year. The same PLF may be achieved by operating the plant at 50% part load for twice the duration. Other operation regimes may be applied to also achieve same PLF value.

While different operating regimes may result in same PLF value, the actual effective heat rate value (and emissions intensity) for the operating duration will be dependent on hours for which the plant was operating at full load or at any other part loads. This will be entirely dependent on the operation regime planned for a particular plant.

Adjustments with additions of 0.1% of full load heat rate values are made to allow for plants' start-up fuel usage. GT PRO modelling considered the gas pressure expected at the plant boundary, and hence already considers the gas compressors' auxiliary power consumption.

3.3 Degradation

Gas turbine plant power and heat rate degradation constitute both "recoverable" and "non-recoverable" degradation.

Recoverable degradation is degradation of performance that occurs to the plant that can be recovered within the overhaul cycle. Recoverable degradation can be substantially remediated by cleaning or replacement of air inlet filters, water washing of the compressor, ball-cleaning of condensers, and other cleaning activities. These cleaning activities are typically undertaken many times within a year depending on the site characteristics and the economic value of performance changes.

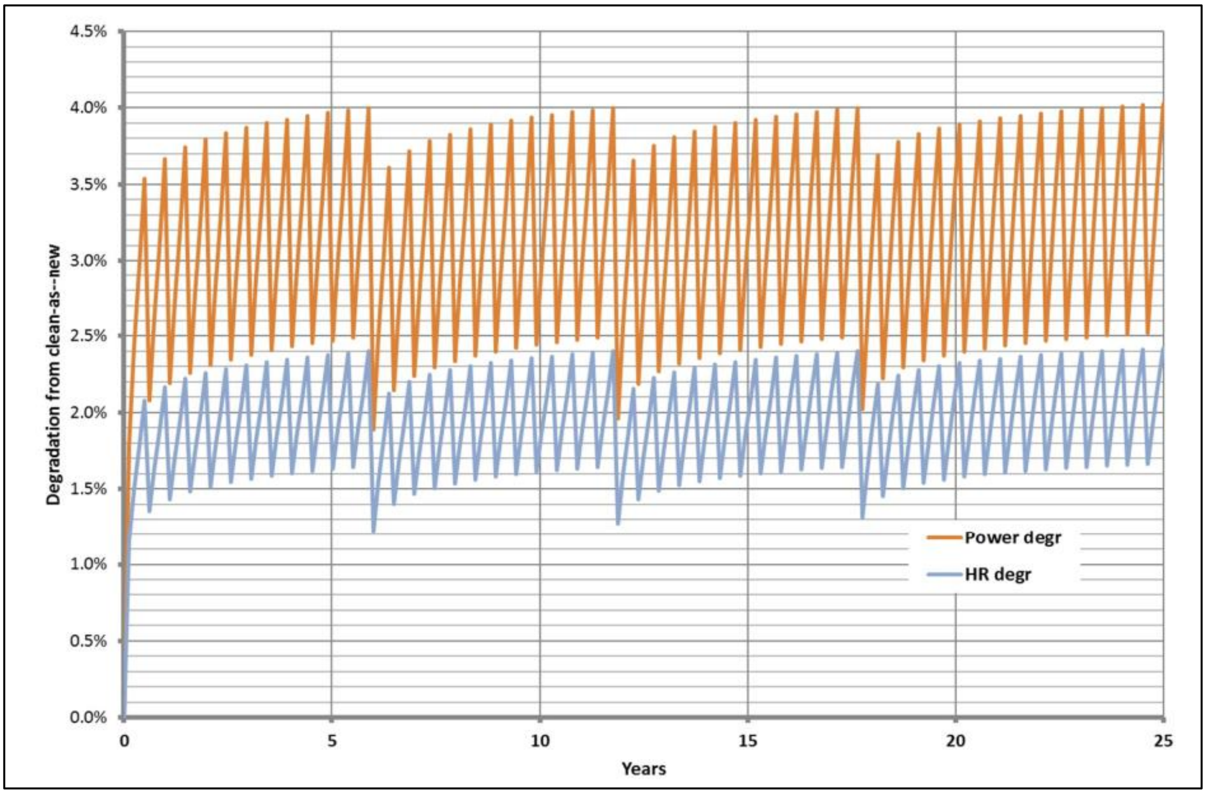
Non-recoverable degradation is caused by the impacts of temperature, erosion, and corrosion of parts within the plant. This type of degradation is typically substantially remediated at overhaul when damaged parts are replaced with new or refurbished parts. Given that a typical industry repair practice uses an economic mix of new and refurbished parts within overhauls, it is possible that not all the original clean-as-new performance is recovered at the overhaul.

The heat rate degradation amount (from recoverable degradation) varies over the maintenance cycles, and, in addition, there will be non-recoverable degradation over the plant life. These typically have the form similar to that shown in Figure 3-1. Past project experience indicates degradation for a plant in a particular year is expected to range between non-recoverable degradation (until the particular year) plus average recoverable degradation, and a maximum of 2.08% (averaged for 25 years, which includes both recoverable and non-recoverable degradation). The values in Table 3-2 have been considered for this study. Degradation rates are not considered to be materially affected by load factor or capacity factor. These are approximate values only. Actual degradation of a specific plant will depend on the operating conditions and achieved Equivalent Operating Hours (EOH).

Table 3-2. Degradation values

Degradation	Range	Note
Non-recoverable degradation	1.4% over 25 years	Applied as geometric mean
Recoverable degradation	0.62% averaged for a year	
Total degradation	2.08% over 25 years	Max at a particular time is estimated around 2.4% before compressor washing, etc.

Figure 3-1. Typical degradation curve for gas turbine plants



The blue line in Figure 3-1 shows the total of both recoverable and non-recoverable heat rate degradation for a typical plant, which varies in a particular year based on maintenance works carried out to recover performance at certain intervals for general compressor washing works and improves considerably during major overhaul when components are replaced. This variation between lower value and higher value continues through the operational life of the plant. The orange line indicates the power output degradation following a similar trend.

3.4 Fuel specification

3.4.1 Gas fuel composition variation

Plant performance modelling was based on a natural gas composition, compliant with Singapore's gas supply code as is the diesel fuel composition. Both of these have come from GT Pro's fuel specification library and have been used in previous EMA RVCTP studies.

The impact of varying gas composition (yet meeting the Gas Supply Code) was investigated using GT PRO modelling considering possible variations in methane, ethane, and propane content. Table 3-3 shows the heat rate variation of the lower and upper bound gas composition. The review showed only around 0.15% difference in heat rate given the possible variation. Emissions intensity would only be affected in a similar range. As the variation is minimal, no separate modelling has been performed for variation in the gas composition.

Table 3-3. Heat Rate Variation with Gas Composition

Parameter	Gas composition 1	Gas composition 2
Heating Value (kJ/kg, HHV@ 25 deg. C)	44,620	53,866
Net Power (MW)	579.5	573.6
Net Heat Rate (HHV), kJ/kWh	6563	6571
Difference in net heat rate	Less than 0.15%	

3.4.2 Diesel operation

Advanced gas turbines power generation capacity with distillate oil no:2 (herein referred as diesel) firing is limited to around 75% part load (with an equivalent PLF of 70%) to comply with NOx emissions requirements. This limitation has been considered for the emissions intensity calculations.

4. Plant general characteristics

The following plant general characteristics, adapted from the RVCTP (for the period of 1 January 2021 to 31 December 2022) Technical Parameters have been used for the purpose of this study. Calculations considered degradation factors averaged values in a particular year.

Technical parameters applied are as listed in Table 4-1.

Table 4-1. Plant general characteristics

Subject	Reference
Site reference conditions	32 deg. C dry bulb temperature
	85% relative humidity
	1013 mbar(a) ambient pressure
	Sea level altitude
	Seawater Cooling Water Temperature: 29.2 deg. C
Maximum generation capacity reference conditions	32 deg. C dry bulb temperature Others as above
Power measurement point	Step-up transformer HV terminal
Net plant output	Circa 600 MW
Gas fuel	Refer to Section 3.4 (Fuel specification)
PLF	Performance modelling considers variation between 50% to 100% in 5% increment
PLF = Annual generation / (NACF x 8760 x Net capacity)	
NACF	93.2% Assuming a base load operation plant
NACF = 100% - FOR – POR	
Assumes Forced Outage Rate (FOR) and Planned Outage Rate (POR) Totals 6.8%	
Part load factor = NACF/PLF	Varies according to selected PLF value
Non-recoverable Degradation over Operating Years	1.4%
Recoverable Degradation over Operating Years	0.62%
Max Degradation Averaged for the Operating Year	2.08%
Maximum degradation (at any one time)	2.40%
Adjustment to reflect fuel usage for starts	0.10%
Power transmission	230 kV
Cooling water system (CWS)	Once through CWS (8 deg. C temperature rise across condenser)
Cold water temperature	29.2 deg. C
Operational life	25 years
Environmental standards	International Finance Corporation Guidelines
	Singapore Emission Guidelines

5. Emissions intensity of Advanced CCGTs

Emissions intensity review in a particular year may consider the following degradation values:

- New condition (after adjustments for start-up fuel)
- Average (non-recoverable degradation till a particular year plus averaged recoverable degradation), and
- Maximum (considering maintenance cycles for degradation recovery) in a particular year.

Table 5-1 considers comparisons across the PLF variation and year 25 of operation. Calculations in this table consider 99% operation duration with gas firing and 1% with diesel firing to reflect the typical combustion fuel mix.

As shown in Figure 5-1, emissions intensity year-to-year generally follows a linear trend across the years and at different PLF factors. The linear trend is due to an assumption that non-recoverable degradation increases at relatively constant rate in addition to a fixed averaged recoverable degradation. This chart considers the average degradation expected in a particular year for a fleet of similar plants. For individual plants, the actual heat rates will vary in non-linear fashion dependent on plant specific maintenance intervals from year-to-year, however with an increasing trend.

The heat rate values from respective OEMs' plants were calculated considering GT PRO modelling output and OEM information. The intermediate values were interpolated using trendline formula. Based on experience, OEMs are continuously performing research and development for efficiency improvement as well as emissions reduction. Such development upgrades in the future may be retrofitted to further improve the heat rate performance and emissions intensity during the lifespan of the plant.

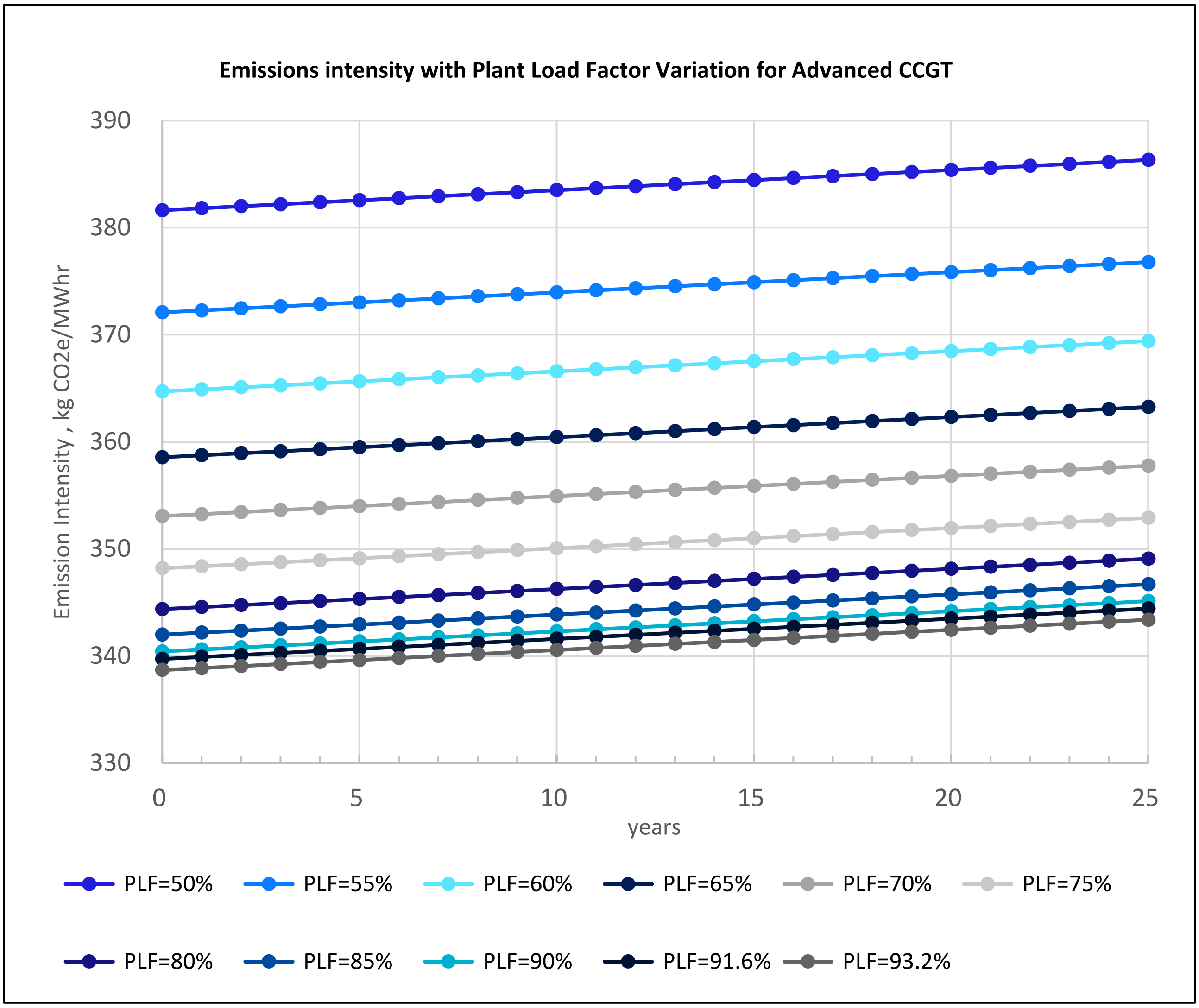
5.1 Advanced CCGTs

Table 5-1 shows emissions intensity variation for advanced CCGT plants in new and maximum degradation conditions. Figure 5-1 shows the yearly variation of emissions intensity with varying PLF. There is a 2.3% to 2.7% emissions intensity variation between new condition (year zero) and degradation condition in year 25.

Table 5-1. Emissions intensity with PLF variation – Advanced CCGTs

Heat Rate with PLF Variation	Unit	PLF= 50%	PLF= 55%	PLF= 60%	PLF= 65%	PLF= 70%	PLF= 75%	PLF= 80%	PLF= 85%	PLF= 90%	PLF= 93.2%
Plant NACF	%	93.2%	93.2%	93.2%	93.2%	93.2%	93.2%	93.2%	93.2%	93.2%	93.2%
Part Load Factor	%	53.6%	59.0%	64.4%	69.7%	75.1%	80.5%	85.8%	91.2%	96.6%	100%
Emissions intensity (new) HHV	kg CO2e/ MWh	377.8	368.3	360.9	354.8	349.2	344.3	340.5	338.0	336.5	334.7
Emissions intensity, HHV with averaged degradation (averaged for year 25)	kg CO_2e/ MWh	386.3	376.8	369.4	363.3	357.8	352.9	349.1	346.7	345.1	343.4
Emissions intensity, HHV with max degradation (averaged for year 25)	kg CO_2e/ MWh	386.5	377.0	369.6	363.5	358.0	353.1	349.3	346.9	345.3	343.6
Variation between max degradation and new	%	102.3 %	102.4 %	102.4 %	102.4 %	102.5 %	102.5 %	102.6 %	102.6 %	102.6 %	102.7 %

Figure 5-1. Emissions intensity with PLF variation – Advanced CCGT



6. Hydrogen-blended gas power generation

Hydrogen fuel blended with natural gas is considered as an option to shift from fossil fuels to low-carbon fuels. While there have been various pilot plant tests conducted worldwide, deployment of hydrogen-blended power generation is still limited due to technology availability as well as current limited feasible options to generate hydrogen fuel continuously on large quantity basis in an environmentally friendly manner. OEMs' current technology for gas turbine plants allow at least 30% (vol) hydrogen blending.

Based on the Siemens' technical paper (2022) titled "Hydrogen power and heat with Siemens Energy gas turbines," Figure 6-1 shows a non-linear reduction in CO_2 emissions with increasing hydrogen fuel content. Hydrogen blending has a net effect of lowering volumetric energy density of the resultant blended gas. Hence, a disproportionately larger volume of hydrogen blending will be required to meet a larger CO_2 emission reduction. For example, 10% volumetric hydrogen blending with natural gas is expected to result in a reduction of around 2.7% CO_2 emissions. Achieving 50% CO_2 emission reduction will require 77% volumetric hydrogen fuel blending.

Figure 6-1. CO_2 (mass%) variation with hydrogen fuel content (vol%) blended in natural gas

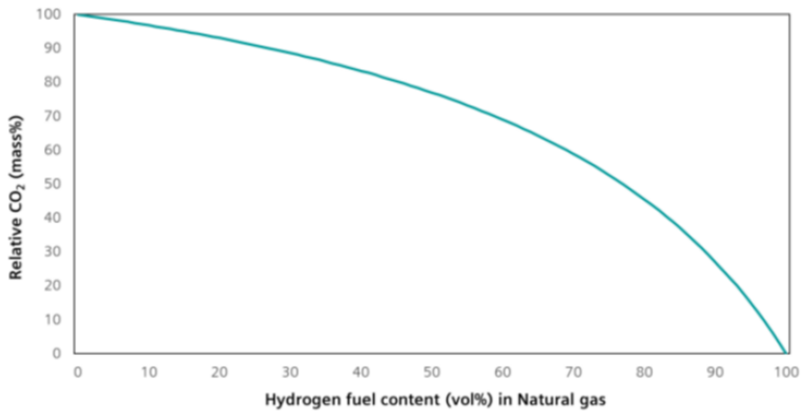


Table 6-1 describes the current capability of various OEMs' advanced gas turbines to generate power with hydrogen-blended natural gas firing. All OEMs covered in this study generally target 100% hydrogen-fired gas turbines by 2030[7], but the current technology commercially available poses limits to maximum amount of hydrogen blending. The combustion of hydrogen-blended fuel in existing gas turbine power plants (using F-class CCGTs) may also be performed via OEM-provided retrofits, which could take around 4 months planning, engineering, and material delivery, plus approximately 2 months for site works completion, allowing 20% to 30% (vol) hydrogen blending.

A major concern for increased hydrogen-firing is the need for a reliable and mature supply chain, infrastructure, and storage facilities to allow long-term sustainable operation with hydrogen-blended natural gas fuel at existing plants and future planned plants. Combustion system design will need to handle specific issues such as flame propagating upstream from the combustion zone into the premixing zone (near the fuel nozzles) due to flame speed of hydrogen, which is higher than many other hydrocarbon fuels, including natural gas. Due to hydrogen's lower volumetric energy density, the fuel system needs to be redesigned as well to allow higher volume flow. Apart from combustor design improvements required to fire higher hydrogen volume in fuel mix, there is also a problem of higher NOx emissions with increased hydrogen blending due to high flame temperature. With increased hydrogen blending, more attention is also needed for material selection and designing the overall safety of fuel supply related systems.

[7] https://www.turbomachinerymag.com/view/gas-and-steam-turbines-adapt.

Table 6-1. OEM Plants' (advanced gas turbines) current capability for hydrogen co-firing (vol% basis)

OEM	Advanced CCGT hydrogen co-firing(vol%)	Project reference
GE	50% With DLN2.6e[8] combustor.	The Long Ridge, U.S. plant[9] which uses GE 7HA.02 combustion turbine, demonstrated capability to co-fire 5% hydrogen(vol) during testing in May 2022. The installed combustion system design allows 15% to 20% hydrogen co-firing for future transition for higher blending and lower emission. GE's factsheet on hydrogen co-firing states that GE advanced gas turbines, 7HAs and 9HAs, are capable of burning as much as a 50/50 hydrogen/natural gas blend when using the DLN2.6e combustor (based on testing facility results).
MHI	30%	Stated figures, as achieved in the Japan combustor testing facility. MHI advised the heat rate at 100% load is higher by around 0.8% (less efficient) with 30% co-firing.
Siemens	30% with SGT5-8000H	H-Class: No actual project. The stated values are results from the combustor testing facility in Germany. The heat rate is approx. 0.4% higher (less efficient) compared to 100% gas-fired operation. For F-Class, the heat rate is approx. 0.2% higher compared to 100% gas-fired operation.

[8] GE's combustor solutions (DLN2.6e and Single annular combustor (SAC), Single Nozzle combustor and Multi Nozzle Quiet Combustors (MNQC) combustors) allow higher hydrogen blending. For H-Class gas turbine DLN2.6e allows up to 50% blending.

[9] Achieved 5% (vol) blending test is considered as the first step for the transition. Further increase in firing will also require suitable blending facility, supply infrastructure.

7. Conclusion

The emissions intensity of power plants is directly influenced by fuel composition and heat rate. The plant heat rate degrades over its operational life. Actual degradation varies in accordance with maintenance works (such as cleaning or replacement of air inlet filters, water washing of the compressor, ball-cleaning of condensers, and other cleaning activities) related to degradation recovery and operating hours of the plant. A higher level of degradation results in lower plant efficiency.

Based on experience, plant heat rate degradation within a particular year varies between non-recoverable degraded condition and total degradation due to plant total equivalent operating hours (non-recoverable) and cleanliness factor (recoverable). Recoverable degradation averages around 0.62% per year and non-recoverable degradation can be around 1.4% in year 25. The expected maximum, averaged-out degradation in year 25 is around 2.08%. These are estimated typical values only and actual plant degradation will vary according to operating conditions and the type of plant.

The emissions intensity values derived in this study is based on a generalised approach based on variation in PLF and corresponding averaged part load factor, and typical degradation trends when a fleet of similar plants are considered. In practice, power generation in any one year will be from multiple power plants that differ in efficiency, operating regime, fuel type, and degradation condition.

Overall, the emissions performance of power plants depends on the OEM technology and plant degradation. However, new advanced CCGTs based on today's technology would be able to achieve around 0.353 tCO_2e/MWh at 75% PLF throughout operational life.

8. References

The following documents were referenced for the purpose of this study:

- Energy Market Authority (EMA) (2020). *Review of Vesting Contract Technical Parameters for the Period of 1 January 2021 to 31 December 2022*
- Energy Market Authority (EMA) (2022). *Energy 2050 Committee Report*: *Charting the Energy Transition to 2050*
- IPCC (2021). *Climate Change 2021: The Physical Science Basis*. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157896.
- IPCC (2006). 2006 IPCC *Guidelines for National Greenhouse Gas Inventories*. Published: IGES, Japan.
- Jacobs (2019). *Facilitating Advanced CCGTs Study*. Technical Parameters for Robinson Bowmaker Paul (H-Class).
- Siemens (2022). *Hydrogen power and heat with Siemens Energy Gas Turbine*. Siemens Technical Paper

Appendix A. Heat Balance

Heat balance was modelled for the following plants:

- GE 9HA.01 CCGT (gas- and diesel-fired operation)
- SIEMENS SGT5-8000H CCGT (gas- and diesel-fired operation)
- MHI M701JAC CCGT (gas-fired operation only)